

Morphogenetic Robotics: An Emerging New Field in Developmental Robotics

- Yaochu Jin, Senior Member, IEEE, and Yan Meng, Member, IEEE

EE

2012314156

LEE DONGHYEON

What Is and Why Morphogenetic Robotics?

- The term *developmental robotics* is often used interchangeably with other two terms, namely, *epigenetic robotics* and *ontogenetic robotics*.
- Language, emotion, anticipation, social skills
- Due to the attractive properties that biological morphogenesis exhibits, much attention has been paid to employing genetic and cellular mechanisms for designing robotic systems, in particular for self-organizing swarm robotic systems and self-reconfigurable modular robots.
- → Morphogenetic Robotics에 관심을 가져야 한다!

What Is and Why Morphogenetic Robotics?

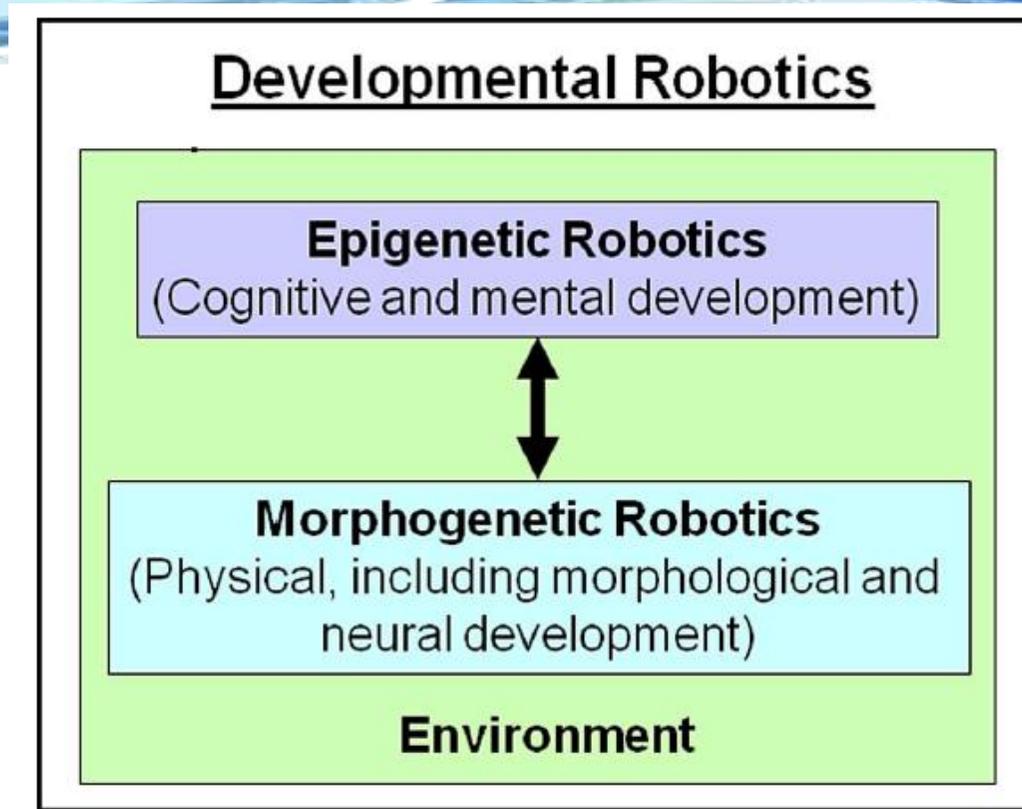


Fig. 1. Relationships between morphogenetic robotics, epigenetic robotics, and developmental robotics. Developmental robotics includes both morphogenetic robotics and epigenetic robotics, and morphogenetic robotics and epigenetic robotics are closely coupled not only directly in that the body plan and nervous system are the basis of cognitive development, but also indirectly through the environment.

- We believe that developmental robotics should include both morphogenetic robotics and epigenetic robotics.

Biological Morphogenesis and Metamorphosis

Morphogenesis

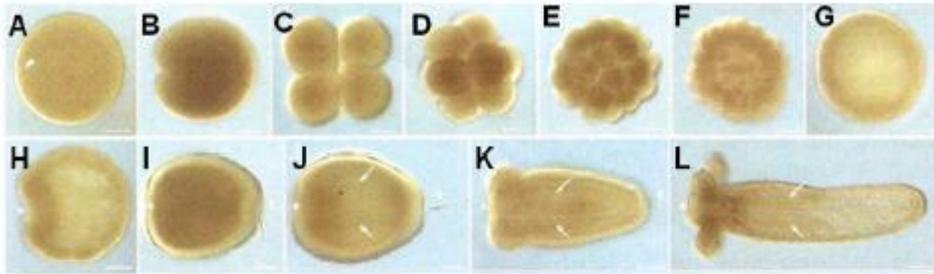


Fig. 2. Morphogenesis of *Nematostella vectensis*. The development stages are: egg (A), morula (B–F), blastula (G), gastrula (H), planula (I–J), and polyp (K–L). Taken from [53].

Metamorphosis

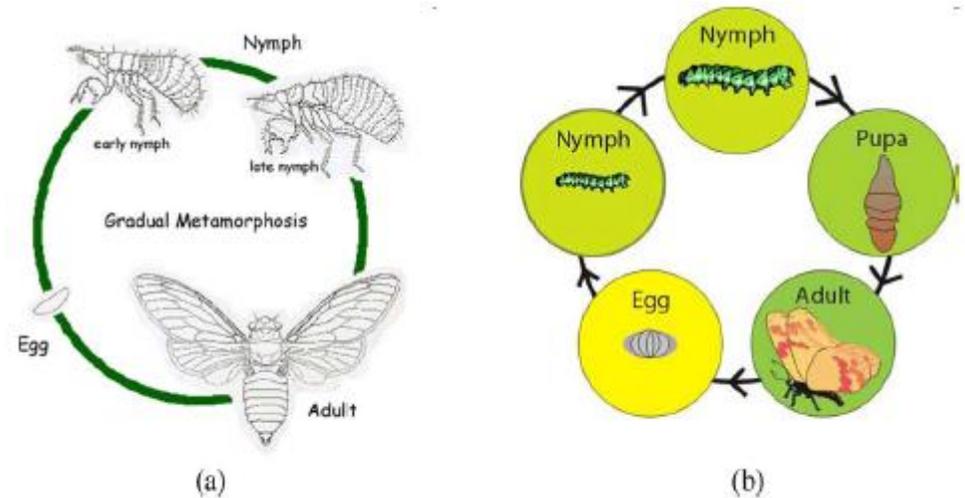


Fig. 3. (a) Incomplete and (b) complete metamorphosis.

