Understanding the Regulation of Predatory and Anti-Prey Behaviours for an Artificial Organism

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Abstract. An organism's behaviour can be categorised as being either predatory or anti-prey. Predatory behaviours are behaviours that try to improve the life of an organism. Anti-prey behaviours are those that attempt to prevent death. Regulation between these two opposing behaviours is necessary to ensure survivability—and gene regulatory networks and metabolic networks are the mechanisms that provide this regulation. We know that such regulatory behaviour is encoded in an organism's genes. The question is, how is it encoded? The understanding of this encoding can help with the development of an artificial organism, for example an autonomous robotic system; whereby the robot will have the ability to autonomously regulate the switching between the opposing behaviours using this encoded mechanism, in order to ensure its sustainable and continuous system operations. This paper aims to look into the properties of an artificial bio-chemical network consisting of a genetic regulatory network and a metabolic network that can provide these capabilities.

Keywords: artificial organisms, artificial biochemical networks, robotics

1 Introduction

An organism is constantly faced with the dilemma of balancing two principal opposing behaviours: either to perform predatory behaviours or to avoid becoming a prey (anti-prey behaviours). Examples of predatory behaviour include working, fighting and killing in order to gather as much food as possible. Anti-prey behaviours are those that avoid potentially deadly situations or conditions, for example hibernation. If an organism only performs predatory behaviour, it may exhaust itself and have insufficient energy to continue living. If an organism only concentrates on anti-prey behaviours, the organism will be faced with the likelihood of insufficient energy and therefore be unable to survive. An organism must therefore regulate between these two behaviours to ensure survivability.

The authors of [1] describe that the biochemical networks within the body underline the functional and structural complexities within biological organisms. They state that the functionalities of biological organisms emerge from the orchestrated activities of the biochemical networks operating within individual cells.

If we were to develop an artificial organism, for example an autonomous robotic system, (i) how can we categorise the behaviours of the robot into predatory and anti-prey behaviours and (ii) how are these behaviours encoded by its genes. Also (iii) is there a mechanism that regulates and maintains a balance between these two opposing behaviours in order to ensure sustainable and continuous system operations?

This paper attempts to answer these question by investigating how the regulatory balance is achieved for an artificial (single-celled) organism whose behaviour is governed by coupled artificial genetic and metabolic networks (described in [1] and [2]). This paper is further divided into four sections: Section 2 describes what are the predatory and anti-prey behaviours. Section 3 introduces the artificial biochemical network (ABN) and section 4 discusses how the regulation of these two behaviours is captured by the ABN. Section 5 concludes the paper.

2 Predatory and Anti-Prey Behaviours

We propose the categorisation of behaviours into the two opposing predatory and anti-prey categories of behaviours. Such behaviours are observed in nature, both in multicellular and single-celled organisms.

2.1 Single celled organisms

By way of example, we describe the behaviours performed by two types of single-celled organisms, the flora bacteria and bacteriophage lambda:

Bacteriophage lambda survives in two phages. When it infects a host, for example *E. Coli* bacteria, it is either lysic or lysogenic. Lysogenic, the incorporation of the bacteriophage's DNA into *E. Coli*'s genome, ensures the survivability of its DNA through the evolution of the *E. Coli* bacteria. Lysic causes the destruction of its host to create more offspring. The bacteriophage becomes lysic when it senses its host is unhealthy [3]. We can thus characterise lysogenous as anti-prey phage (behaviour) and lysis as predatory phage.

Flora bacteria, in turn, ensure their survivability by continually resisting their destruction within the hostile environment of the human gut. Flora bacteria perform this functionality by creating a symbiotic relationship with the human gut. The flora bacteria must also ensure they have sufficient energy, by capturing the available energy resources within the human gut, in order to reproduce (and therefore evolve) at a high rate and prevent the eradication of their species [4]. The symbiotic behaviours can be categorised as anti-prey behaviour (since a human can survive with no flora bacteria) and to eat and reproduce at a high rate can be considered as predatory behaviours.

