Can Developmental Biology Inspire Amorphous Computing?

David Irons and Nick Monk
The Kroto Research Institute
University of Sheffield, North Campus, Sheffield, S3 7HQ, UK
Phone: +44 114 222 1956, Fax: +44 114 222 5945
email: {d.irons, n.monk}@sheffield.ac.uk

ABSTRACT: Systems constructed from vast numbers of tiny processors / sensors, connected together in a non-prescribed way, form the basis of novel computing paradigms such as amorphous computing, ubiquitous computing and pervasive computing. Within these systems, the individual computational units may be fragile, unpredictable and only able to communicate locally. However, despite these individual restrictions, they still need to be able to self-organise to robustly and efficiently carry out a set of collective functions. By looking at the development of multicellular organisms, this paper examines how the challenges faced by these amorphous systems are similar to those faced by, and solved by, biological systems. We also examine the properties of developing systems that may be useful for amorphous computing; such as self-organisation, robustness and scalability.

Keywords: Developmental Biology, Amorphous Computing, Task Allocation, Pattern Formation, Robustness, Scalability

INTRODUCTION

The term ‘amorphous computing’ originated from the Massachusetts Institute of Technology, when researching large systems of “irregularly placed, asynchronous, locally interacting computing elements” ([1], [2]). This field of research overlaps with that of other new computing fields, such as ubiquitous computing, pervasive computing and ad-hoc networks. What is fundamental to all these areas is the idea of having vast numbers of computational nodes, which communicate locally and combine to carry out a specified global task. Moreover, it is likely that the underlying communication network is not prescribed, so that each node must use local information to decide which other nodes to communicate with and what task / function to perform. It may also be the case that nodes are identically programmed, can enter the system, leave the system, are error prone and / or are mobile.

One example of such an amorphous computing system is a wireless sensor network (see Figure 1:), where sensors capable of wireless communication are spatially distributed to monitor environmental features such as heat, light, sound and / or motion. These sensor networks are already in use, with a wide range of applications including monitoring volcanoes [3], monitoring crops [4] and monitoring hospital patients [5]. Analogous systems of vast numbers of minute microcomputers, sprayed across an area to execute a function / program, are also envisaged [6]. The future of these systems will be reliant on flexible, intelligent, local communication as sensors / processors decrease in size and become more numerous. Moreover, strategies using flexible local interactions to determine global behaviour could be useful for existing technologies such as mobile networks, peer-to-peer networks and distributed computing.

The current literature describes numerous challenges facing these emerging fields (e.g. [2], [7], [8]). Firstly, even though the nodes may start off identically programmed with no idea about their geographical ‘position’, each one still needs to decide which tasks / functions to carry out to achieve the global aim. Nodes may also need to adapt and change their task in response to changes in the environment. A second challenge is that the whole system needs to be scalable, so that the precise number / density of nodes does not affect the global function of the system. A third challenge is robustness, so that the global properties of the system are reliably achieved despite the fact that nodes may be irregularly connected and susceptible to failure. When nodes fail or send out inappropriate signals, the system must be able to adapt accordingly. In the case of wireless sensor / processor networks, there are further challenges. Wireless nodes only have a limited power source and so need to be as energy efficient as possible. One way in which improved efficiency can be achieved, is by reducing the range of the wireless transmitter (i.e. only using local interactions) and strategically putting individual nodes on standby when not required. A further challenge is to create an efficient

coordinate system so that each node is aware of its geographical position. It is possible to estimate the relative position of each element by comparing it's location to local reference points (e.g. [9]), such as sensors that have already identified their location. However, setting up or reacting to such a prescribed co-ordinate system could be restrictive and not take account of the scale / range of the whole network.

Some of these challenges are faced by, and solved by, biological systems. During the development of multicellular organisms, groups of seemingly identical cells must differentiate in a very precise manner so that the adult has all of the correct features in all the correct places (e.g. eyes, legs, fingers etc). This is not achieved by a global regulator; rather each individual cell uses local information to receive signals, transmit signals and 'decide' its eventual fate. In fact, since cells are irregularly shaped, looking at the local connections between them gives rise to an irregular lattice analogous to one expected for an amorphous system (see Figure 2:). Therefore, it is reasonable to assume that regulatory signalling mechanisms underlying development could be mimicked within amorphous systems.