Biological Morphogenesis and Metamorphosis



- Both multicellular morphogenesis and metamorphosis are under the control of gene regulatory networks.
- Gene regulatory networks (GRN)
- 몇몇의 transcription factors(TFs), '전사인자'라는 단백질이 있는데, 이는 gene의 발현을 활성화하거나 억제시킨다.
- → resulting a complex network

Biological Morphogenesis and Metamorphosis

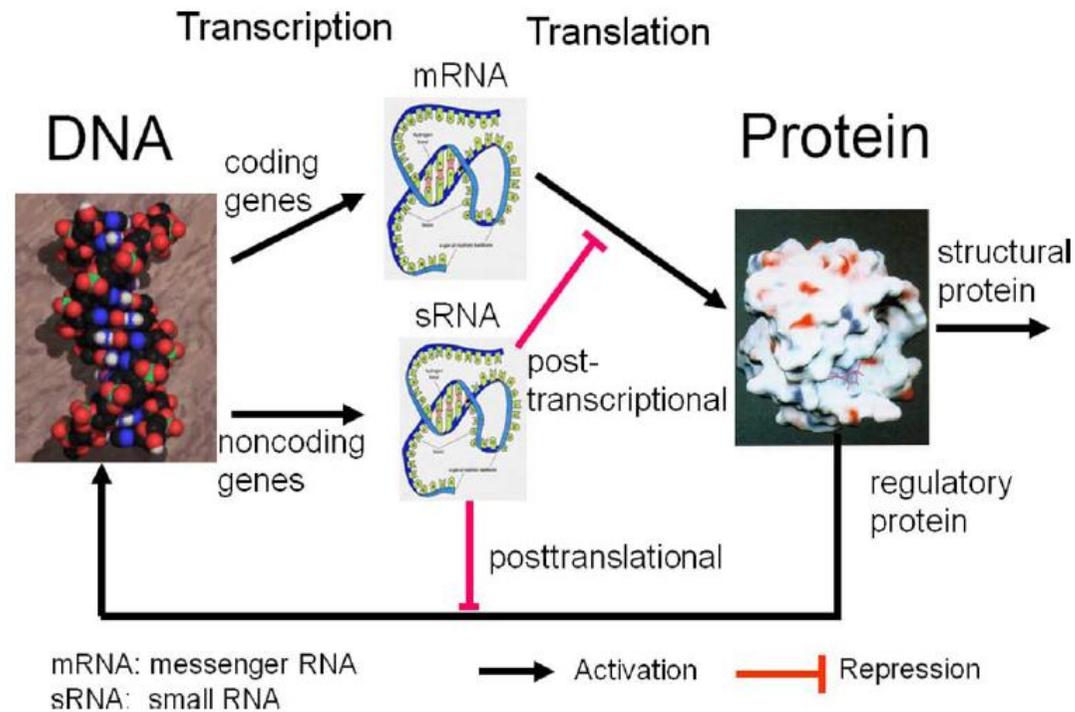


Fig. 4. Illustration of the gene expression process. Coding genes are first transcribed into mRNA, and then translated into proteins, which can have cellular and/or regulatory functions. Some so-called noncoding genes can also be transcribed into small RNAs that can downregulate or fully switch off the expression of some genes through transcriptional or posttranslational interferences.

We will discuss computational modeling of GRNs and show how these models can be used for understanding biology and solving engineering problems.

Computational Modeling of Developmental Gene Networks

A decorative graphic of a water splash, showing a curved, translucent blue surface with white highlights, positioned horizontally across the top of the slide.

- Discrete models, such as random Boolean networks and Markovian models, and continuous models, such as ordinary differential equations and partial differential equations
- Deterministic models and stochastic models

Computational Modeling of Developmental Gene Networks

- For example, the mathematical model of gene expression with autoregulation can be described by

$$\frac{d[R]}{dt} = -\gamma_R [R] + \alpha_R H([P]) \quad (1)$$

$$\frac{d[P]}{dt} = -\gamma_P [P] + \alpha_P [R] \quad (2)$$

where $[R]$ and $[P]$ are the concentration of mRNA and protein, respectively, γ_R and γ_P are the decay rate of the mRNA and protein, α_R and α_P are the synthesis rate of the mRNA and protein, and $H(X)$ is the Hill function. If the autoregulation is a repression, also known as negative autoregulation, the Hill function can be described by

$$H_r(x) = \frac{\beta}{\theta^n + x^n} \quad (3)$$

and if the autoregulation is activation, the Hill function can be written as

$$H_a(x) = \frac{\beta x^n}{\theta^n + x^n} \quad (4)$$

where β is the activation coefficient, θ is the threshold, and n is the Hill coefficient.

Computational Modeling of Developmental Gene Networks

- Mjolsness *et al.* [66] has suggested a generalized GRN model that considered diffusion of TFs among the cells:

$$\frac{dg_{ij}}{dt} = -\gamma_j g_{ij} + \phi \left[\sum_{l=1}^{n_g} W^{jl} g_{il} + \theta_j \right] + D_j \nabla^2 g_{ij} \quad (5)$$

where g_{ij} denotes the concentration of j th gene product (protein) in the i th cell. The first term on the right-hand side of (5) represents the degradation of the protein at a rate of γ_j , the second term specifies the production of protein g_{ij} , and the last term describes protein diffusion at a rate of D_j . ϕ is an activation function for the protein production, which is usually defined as a sigmoid function $\phi(z) = 1/(1 + \exp(-\mu z))$. The interaction between the genes is described with an interaction matrix W^{jl} , the element of which can be either active (a positive value) or repressive (a negative value). θ_j is a threshold for activation of gene expression. n_g is the number of proteins. An illustration of cell-cell interactions is provided in Fig. 5, where gene 1 of cell 1 is activated by its own protein and repressed by the protein produced by gene 1 of cell 2 through diffusion. Similarly, gene