2.2 Early multi-cellular organisms

Early multi-cellular organisms or colonies of single-celled organisms coordinate their individual behaviours for the greater good of the collective. An example of

early multi-cellular organism is the social amoeba *Dictyostelium discoideum* [5]. The collective and singular behaviour of the single-celled organisms can also be categorised in these two categories of behaviours. The organism(s) must find food (fight, kill and eat) in order to have sufficient (collective) energy to construct shapes or move in the environment. This allows the colony to escape and/or avoid danger from other predators or the effects of its environment. The former can be characterised as predatory behaviour and the later as anti-prey behaviour.

Sufficient energy is also necessary for reproduction. To ensure sufficient energy for the collective, unhealthy cells will scarify itself (apoptosis) for the greater good of the collective. This behaviour can also be characterised as anti-prey behaviours [5].

2.3 Regulation between the two opposing behaviours

Because of the simplicity of the single-celled organisms, the regulation of the single celled organism's behaviours is directly provided by the genetic regulatory network or GRN [5], [6]. Therefore, this blueprint that governs the characterisation and the switching between these two categories of behaviours can help us with (i) the characterisation of the system's behaviours for an artificial organism into the two opposing categories of behaviours: predatory and anti-prey, and (ii) to allow the regulation that controls the switching between these two categories of behaviours to ensure stable system (equilibrium) is achieved and maintained.

The authors of [2] noted that the most significant interaction between biochemical networks in biological cells is the manner in which the genetic network controls when and where proteins are expressed, and thereby determines which enzymes are present in the metabolic network and hence which reactions can take place within a cell. In effect, the genetic network is able to reconfigure the cell's processing machinery over the course of time.

Therefore, we proposed the use of an artificial bio-chemical network to help answer our presented questions.

3 Artificial Biochemical Network

The coupled artificial biochemical network (ABN) model presented in [1] comprises an artificial genetic regulatory network (AGN) coupled to an artificial metabolic network (AMN) using a function $X : g_C \rightarrow E$, where $g_C \subseteq G$ is the set of enzyme coding genes (each enzyme (e_i) coupled to a single gene (g_i)). Coupling is achieved by giving each enzyme an expression level Ei set to the expression level of the gene it is coupled with, $\forall(g_i, e_j) \in X : Ej := Gi$. This expression level then determines the relative influence of each enzyme when calculating the new concentration of a chemical, $X : E \rightarrow C$. This captures the idea that changes in the genetic network lead to changes in the balance between competing pathways in a metabolism [1].

The genetic coding for the ABN (Fig. 1) originally presented in [1] and [2] is used. The sigmoid function $f(x) = (1 + e^{s \sum wx+b})^{-1}$ is used as the regulatory

function $f_i(x)$ (that determines the gene expression level Gi) and metabolic reaction $m_i(x)$ (that determines the chemical expression C_i). wx is the weighted sum inputs to g_i and C_i, s is the slope and b is the bias ($b = 0$). The sigmoid function was chosen because this function allows easy inference of whether a gene and/or enzyme is generating predatory or anti-prey behaviours.

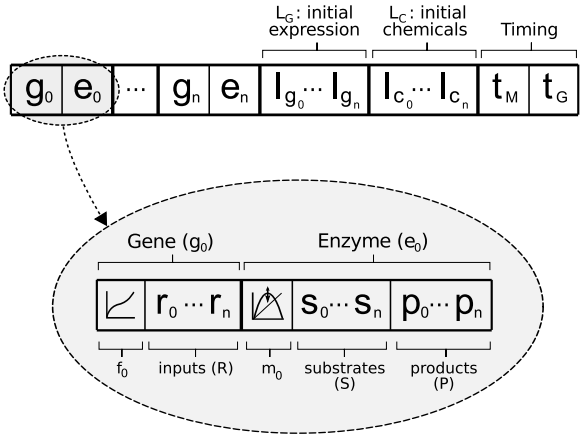

Fig. 1. Genetic encoding of an artificial bio-chemical network, taken from [1]. $s_i := Gi := Ei$ and $p_i := C_i$.