There are many reasons why one may want to do this, since many of the properties of developmental biology represent possible solutions to the challenges that amorphous systems face. Firstly, development of multicellular organisms is scalable so that tissues / organs are always in the correct proportions, even though the exact size and number of cells is variable (from one individual to the next). Moreover, development can still robustly take place, even though important regulatory and signalling mechanisms (e.g. transcription, translation and protein interactions) are 'noisy' [10], environmental conditions are changeable and cells are susceptible to DNA damage and death. It is not that developing systems are exact models for amorphous computing, but rather the regulatory mechanisms underlying development could help find solutions for **some** of the challenges faced within amorphous computing.

For the remainder of this paper, we review some of the key regulatory mechanisms and properties associated with the development of multicellular organisms. In particular, we focus on properties that overlap with those challenges of amorphous systems, namely

1. Cells types are correctly specified based on their 'relative position'.
2. Development of multicellular organisms is scalable.
3. Development of multicellular organisms is robust.

Further biological properties, such as adaptability and versatility, which could be advantageous to amorphous computing systems, are also considered in the discussion.

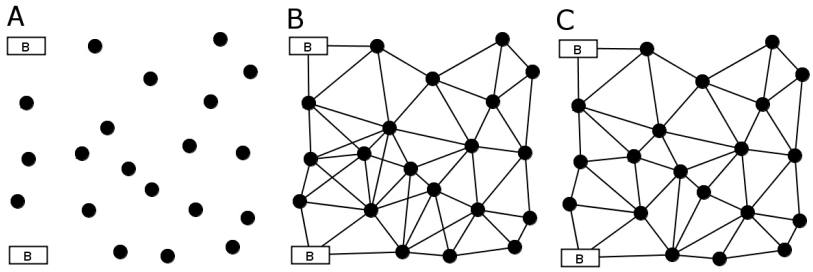

Figure 1: (A) Possible set-up for a wireless sensor network or network of wireless microprocessors. Here nodes are spatially distributed (irregularly), along with base stations that retrieve the data from the rest of the nodes. (B) Network formed when each node communicates (by line of sight) with all other nodes within a fixed radius. (C) The resulting network if edges are not allowed to cross in (B)

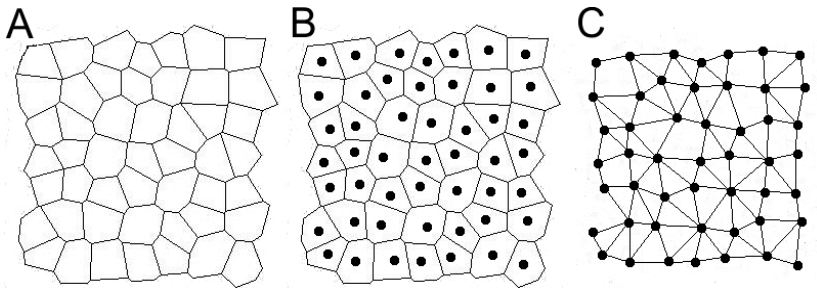

Figure 2: (A,B) Biological cells often form irregular lattices with cells varying in size and shape. (C) The local interactions amongst these cells can also be viewed as irregular local interactions between irregularly distributed nodes, as may be the case in amorphous computing (see Figure 1:B,C).

DEVELOPMENT OF MULTICELLULAR ORGANISMS AND THEIR DESIRABLE PROPERTIES

KEY MECHANSIMS UNDERLYING CELL TYPE SPECIFICATION DURING DEVELOPMENT

In developing systems, a hierarchical cascade of regulatory events leads to each cell being correctly specified in the correct position within the organism. This notion of cells being able to determine their position is commonly known as 'positional information', which was first popularised by [11]. One common mechanism underlying positional information is the establishment of morphogen gradients (Figure 3:), whereby cells in a localised signalling centre (often a boundary) produce factors (morphogens) that diffuse away from source and affect neighbouring cells in a concentration dependent manner. Many different factors act as morphogens during development, including a range of secreted proteins and small molecules such as retinoic acid. Although the morphogen signal itself is continuous (Figure 3:A,B), inter and intra cellular interactions are able to process this signal in such a way that the response of each cell is discrete and dependent on its distance from the source (Figure 3:C). This is achieved by internal cellular mechanisms that have a small number of states, each triggered by a discrete range of signal strength. While these gradient interpretation mechanisms are often rather imprecise, further signalling between cells can be used to achieve local consensus [12]. As well as signal strength, signal duration can also influence a cell's response [13].