Computational Modeling of Developmental Gene Networks

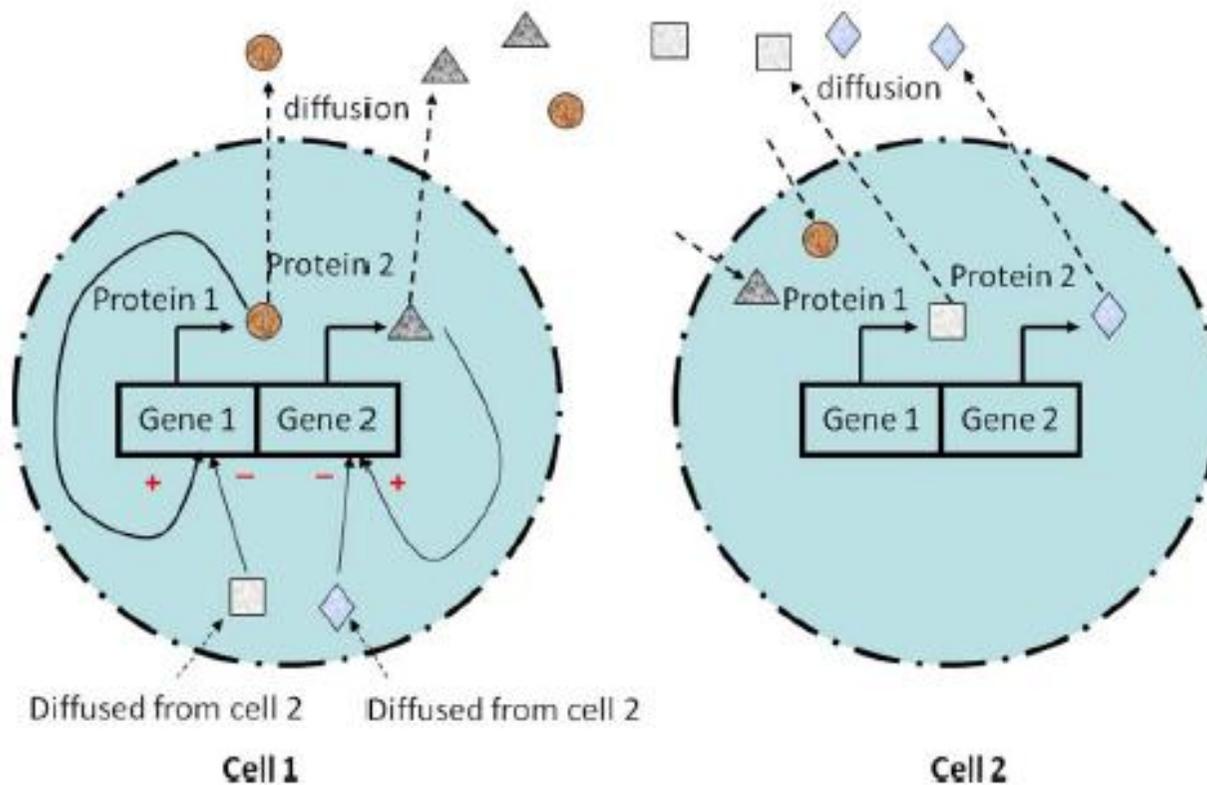


Fig. 5. Illustration of cell signaling in a multicellular system.

Application of Computational Models of GRN

- Computational models have widely been used for analyzing the dynamics of GRNs, particularly regarding robustness of GRN motifs, synthesizing *in silico* typical regulatory dynamics such as bistability and sustained oscillation, and designing engine.
- → GRN Motifs의 robustness를 따라 Computational Model이 구성된다.
- Application
- 1) Analysis of GRN Motifs
 - autoregulations, feedforward loops, and feedback loops
 - cis-regulation
- 2) In Silico Synthesis
- 3) Artificial Embryogeny

Swarm Robotic System



- A swarm robotic system is a multirobot system consisting of a large number of homogeneous simple robots.
- Swarm robots are often used to fulfill tasks that are difficult or even impossible for a single robot, especially in the presence of uncertainties, or with incomplete information, or where a distributed control or asynchronous computation is required.
- Typical applications of swarm robotic systems
 - Group transport, foraging, shape formation, boundary coverage, urban search and rescue, and unknown environment exploration

Metaphor Between Swarm Robotic Systems and Multicellular Systems



- **Cell-Robot Mapping**

- The basic idea in applying genetic and cellular mechanisms in biological morphogenesis to self-organized control of swarm robots is to establish a metaphor between a cell and a robot.
- In other words, it is assumed that the movement dynamics of each robot can be modeled by the regulatory dynamics of a cell.

Metaphor Between Swarm Robotic Systems and Multicellular Systems

$$\frac{dg_{i,x}}{dt} = -az_{i,x} + mp_{i,x}$$
$$\frac{dg_{i,y}}{dt} = -az_{i,y} + mp_{i,y} \quad (6)$$

$$\frac{dp_{i,x}}{dt} = -cp_{i,x} + kf(z_{i,x}) + bD_{i,x}$$
$$\frac{dp_{i,y}}{dt} = -cp_{i,y} + kf(z_{i,y}) + bD_{i,y} \quad (7)$$

$g_{i,x}$ is the x position of the i th robot, respectively, which corresponds to the concentration of a proteins of type G.

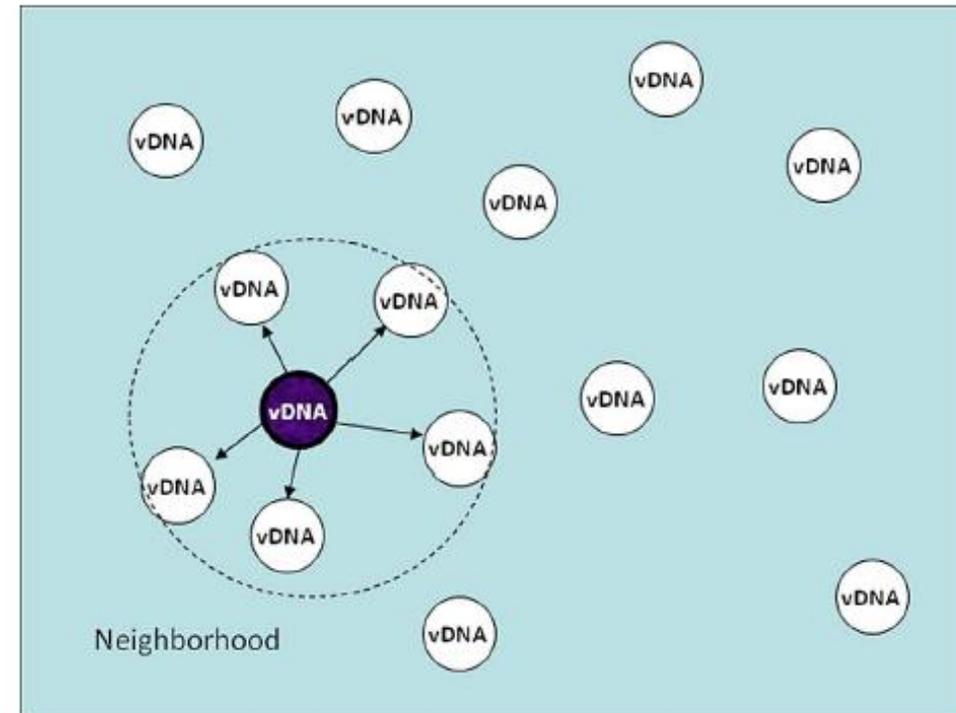


Fig. 6. Swarm robotic system represented by a multicellular system. Each circle represents a cell or a robot, and the dashed large circle denotes the neighborhood of a cell/robot (shaded), to which information can be passed.

Metaphor Between Swarm Robotic Systems and Multicellular Systems

- For a swarm robotic system, this entails that each robot is able to detect the distance to its neighboring robots, which is practical and easy to realize.

$$D_{i,x} = \sum_{j=1}^{N_i} D_{i,x}^j \quad D_{i,y} = \sum_{j=1}^{N_i} D_{i,y}^j \quad (8)$$

$$D_{i,x}^j = \frac{(g_{i,x} - g_{j,x})}{\sqrt{(g_{i,x} - g_{j,x})^2 + (g_{i,y} - g_{j,y})^2}} \quad (9)$$

$$D_{i,y}^j = \frac{(g_{i,y} - g_{j,y})}{\sqrt{(g_{i,x} - g_{j,x})^2 + (g_{i,y} - g_{j,y})^2}} \quad (10)$$