4 How are the behaviours encoded within the networks?

To investigate how behaviours are executed and regulated by the ABN, a population of 100 ABNs were evolved using a multi-objective evolutionary algorithm. Each ABN is evolved to allow the artificial (single-celled) organism the ability to perform the three basic survival behaviours:

1. When an organism is exhausted, it requires "food" to replenish its demand for energy (E_D). When in this state, the organism must make use of the available energy resources in the environment (E_R), in order to meet with the energy demand of the "body".
2. If the environment provides more "food" than it requires, the organism should not consume the excess energy resources but rather to save the excess resources (S_E) for later usage; for example at a time of limited "food" availability. This is because over-indulgence can cause the organism to become lethargic, and limits its capabilities. A failure to save the excess energy resources can cause "starvation" (at times of limited "food") and thus limit the organism's ability to survive.
3. At times of limited food, the organism should use the previously stored energy resource (E_S) to meet with its demand for energy.

For the experiments, E_D and E_R are visualised as sinusoidal values with a minimum level of 0 indicating zero energy demand and energy availability and a maximum level of 1 indicating maximum energy demand and energy availability (illustrated in Fig 4) and are the inputs signals to the ABN.

In summary, the ABN for the artificial organism (the robot) will carry out the following regulatory behaviours in order to ensure the survivability of the organism:

1. make use of the available energy resource (E_R) to meet with the required energy demand (E_D), $U_E = E_R.C_{O2}$,
2. save energy (S_E) in storage E_S, $S_E = E_R.(1 - C_{O2})$ and $E_S = E_S + S_E$.
3. use energy in E_S to help meet with the demand E_D, $U_E = E_S.C_{O1}$ and $E_S = E_S - U_E$.

Each ABN consists of 6 genes, comprising 54 weights (w) and 6 slopes (s), coding for 6 gene expression levels leading to the production of 2 chemical outputs C_{O1} and C_{O2} ($6w$ and $2s$) that govern the three described behaviours. $w \in [-1, 1], s \in [-1, 1]$ and $C_{Oy} \in [0, 1]$. The values of w and s are evolved so that the best evolved ABNs achieved the fitness objectives of:

1. $E_D \approx (U_E + U_S)$.
2. $S_E > 0$.

4.1 The evolved ABN

After investigating the properties of the evolved ABNs in the population, the following observations were made:

1. to make use of the available energy in E_S to meet with the required E_D is considered as anti-prey behaviour. This is because the best evolved ABNs (ABN B and ABN E - Fig. 8) have $C_{O1}(x) < 0.5$. [1].
2. to use E_R to meet with the required E_D is considered as as predatory behaviour because $C_{O2}(x) > 0.5$.

These observations show that behaviours of the artificial organism can be placed into the two categories: (i) predatory and (ii) anti-prey; and that the genes' and enzymes' w and s values encode these behaviours. If incorrect values of w and s are used within the AGN, the artificial organism has a lesser inability to meet with E_D.

If we compare ABN A and ABN B (see Fig 4), ABN B is more effective at meeting with E_D, since $(U_E + U_S) - E_D$ is larger for ABN A than ABN B. This is because, if we follow the previously stated rules:

1. If the gene is always producing $g_y(x) > 0.5$, this gene is considered a predatory gene.
2. If the gene is always producing $g_y(x) < 0.5$, this gene is considered a anti-prey gene.

[1] $C_{On}(x) = m_n(x) = (1 + e^{(s \sum w(x))})^{-1}$.

ABN B has 3 predatory genes, 2 anti-prey genes and 1 neutral gene[2], in comparison to ABN A that has 4 predatory genes, 0 anti-prey genes and 2 neutral genes. The additional anti-prey genes for ABN B allows the organism to perform the anti-prey behaviour of using available energy in E_S to meet the required E_D more effectively. Figure 2 illustrates that solutions with similar network characteristics have greater ability to meet with E_D.