One of the effects of morphogen gradients is the establishment of a series of boundaries that spatially demarcate groups of cells, based on their position within the developing organism. During the early stages of development of the wing of the fruit fly *Drosophila melanogaster*, morphogen gradients running perpendicular to one another give rise to several boundaries that create a 2 dimensional grid coordinate system (Figure 4:). It is this coordinate system that controls which cells become vein cells, inter-vein cells and hair cells, as well as controlling wing growth and shape. As well as influencing cell type specification, morphogens can also exert their influence on development by regulating cell proliferation and growth. For example, in the *Drosophila* wing, the slope of the gradient for the morphogen Dpp plays a role in regulating cell proliferation [14], with cells growing and proliferating where morphogen concentrations differ significantly between cells (i.e. where the gradient of the slope in Figure 2:A is large).

Since boundaries are crucial to the regulation of developing organisms, it is also crucial that they are properly aligned and maintained. Local cell-cell interactions and affinities are crucial when forming and maintaining boundaries. At the dorsal-ventral boundary in the *Drosophila* wing (the central vertical boundary in Figure 4:E), local cell-cell interactions amongst dorsal cells expressing Apterous (Ap) and ventral cells (that don't express Apterous), lead to the expression of Notch (N) in a 2-cell wide stripe. Apterous and Notch then combine to ensure an affinity difference between dorsal and ventral cells [15], which ensures the two cell populations remain spatially separated and the border is maintained (i.e. cells with different affinities are pushed away from one another)

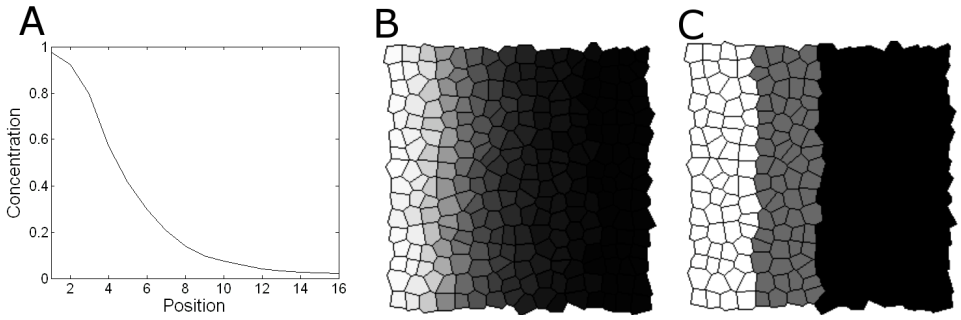

Figure 3: Classical view of morphogen gradients and 'positional information'. (A,B) Proteins called morphogens are produced from the leftmost row of cells and then diffuse across the array. The process of morphogen production, diffusion and degradation gives rise to a concentration profile called a 'morphogen gradient' (B is a visualisation of the profile in A). (C) Cell type specification occurs in response to the local morphogen concentration, with different thresholds causing cells to be specified according to their distance (position) from the source.