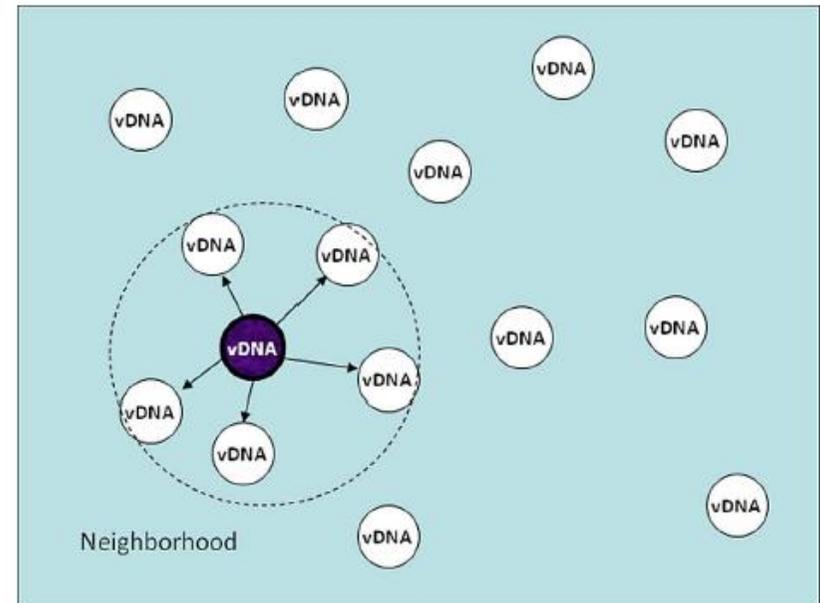


Fig. 6. Swarm robotic system represented by a multicellular system. Each circle represents a cell or a robot, and the dashed large circle denotes the neighborhood of a cell/robot (shaded), to which information can be passed.

Position → Concentration

Velocity → Differentiation of concentration, Diffusion

D → Sum of distances between *i*th robot and its neighbors

Metaphor Between Swarm Robotic Systems and Multicellular Systems

- **Morphogen Gradients for Target Shape Representation**
- In biological morphogenesis, morphogen concentration gradients control cell fate specification and play a key role in understanding pattern formation.

$$\begin{aligned} f(z_{i,x}) &= \frac{1 - e^{-z_{i,x}}}{1 + e^{-z_{i,x}}} \\ f(z_{i,y}) &= \frac{1 - e^{-z_{i,y}}}{1 + e^{-z_{i,y}}} \end{aligned} \quad (11)$$

where $z_{i,x}$ and $z_{i,y}$ are the gradients along x -axis and y -axis, respectively, of an analytic function h , which is described as

$$z_{i,x} = \frac{\partial h}{\partial g_{i,x}} \quad z_{i,y} = \frac{\partial h}{\partial g_{i,y}} \quad (12)$$

where h defines the shape the robots should form.

Metaphor Between Swarm Robotic Systems and Multicellular Systems

- **Illustrative Results on GRN-Based Swarm Robot Self-Organization**
- The robots are randomly distributed in the area in the beginning. A reference robot is chosen through a competition process, during which the robot that has the maximum number of neighbors wins.

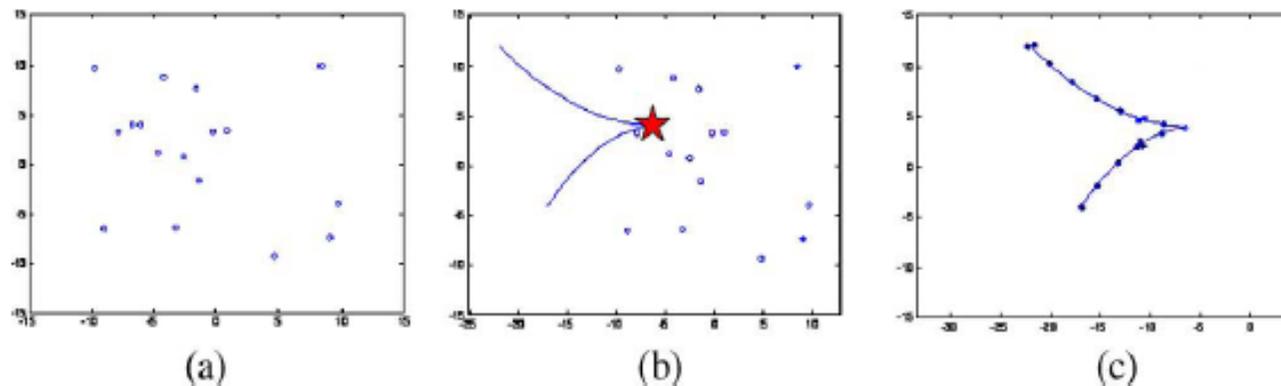


Fig. 7. Snapshots showing the emergence of a pattern from 17 robots similar to bird flocking [31]. (a) Random initialization; (b) determination of a reference robot (denoted by a star) through competition; (c) emergence of the target shape.

Metaphor Between Swarm Robotic Systems and Multicellular Systems

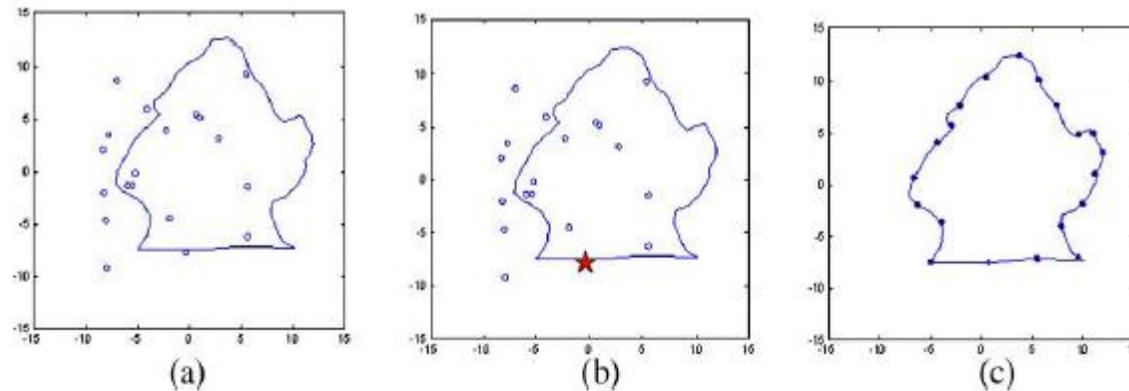


Fig. 8. Snapshots of 20 robots covering a boundary simulating that of the Brooklyn Borough of New York City [31]. (a) Random initialization; (b) robot that first detects the boundary is chosen as the reference robot; (c) coverage of the boundary.

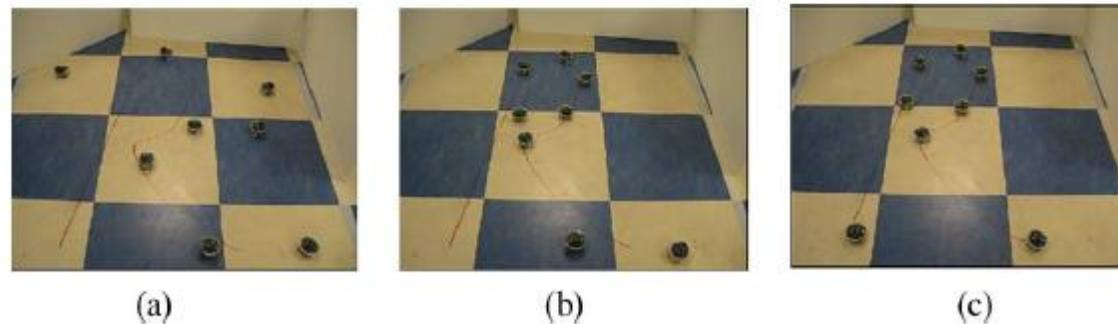


Fig. 9. Snapshots of 8 E-Puck robots forming the letter 'R' [61]. (a) $t = 0$ s. (b) $t = 6$ s. (c) $t = 11$ s.