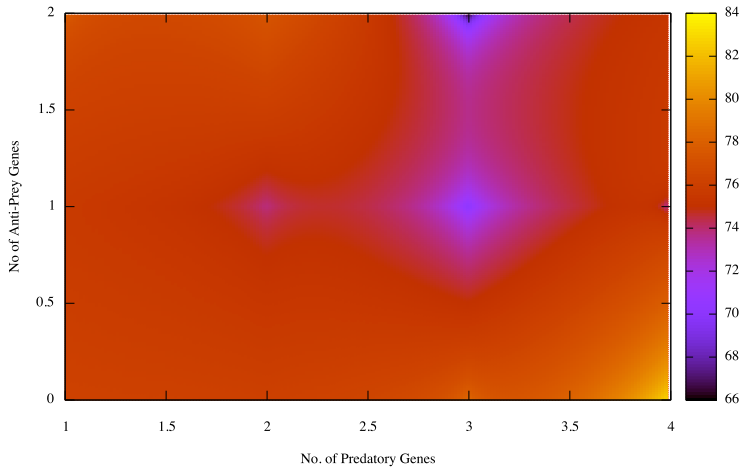

Fig. 2. The relationship between the number of anti-prey and predatory genes within the AGN and the organism's fitness value. Each AGN consists of 6 genes. Three types of gene characteristics were found. If a gene is constantly producing $g_y(x) > 0.5$, this gene is considered a predatory gene. If a gene is constantly producing $g_y(x) < 0.5$, this gene is considered a anti-prey gene. If the gene oscillates with a mean of 0.5, this is considered a neutral gene. The lower the fitness value the better the AGN is at meeting its E_D. AGN B and E have fitness values of 64. The figure shows that the organism requires all the predatory genes, anti-prey genes and the neutral genes in order to meet its objectives, with the best network configuration of 3 predatory genes, 2 anti-prey genes and 1 neutral gene within the AGN. Note: the 1/2 values in the x- and y-axis should be ignored.

Figure 2 illustrates that there are two best network configurations:

1. 3 predatory genes, 2 anti-prey genes and 1 neutral gene, or
2. 3 predatory genes, 1 anti-prey gene and 2 neutral genes

[2] its values oscillate with a mean of 0.5

Figure 3 shows that in order for the second network configuration to produce the desired output, its C_{O2} should produce more < 0.5 values (and code for anti-prey behaviour). If this balance is not created, the organism will be unable to meet with E_D.

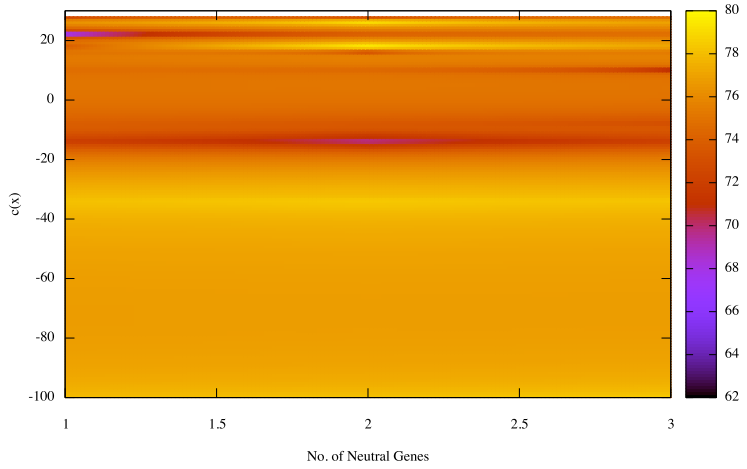

Fig. 3. If there are 3 predatory genes, 1 anti-prey gene and 2 neutral genes, C_{O2} should encode for anti-prey behaviour to allow the organism to meet with E_D. $c(x) > 0$ indicates that C_{O2} codes for predatory behaviour and $c(x) < 0$ indicates that C_{O2} codes for anti-prey behaviour. If $C_{O2} > 0.5$, $c(x) = c(x) + 1$ and if $C_{O2} < 0.5$, $c(x) = c(x) - 1$. Initially $c(x) = 0$. Note: the 1/2 values in the x-axis should be ignored.