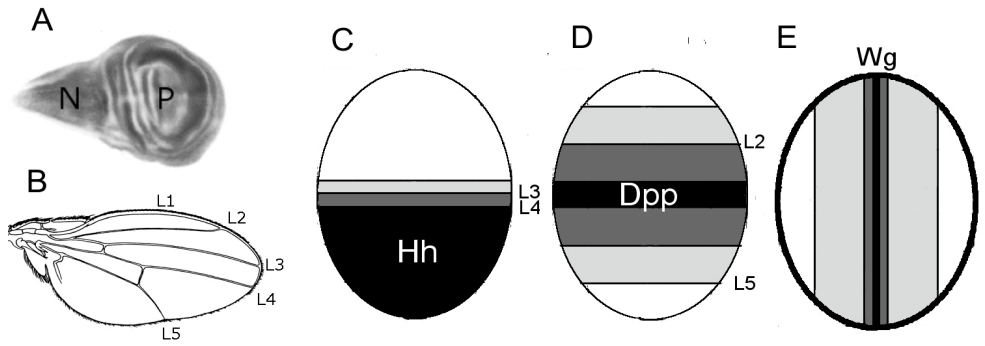

Figure 4: (A) The wing disc is a collection of cells that eventually develops into the adult wing (pictured in B). The wing disc consists of several compartments including the notum (N) and wing pouch (P). (C-E) 3 morphogens Hh, Dpp and Wg are produced in the wing pouch. These morphogen give rise to several boundaries that control wing development and the position of the longitudinal veins (L2 – L5). Superimposing C, D and E, it is evident that we get a grid made up of many compartments, each one corresponding to a distinct gene expression profile. (B) Figure reprinted from [25] (pg 1066), with permission from Elsevier.

Boundary formation and signalling is often hierarchical during development, with boundaries produced from one morphogen acting as a signalling centre to express secondary morphogen gradients, which trigger more specialised regulatory events later on in development. Moreover, these secondary signals may act to preserve the boundary and maintain its relative position (compared to other boundaries). For example, during zebrafish development, the midbrain-hindbrain boundary (MHB) forms in response to the Wnt8 morphogen gradient ([16], [17]). The MHB then acts as a signalling centre, producing morphogens such as Fgf8, which regulate specification in adjacent cells and maintain the position of the MHB relative to other boundaries in the neural tube [17].

SCALABILITY DURING DEVELOPMENT

Scalability is present at all stages of development to ensure that limbs, tissues and organs are positioned appropriately along the body plan, regardless of its exact size. For example, although the size of human heads can be highly variable, eyes are positioned approximately 50% along the vertical head axis.

Although controlling growth plays a role in scalability during some aspects of development, there are many cases where this is not the case. For example, scalability has been studied and experimentally observed in early *Drosophila* embryonic development where individual embryos are not growing in volume. Here, the boundary of *hunchback* (*hb*) expression is correctly proportioned (49 ± 1% along the embryo), despite embryo to embryo size variations and embryo to embryo variability in the gradient of the upstream morphogen Bicoid [18]. The precise mechanisms that underlie scalability, in this case, are not precisely understood and it is doubted whether a single morphogen, produced at one pole of the embryo, is sufficient to achieve this. Some papers have proposed models involving a second competitive morphogen, produced from the opposite pole ([19], [20]). However, there is currently no experimental evidence of a secondary morphogen and the origin of scalability in this case is still an active area of research.

Another form of scalability can be seen when looking at homologous structures, which vary in size within an individual. For example, human fingers and toes are different sizes but analogously proportioned. In *Drosophila*, there are two different flight appendages, the wings and the halteres (where the halteres are essentially miniature versions of wings). Here, expression of the gene *Ultrabithorax* (*Ubx*) in the haltere (but not the wing) limits the range of the morphogen Dpp and its effect on cell proliferation [21]. Therefore, in Figure 4:D, the same outer boundaries exist but at a closer distance to the central boundary. Although this single gene does not fully explain the differences between wings and halteres, it provides a clue as to how the size of digits / limbs / appendages can be regulated without affecting the proportions of the digit / limb / appendage itself.