Reconfigurable Modular Robots

- Self-reconfigurable modular robots consist of a number of modules and are able to adapt their shape (configuration) by rearranging their modules to changing environments.
- The connection mechanism between the two cubic parts allows the modules to perform basic motions such as lifting or rotating.



(a)



(b)



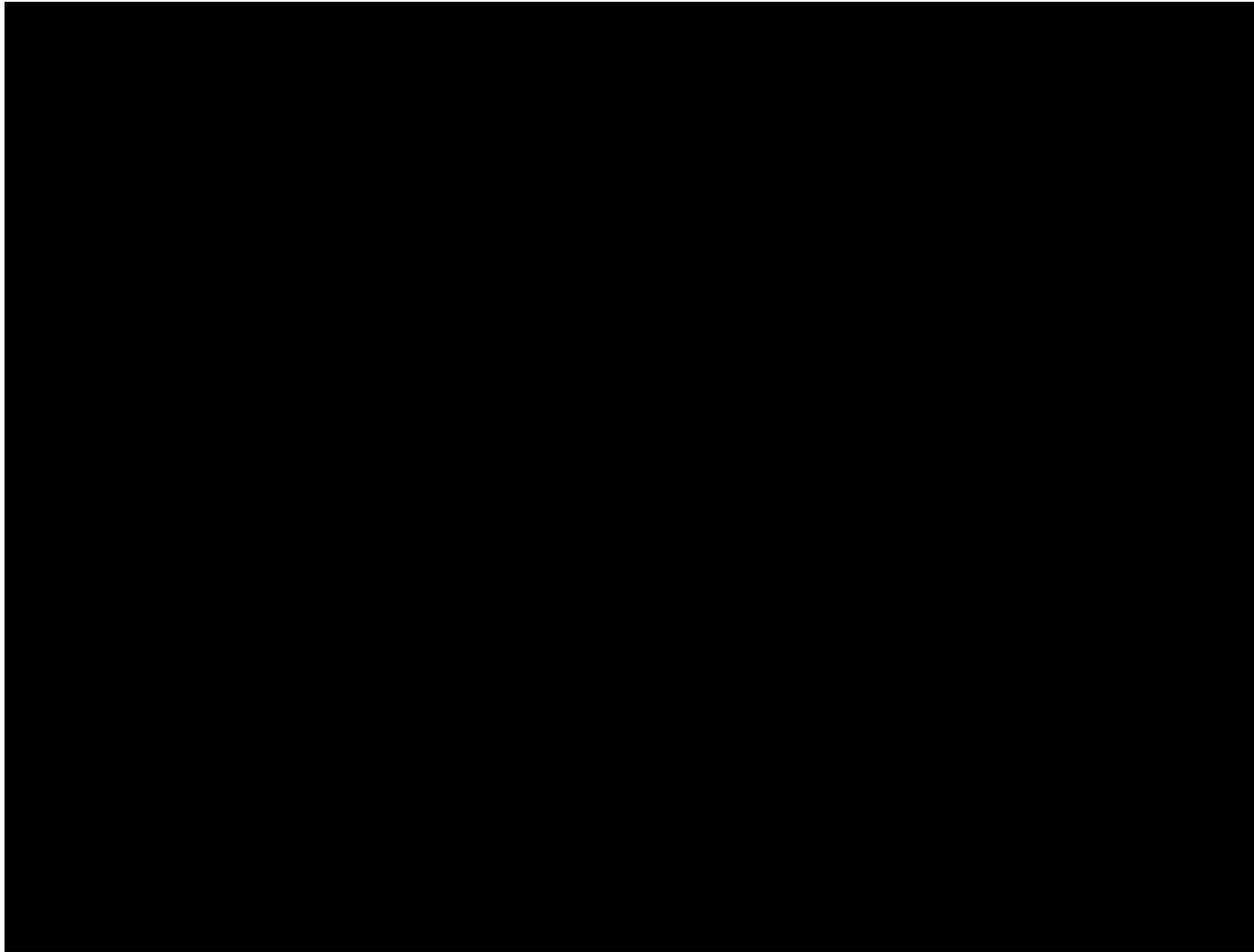
(c)



(d)

Fig. 10. Examples of physical and simulated modular robots. (a) M-TRAN, (b) molecube, (c) Karl Sims' virtual creature, and (d) Framsticks.

Reconfigurable Modular Robots



<http://youtu.be/4oSavAHf0dg>

CrossCube - A simulated Modular Robot

- CrossCube adopts a lattice-based cube design.
- Each module in CrossCube is a cubical structure having its own computing and communication resource and actuation capability.
- → 각 노드마다 같은 구조를 가지며 각각이 computing, communication 등을 할 수 있다.
- The core is a cube with six universal joints.
- Their default heading directions are bottom, up, right, left, front, and back, respectively. Each joint can attach to or detach from the joints of its neighbor modules. The axis of each joint can be actively rotated, extended, and return to its default direction.

CrossCube - A simulated Modular Robot

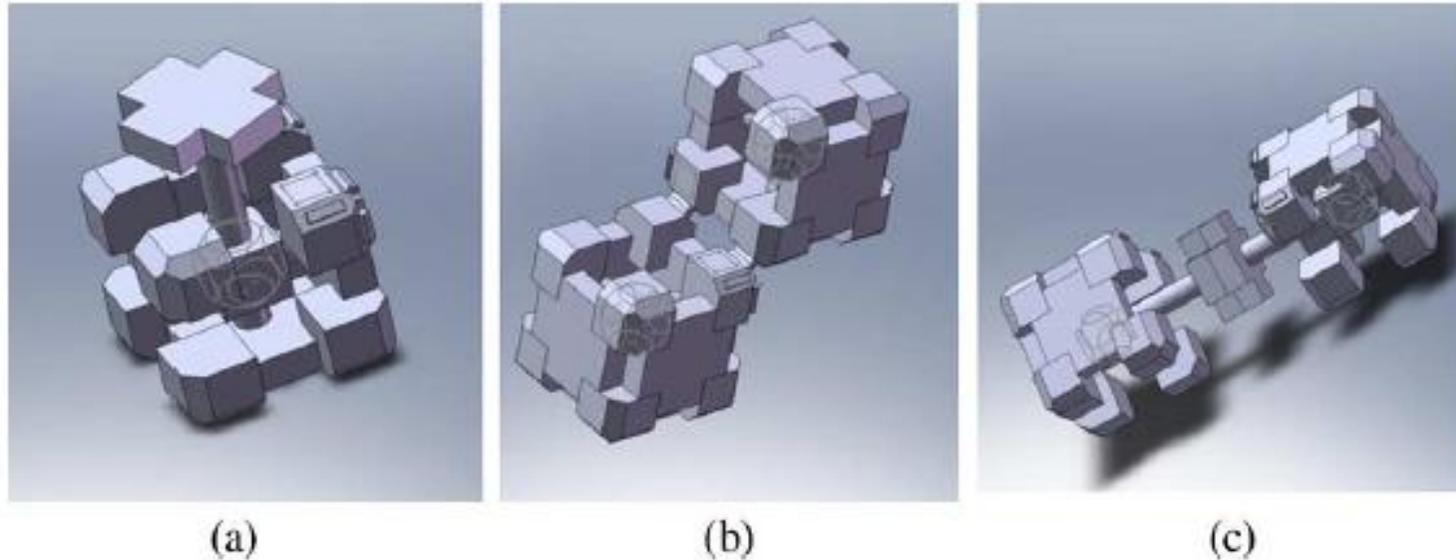


Fig. 11. Mechanical demonstration of CrossCube [63]. (a) Joints; (b) Locks on the boundaries of the modules. (c) Rotation and extension of the joints of the modules.