4.2 Assigning the w and b values

Comparing ABN G with ABN F, Fig. 6 shows that the more similar $+w$ values (and the higher their magnitude) are for a gene, the higher the likelihood the gene will be turned on ($g_1 - g_3$ of AGN G). The more similar are the $-w$ values (and the higher their magnitude) for a gene, the higher the likelihood that the gene will be turned off; for example C_{O1} and C_{O2} of AGN G (Fig. 5). Also, the less varying the w values (for example the large number of w with $+0.2 < w < 0.2$ for g_4 of ABN F), the less likely that the gene will become an oscillator. Similar observations were made when comparing AGN E and AGN H (Fig. 7).

These results agree with the observations presented in [3] and [6], where the authors state that the cell behaviour is produced through the interplay between

positive regulation and negative regulation, creating a behavioural toggle switch with sustained oscillation [3], [6].

5 Conclusion

If we were to develop a biochemical network controlling the behaviour of an artificial organism, for example an autonomous robotic system:

1. how can we categorise the behaviours of the robot into the two opposing predatory and anti-prey behaviours?
2. how are these behaviours encoded by its genes?
3. is there a mechanism that regulates and maintains a balance between these two opposing behaviours in order to ensure sustainable and continuous system operations?

Based on our observations presented in this paper, we can state the following heuristics:

1. If we wish to encode for a predatory behaviour, the chemical output leading to this behaviour should be: $C_y(x) > 0.5$.
2. Similarly, if we wish to encode for an anti-prey behaviour, the chemical output should be: $C_y(x) < 0.5$.

Furthermore, to allow the genes to act as a toggle switch which enables oscillation between the two opposing categories of behaviour, the AGN should consist of approximately:

1. 50% predatory genes or genes that are constantly producing $g_y(x) > 0.5$.
2. 25% anti-prey genes or genes that are constantly producing $g_y(x) < 0.5$.
3. 25% neutral genes or genes that oscillate with a mean of 0.5.

If there are more neutral genes in the AGN in comparison to anti-prey genes, one of the C_{Oy} that codes for a predatory behaviour should code for an anti-prey behaviour instead.

Also,

1. The more positive weights w within a gene/enzyme, the higher the likelihood for the gene/enzyme to be switched off.
2. The more negative weights w within a gene/enzyme, the higher the likelihood for the gene/enzyme to be switched on.
3. The more varied its weights w, the higher the likelihood that the gene/enzyme will become an oscillator.

In future work, we plan to use the above heuristics as guidelines when evolving an ABN for an artificial organism that is to perform two opposing categories of behaviour. A potential example of this is an autonomous robot with self charging capabilities, where the robot must perform its functionalities whilst ensuring a sustainable amount of energy is maintained within the system.