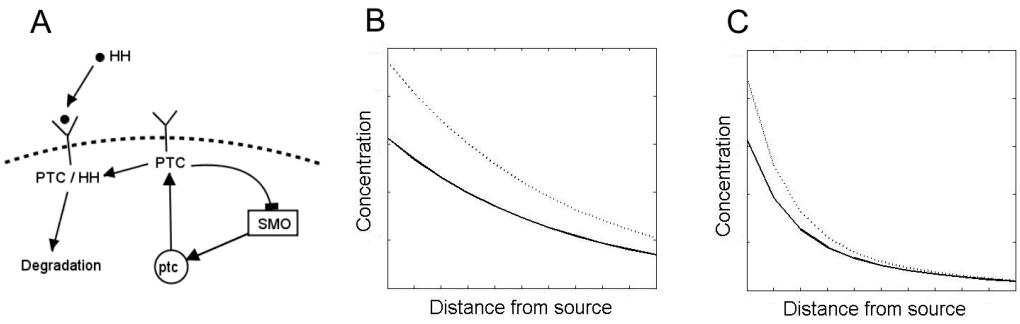

Figure 5: Robustness of the Hedgehog (HH) gradient (seen earlier in Figure 4:C). (A) HH and PTC form a feedback loop so that the more extra-cellular HH there is, the more PTC is produced and the more HH is captured (preventing its diffusion to neighbouring cells). When extra-cellular HH binds to the cellular receptor PTC, it removes PTC from the cell surface and leads to its degradation. This in turn frees up SMO which leads to the production of more PTC. (B) Morphogen gradient **without** the feedback loop in A. (C) Morphogen gradient **with** the feedback loop in A. 50% increase in morphogen production (dotted line vs normal line) is buffered when feedback exists, so that the lower end of the morphogen gradient is still extremely reliable. Simulations are based on the model in reference [22].

FEEDBACK, ROBUSTNESS AND FAULT TOLERANCE

Cells are inherently 'nosiy', in that gene expression (and hence protein production) is highly variable from one cell to the next [10]. Hence, morphogen production can also be variable and noisy, and so the developing system needs to be able to filter out any irregular / unwanted signals. A common regulatory mechanism used by cells to respond to morphogens is signal-induced feedback (Figure 5:), whereby the cellular response of morphogen signalling regulates cell surface receptors (which in turn affect the morphogen gradient). In some cases, it is believed that these feedback mechanisms can ensure morphogen gradients are robust to genetic or environmental fluctuations that alter production rates at the source [22]. Such feedback can lead to non-linear morphogen degradation, whereby at high concentrations, the feedback mechanism increases degradation and reduces the amount of morphogen that diffuses away from the cell. On the other hand, at low concentrations, degradation occurs at a lower rate and the morphogen can diffuse across the field (as it would do without feedback). The overall effect of this is to buffer against high morphogen production rates, whilst still allowing the morphogen gradient to form (Figure 5:C).

As well as being robust against noisy / unpredictable signals, developing systems are also robust to failures in individual cells. Organisms will still continue to develop normally despite the fact that cells are damaged and die (because of either internal DNA damage or external environmental effects). In some cases, developing organisms can even adapt to massive multicellular faults / alterations. For example, in the amphibian *Xenopus*, the tail is able to grow back (regenerate) after it has been amputated [23]. Although the mechanism for this is not completely understood, experimental evidence exists that indicates the morphogen BMP plays a role. It is interesting that this regenerative process is affected by a morphogen, indicating that the mechanisms underlying regeneration are linked to those directing normal development.

DISCUSSION

In amorphous computing systems, vast numbers of computational nodes (sensors / processors) must use local information and communication, so that system carries out the correct global task. Presented in this paper, is a discussion that rationalises why regulatory mechanisms from developmental biology may be of assistance when designing these amorphous systems. Much of the focus has been on the biological mechanisms themselves, since a good understanding of them is required if they are to be successfully transferred to computing problems.

During development, a hierarchical cascade of signals 'patterns' the organism by creating boundaries and compartments. These boundaries and compartments create an inherent coordinate system that allows cells to be specified based on their 'position' within the organism. Since this process is robust and scalable, it is reasonable to assume that the logic / mechanisms underlying development will be advantageous to amorphous computing systems.

Moreover, the developmental processes discussed here can be modelled using only local interactions between cells (as may be necessary in amorphous computing). The individual cells themselves only use local information to determine which genes they express and at what levels they express them. This in turn determines the eventual fate / function of the cell. Even the diffusive movement of morphogens can be modelled on the local cellular level. In numero, this can be done by cells adjusting their morphogen concentration based on (a) a diffusion coefficient, (b) the average morphogen concentration from surrounding cells and (c) the amount of morphogen being produced from the cell itself, if any. In fact, cellular modelling of morphogens is essential, since interactions between extra-cellular morphogen levels and cell-surface receptor levels occur at the cellular level.