- Each unit in modular robots can be seen as a cell, and there are similarities in control, communication, and physical interactions between cells in multicellular organisms and modules in modular robots.

Self-Reconfiguration as Morphogenesis

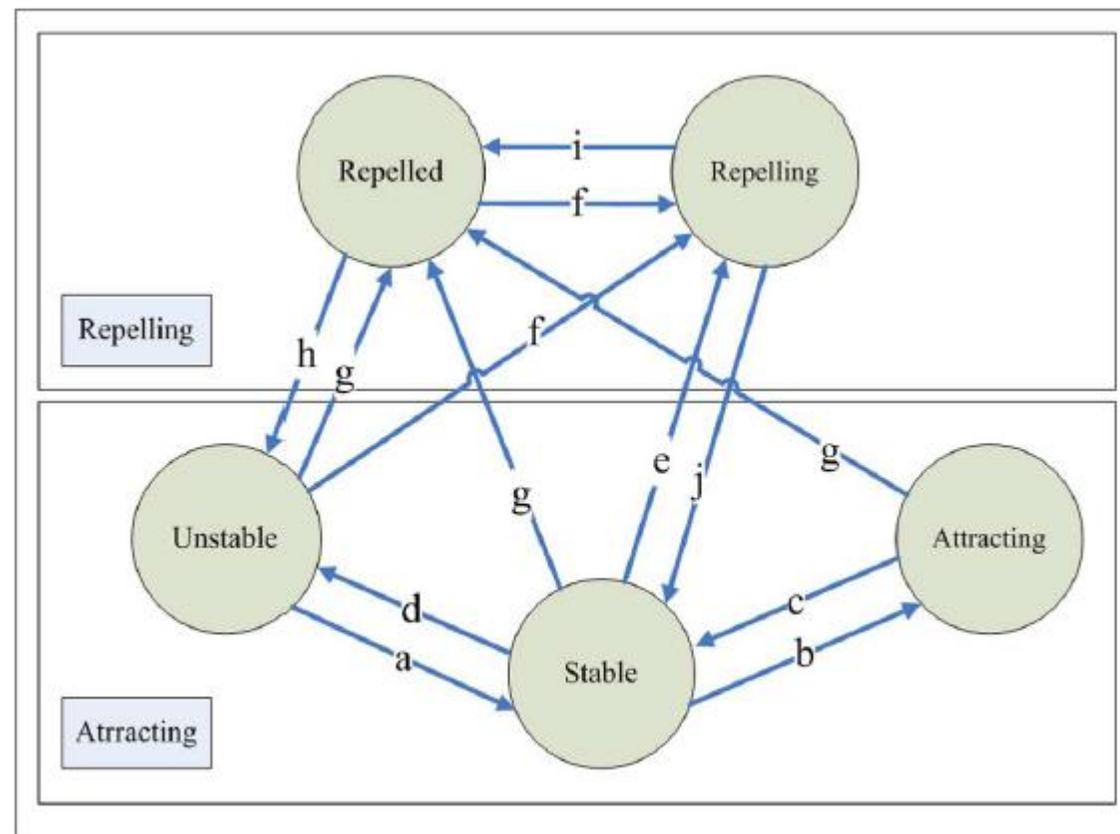


Fig. 12. State transition of each module in CrossCube [63].

- 1) GRN-Based Pattern Transition
- 2) Gene-Protein Pair for Attraction
- 3) Gene-Protein Pair for Repelling
- 4) Lookup Table-Based Configuration Representation

Self-Reconfiguration as Morphogenesis

Gene-Protein Pair for Attraction

$$P_A^{ij} = \{AP^{ij}, S^i, C_A^{ij}\} \quad (15)$$

where P_A^{ij} is the attracting protein generated by the i th module for its j th neighbor. AP^{ij} is the j th neighboring attracting grid of the i th module. S^i is the identification label of the i th module, and C_A^{ij} is the concentration of the protein P_A^{ij} , which equals to the morphogen gradient of AP^{ij} . P_A can regulate G_A in the same cell and can also diffuse into neighboring modules to regulate G_A of neighbors as well.

The dynamics of G_A and P_A can be described by the following GRN model:

$$\frac{dg_A(t)}{dt} = -ag_A(t) + b \sum p_{A_local} - c \sum p_{A_rec} \quad (16)$$

where $g_A(t)$ is the gene expression level of G_A at time t . p_{A_local} and p_{A_rec} are protein concentrations of locally generated protein and received protein from other modules, respectively. a , b , and c are constant coefficients, which can be determined, e.g., using an evolutionary algorithm.

$$\text{state} = \begin{cases} \text{unstable when } g_A < G_{A_L} \\ \text{stable when } G_{A_L} < g_A < G_{A_H} \\ \text{attracting when } g_A > G_{A_H} \end{cases} \quad (17)$$

Self-Reconfiguration as Morphogenesis

- In summary, the gene–protein pair ($GA - PA$) can regulate each other by the GRN-based model described in (16) and (17).
- More specifically, PA can regulate GA through (16), while GA can determine when PA is allowed to diffuse into neighboring grids based on (17).
- Gene-Protein Pair for Repelling

$$\frac{dg_P(t)}{dt} = dg_P(t) - e \sum p_{P_rec}$$

state = repelled when $g_P < G_{P_L}$ (19)

Self-Reconfiguration as Morphogenesis

- For the sake of simplicity, a number of basic configurations for different environments can be predefined in terms of a lookup table for a given mission, for instance locomotion.