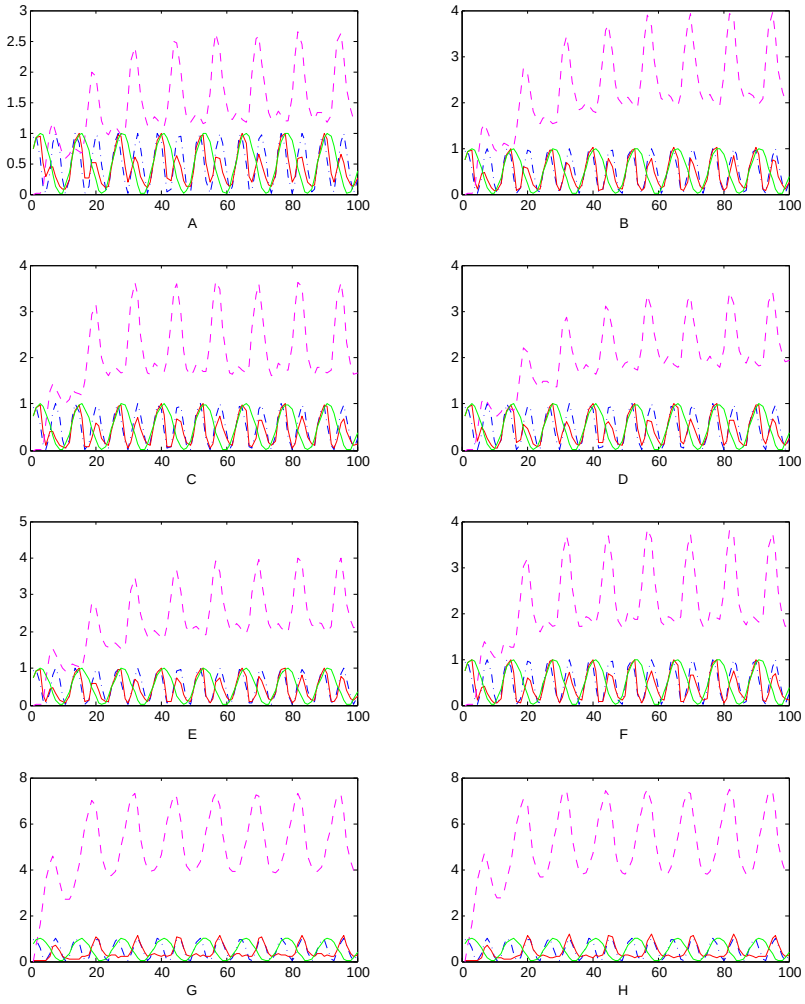

Fig. 4. The outputs produced by eight evolved ABNs. Red line = $U_E + U_S$, blue line = E_D, green line = E_R and the magenta line = S_E.

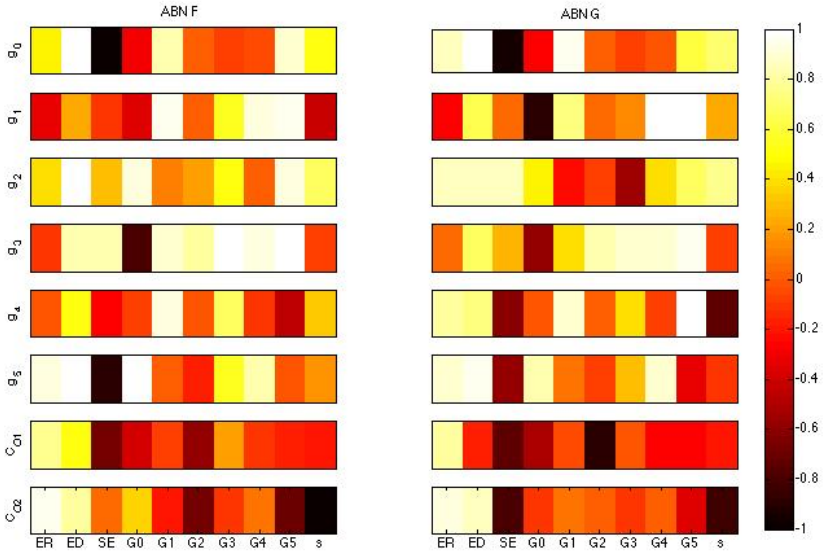

Fig. 5. The w and b values for the ABNs.