We do not claim that amorphous computing systems should just replicate developmental biology. It is just that many of the challenges faced by amorphous computing are the same as those faced by, and solved by, developing organisms. Where these challenges overlap, it is plausible that developmental biology can help provide a solution or a trick to solve it. This is especially true since developing organisms primarily use local information to transmit and react to signals. This paper focussed on three challenges where these overlaps occurred, namely (1) assigning nodes tasks / functions based on their position within the system, (2) robustness and (3) scalability.

However, there are many other biological properties, not explicitly discussed in this paper, which could be of use to amorphous computing. Firstly, although we have focussed on boundaries and compartments, many other patterns are regulated at the cellular level. For example, 'lateral inhibition' can ensure two cells of a particular type don't occur next to one another (a mechanism that is directly applicable to amorphous computing). Other patterns such as spots, stripes and patches are also prevalent in biology. Secondly, biological systems have evolved so that they can appropriately adapt to changes in the environment. For example, stomata on plant leaves and stems adapt to variations in light, CO_2 and hormone levels to control water levels [24]. Moreover, different species have evolved to specialise in different conditions. Understanding both the cellular responses and evolutionary changes in these systems could help develop adaptive strategies for amorphous systems. Thirdly, cellular mechanisms within biological systems are very versatile, in that they can be re-used in multiple settings to give different results. For example, the morphogen Dpp forms a gradient at different stages of *Drosophila* development, with different context dependent effects. Such versatile approaches allow biological systems to evolve, and achieve greater functionality, with relatively few new genes / proteins (if any). Such versatile (or modular) approaches in amorphous computing would allow the engineer to adapt systems, without the need for large scale reprogramming.

During the development of multicellular organisms, there are stages where the system is growing and there are stages where the system is not growing. For example, there is no growth during early *Drosophila* embryonic development or *Xenopus* mesoderm induction, but growth is involved in *Drosophila* wing development. Scalability, robustness and other desirable properties are found in both of these cases and, if trying to apply mechanisms from developmental biology to amorphous computing, it may be advantageous to focus on a stage that best matches the computing problem. Take for example wireless sensor networks, where it is often the case that a fixed number of nodes are spatially distributed and then remain static. Here, mechanisms from the 'no growth' biological examples could be applied directly with little fuss. However, it is still possible that mechanisms from the 'growth' examples could be applied to static wireless sensor networks. Starting from a small group of nodes in the centre of the system, a subsystem could grow outwards as more nodes are added to it. In such a scenario, a new node would impose itself on an existing node within the subsystem (node A). The previous node A would then get pushed away and transfer its information to a neighbour (node B), and so on and so on until an unspecified node is reached on the outside of the subsystem. Mechanisms based on cell affinity differences, between different cell types, could be used to ensure boundaries are maintained and nodes are pushed in the correct direction.

Controlled cell proliferation, in the stages of development where growth is a factor, can act as an inspiration for other computing problems. In distributed systems, such as peer-to-peer networks, nodes can enter and leave the system over time and are allocated one of a number of files are they enter. Rather than a node being allocated files according a master program, it may be beneficial for the existing nodes themselves to work out what extra files are required within their local environment. These nodes could then send out a call to 'recruit' an extra node as it enters the system. Such an approach would be related to cell proliferation in developing systems, because cell proliferation is often controlled and regulated by local interactions between cells. This controlled approach ensures that cell proliferation occurs when the system needs more cells of a particular type in a particular place.

REFERENCES

[1] Abelson, H., Allen, D., Coore, D., Hanson, C., Homsy, G., Knight, T., Nagpal, E., Sussman, G., and Weiss, R. 2000. "Amorphous Computing*", Communications of the ACM*, **43**(5), 74 - 82.

[2] Coore, D. 2005. "Introduction to Amorphous Computing", *Lecture Notes in Computer Science*, **3566**, 99-109

[3] Werner-Allen, G., Johnson, J., Ruiz, M., Lees, J., and Welsh, M. 2005. "Monitoring volcanic eruptions with a wireless sensor network", in *Proceedings of the Second European Workshop on Wireless Sensor Networks* (EWSN'05)

[4] Burrell, J., Brooke, T., and Beckwith, R. 2004. "Vineyard computing : Sensor networks in agricultural production", *IEEE Pervasive Computing*, **3**, 38-45