TABLE I
VEHICLE CONFIGURATION

Positions (x, y, z, ML, PID)		Joints (PID1, PID2, RD)
(0, 0, 0, 10, 0)	(1, 0, 3, 10, 10)	(0, 1, 0)
(1, 0, 0, 10, 1)	(2, 0, 3, 10, 11)	(2, 3, 1)
(2, 0, 0, 10, 2)	(0, 0, 4, 10, 12)	(6, 7, 0)
(3, 0, 0, 10, 3)	(1, 0, 4, 10, 13)	(8, 9, 1)
(1, 0, 1, 10, 4)	(2, 0, 4, 10, 14)	(12, 13, 0)
(2, 0, 1, 10, 5)	(3, 0, 4, 10, 15)	(14, 15, 1)
(0, 0, 2, 10, 6)	(0, 0, 1, -1, 16)	
(1, 0, 2, 10, 7)	(3, 0, 1, -1, 17)	
(2, 0, 2, 10, 8)	(0, 0, 3, -1, 18)	
(3, 0, 2, 10, 9)	(3, 0, 3, -1, 19)	

Illustrative Examples of GRN-Based Self-Reconfiguration

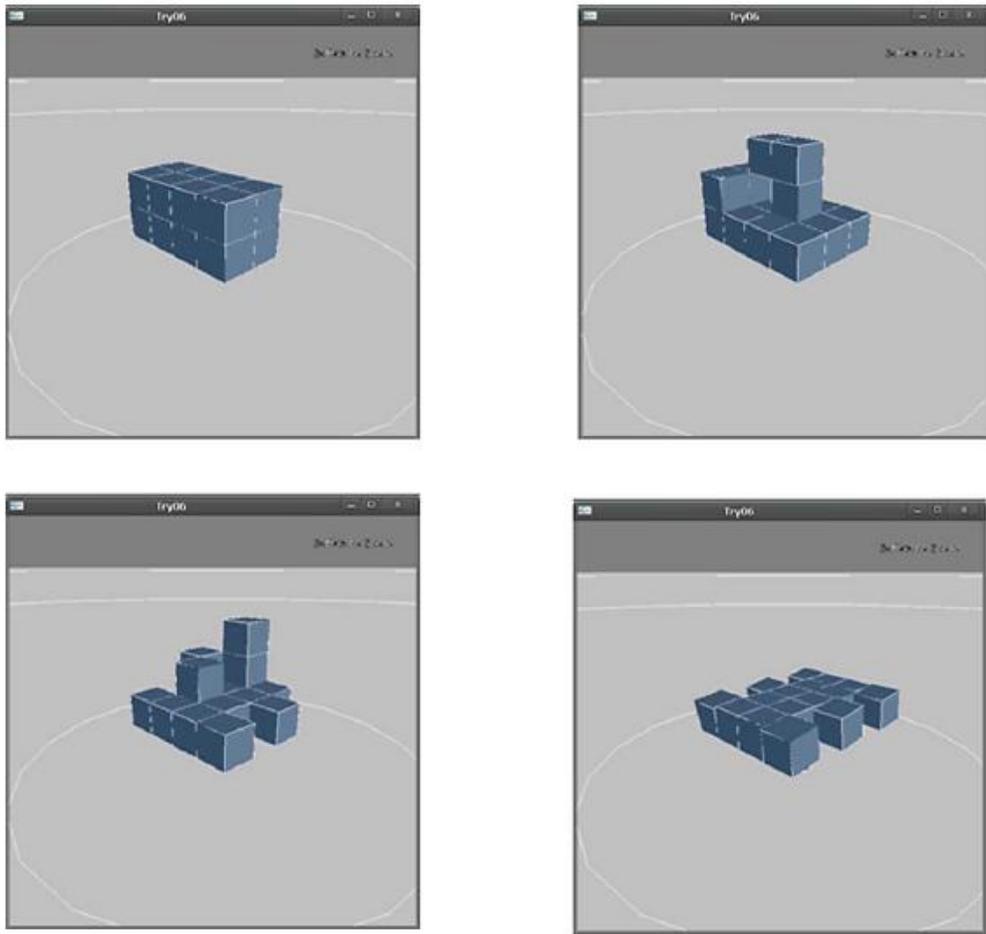


Fig. 13. Autonomous configuration of a vehicle from a rectangle based on the GRN model [63].

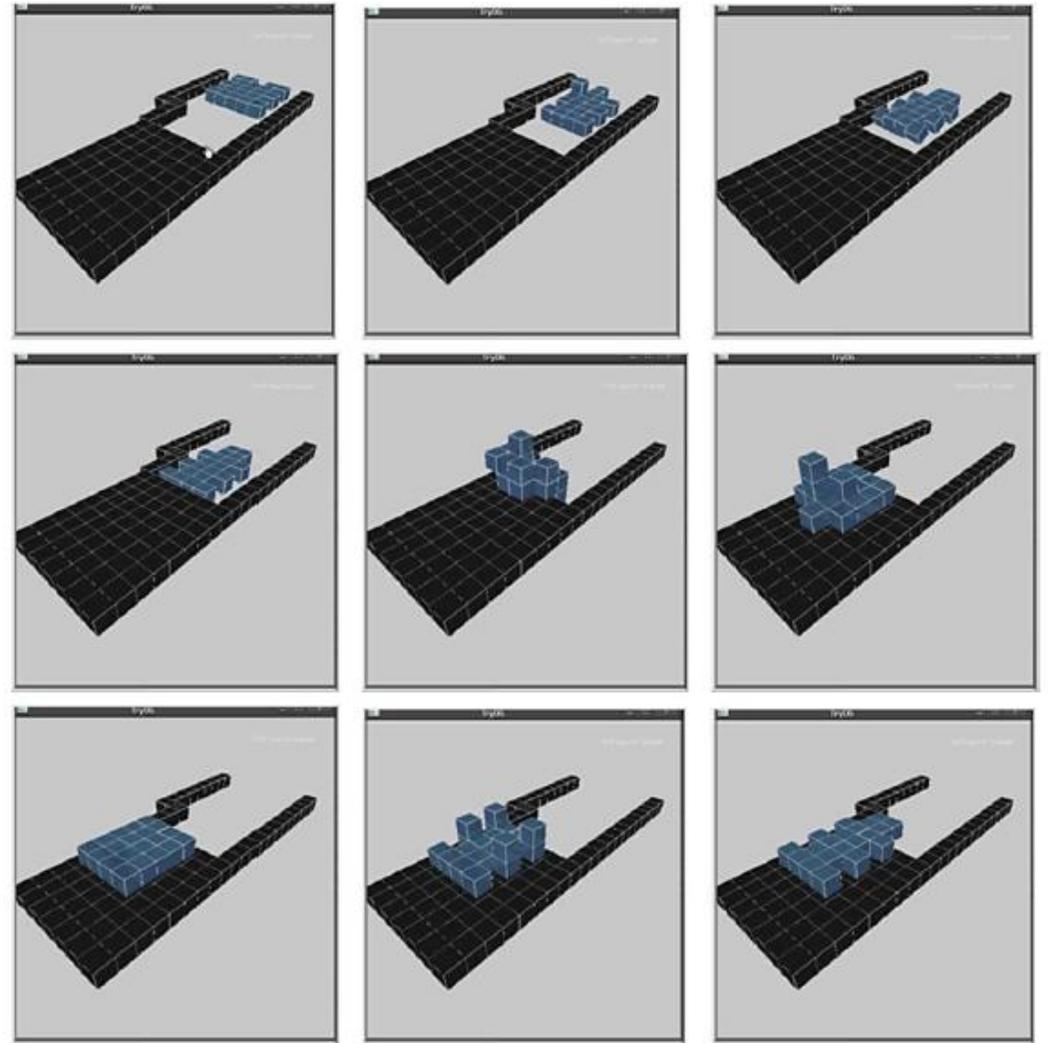
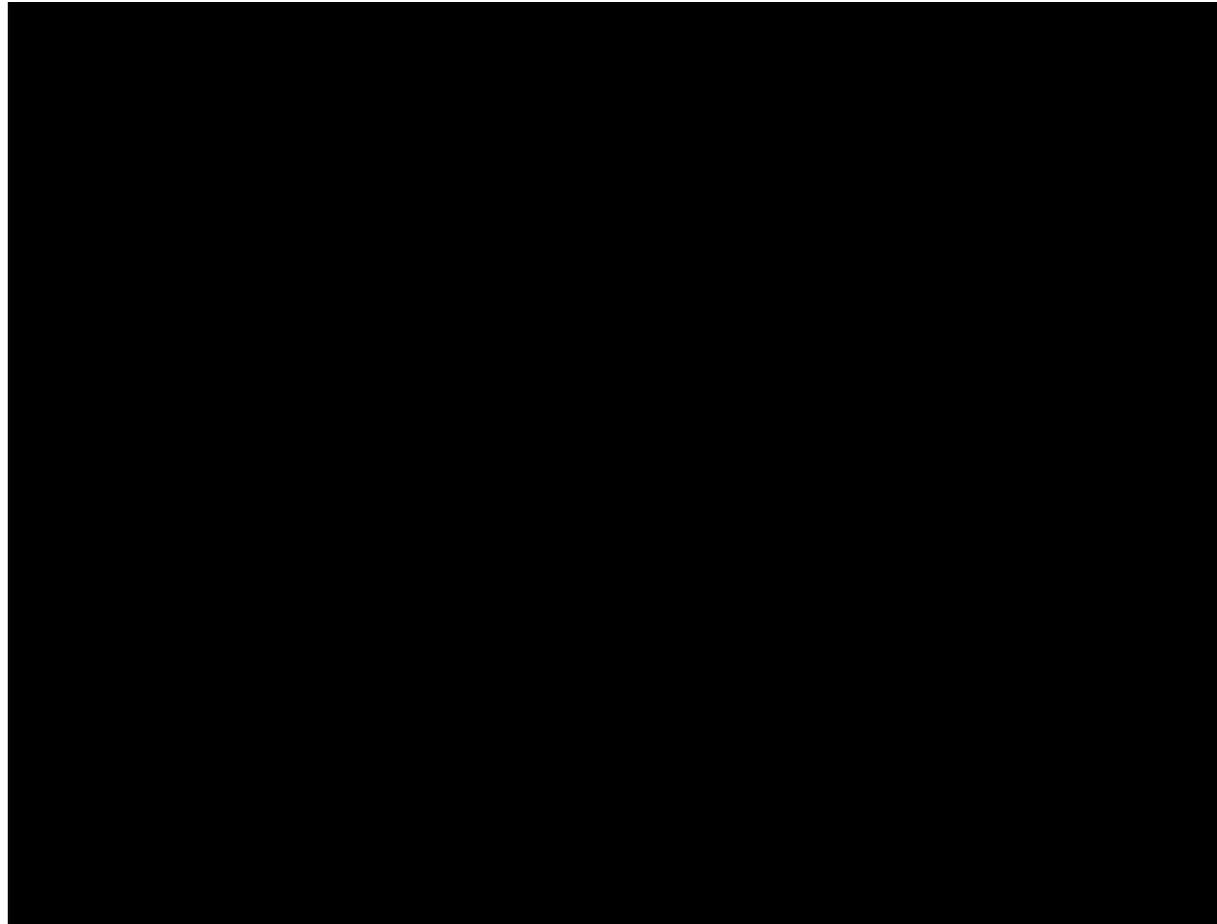