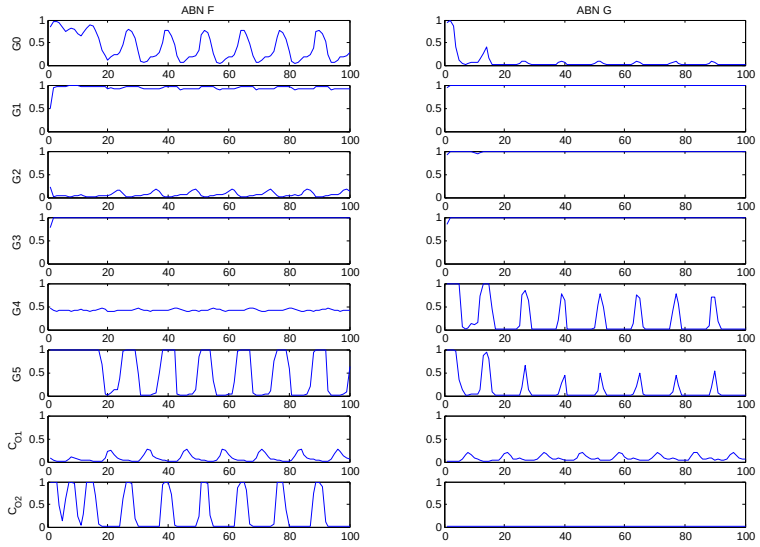

Fig. 6. The genes (g_x) and chemical expressions (C_{Oy}) for the ABN. C_{O2} indicates how E_R is to be used and C_{O1} coordinates how S_E is to used.

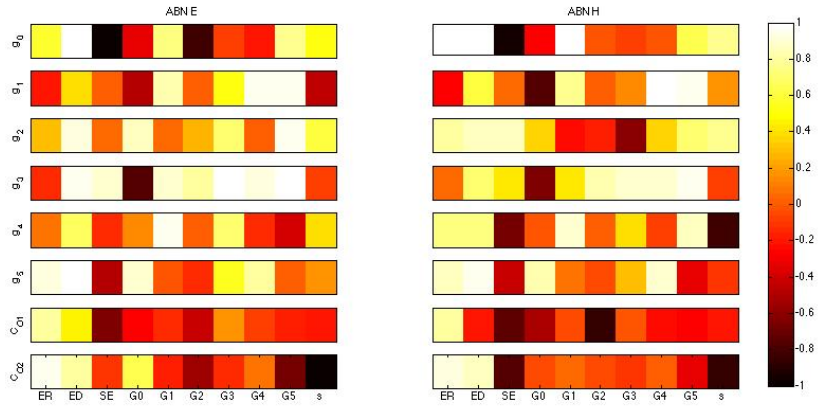

Fig. 7. The w and b values for the ABNs.

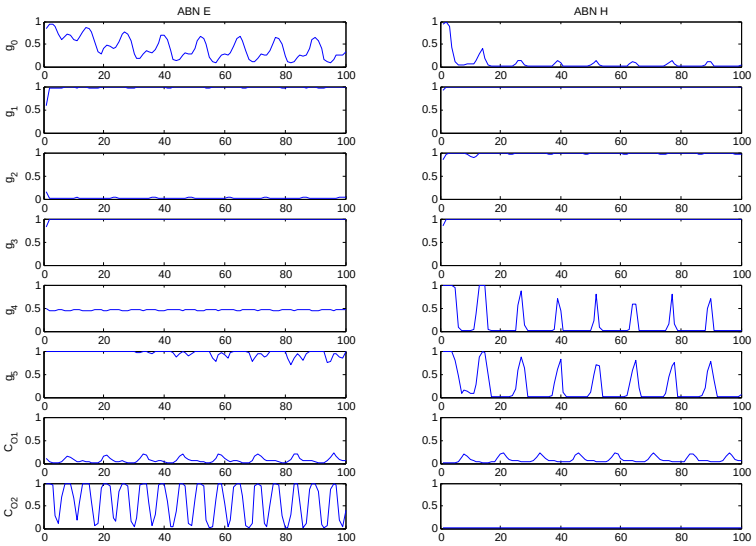

Fig. 8. The genes (g_x) and chemical expressions (C_{Oy}) for the ABN. C_{O2} indicates how E_R is to be used and C_{O1} coordinates how S_E is to used.

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