[5] Fulford-Jones, T., Malan, D., Welsh, M., and Moulton, S. 2004. "CodeBlue: An ad hoc sensor network infrastructure for emergency medical care", in *International Workshop on Wearable and Implantable Body Sensor Networks*, London, UK

[6] Zambonelli, F., Gleizes, M-P., Mamei, M., and Tolksdorf, R. 2005. "Spray computers: Explorations in self-organization", *Pervasive and Mobile Computing*, **1**, 1-20

[7] Want, R., and Pering, T. 2005. "System Challenges for Ubiquitous & Pervasive Computing", in *Proceedings of the 27th international conference on Software engineering*, St. Louis, USA

[8] Puccinelli, D., and Haenggi, M. 2005. "Wireless Sensor Networks: Applications and Challenges of Ubiquitous Sensing", *IEEE Circuits and Systems Magazine*, **5**(3), 19-31

[9] Lazos, L., Capkun, S. and Poovendran, R. 2005. "ROPE: Robust Position Estimation in Wireless Sensor Networks", in *Proceedings of the 4th international symposium on Information processing in sensor networks*, Los Angeles, California

[10] Raser, J.M., and O'Shea, E.K. 2005. "Noise in Gene Expression: Origins, Consequences, and Control", *Science*, **309**, 2010-2013

[11] Wolpert, L. 1969. "Positional information and the spatial pattern of cellular differentiation", *J. Theor. Biol*., **25**, 1-47

[12] Green, J.B, Smith, J.C, Gerhart, J.C. 1994. "Slow emergence of a multithreshold response to activin requires cell-contact-dependent sharpening but not prepattern", *Development*, **120**, 2271-2278

[13] Saha, K., and Schaffer, D.V. 2006. "Signal dynamics in Sonic hedgehog tissue patterning", *Development*, **133**, 889-900

[14] Rogulja, D., and Irvine, K.D. 2005. "Regulation of Cell Proliferation by a Morphogen Gradient", *Cell*, **123**, 449-461

[15] Milán, M. and Cohen, S.M. 2003. "A re-evaluation of the contributions of Apterous and Notch to the dorsoventral lineage restriction boundary in the *Drosophila* wing.", *Development*, **130**, 553-562

[16] Rhinn, M., Lun, K., Luz, M., Werner, M. and Brand, M. 2005. "Positioning of the midbrain-hindbrain boundary organizer through global posteriorization of the neuroectoderm mediated by Wnt8 signalling.", *Development*, **132**, 1261-1272

[17] Rhinn, M., Picker, A., and Brand, M. 2006. "Global and local mechanisms of forebrain and midbrain patterning.", *Curr. Opin. Neurobiol.*, **16**, 5-12

[18] Houchmandzadeh, B., Wieschaus, E., and Leibler, S. 2002. "Establishment of developmental precision and proportions in the early *Drosophila* embryo", *Nature*, **415**, 798-802

[19] Houchmandzadeh, B., Wieschaus, E., and Leibler, S. 2005. “Precise domain specification in the developing *Drosophila* embryo”, *Phys. Rev. E.*, **72**, 061920

[20] McHale, P., Rappel, W-J., and Levine, H. 2006. “Embryonic pattern scaling achieved by oppositely directed morphogen gradients”, *Phy. Biol.*, **3**, 107-120

[21] Crickmore, M.A., and Mann, R.S. 2006. “Hox Control of Organ Size by Regulation of Morphogen Production and Mobility”, *Science*, **313**, 63-68

[22] Eldar, A., Rosin, D., Shilo, B-Z., and Barkai, N. 2003. “Self-Enhanced Ligand Degradation Underlies Robustness of Morphogen Gradients”, *Dev. Cell.*, **5**, 635-646

[23] Slack, J.M.W., Beck, C.W., Gargioli, C., and Christen, B. 2004. “Cellular and molecular mechanisms of regeneration in *Xenopus*”, *Phil. Trans. R. Soc. B*, **359**, 745-751

[24] Hetherington, A.M., and Woodward, F.I. 2003. “The role of stomata in sensing and driving environmental change”, *Nature*, **424**, 901-908

[25] Lindsley, D.L., and Zimm, G.G. 1992. “The Genome of Drosophila melanogaster”, Academic Press