Fig. 14. Set of snapshots demonstrating a series of reconfigurable processes during locomotion and climbing. The robot first adapted its width to the narrow passage, then changed its configuration for climbing up a step, and finally reconfigured itself into a vehicle again to move forward.

Illustrative Examples of GRN-Based Self-Reconfiguration



<http://youtu.be/09TirOH8OIM>

Why Development?

- Coevolution of brain and body has long been recognized both in robotics and artificial life.
- This situation has not been changed a lot to date due to various difficulties in coevolving the development of body and brain.
- 1) developmental mechanism에 대한 지식이 부족
- 2) artificial development on the systems performance가 잘 알려지지 않음.
 - Developmental system과 nondevelopmental system중 무엇이 더 좋을지에 대한 것이 unclear!
- 3) Growing materials, adaptable structures, adaptable sensors, and actuators are still lacking.

Why Development?

- Development is an indispensable phase in which organisms have to interact with the environment constantly and find a way to survive.
- It has been found that development can bias the evolutionary path considerably, as illustrated in Fig. 15.
- In addition, it has been surmised that development can also open up new opportunities for evolution, which has partly been verified in computational developmental systems.

Why Development?

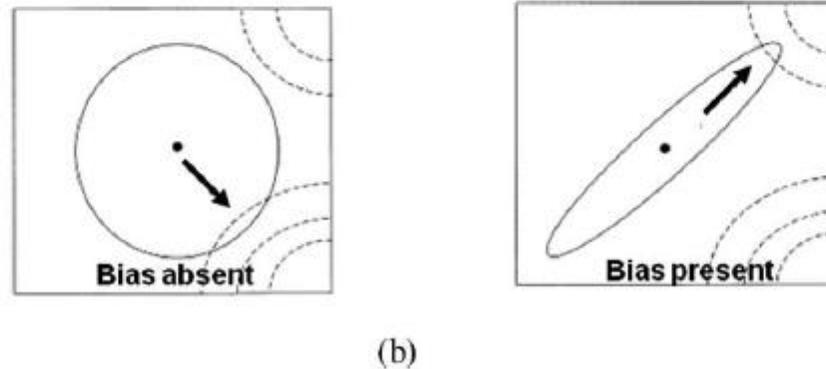
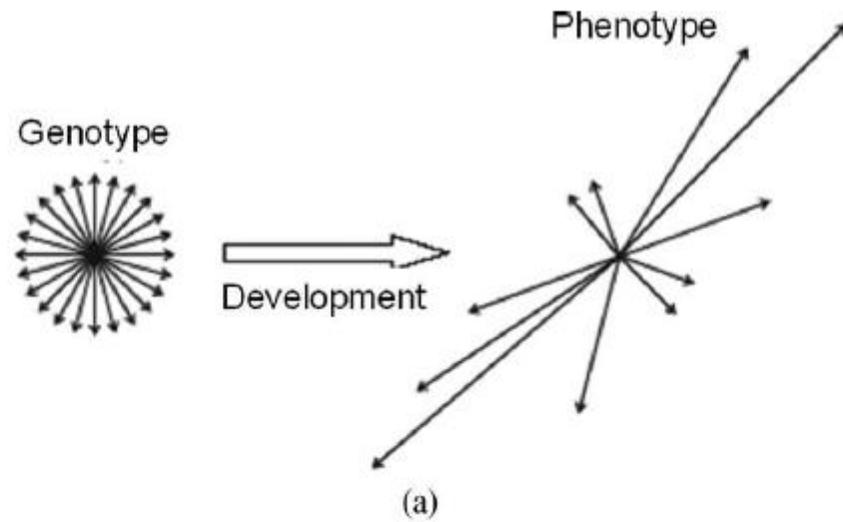


Fig. 15. Influence of development on selection directions. (a) Developmental bias due to nonlinear genotype–phenotype mapping (taken from [77]) and (b) change of selection directions under developmental bias (taken from [4]).

Computational Models for Neural and Morphological Development

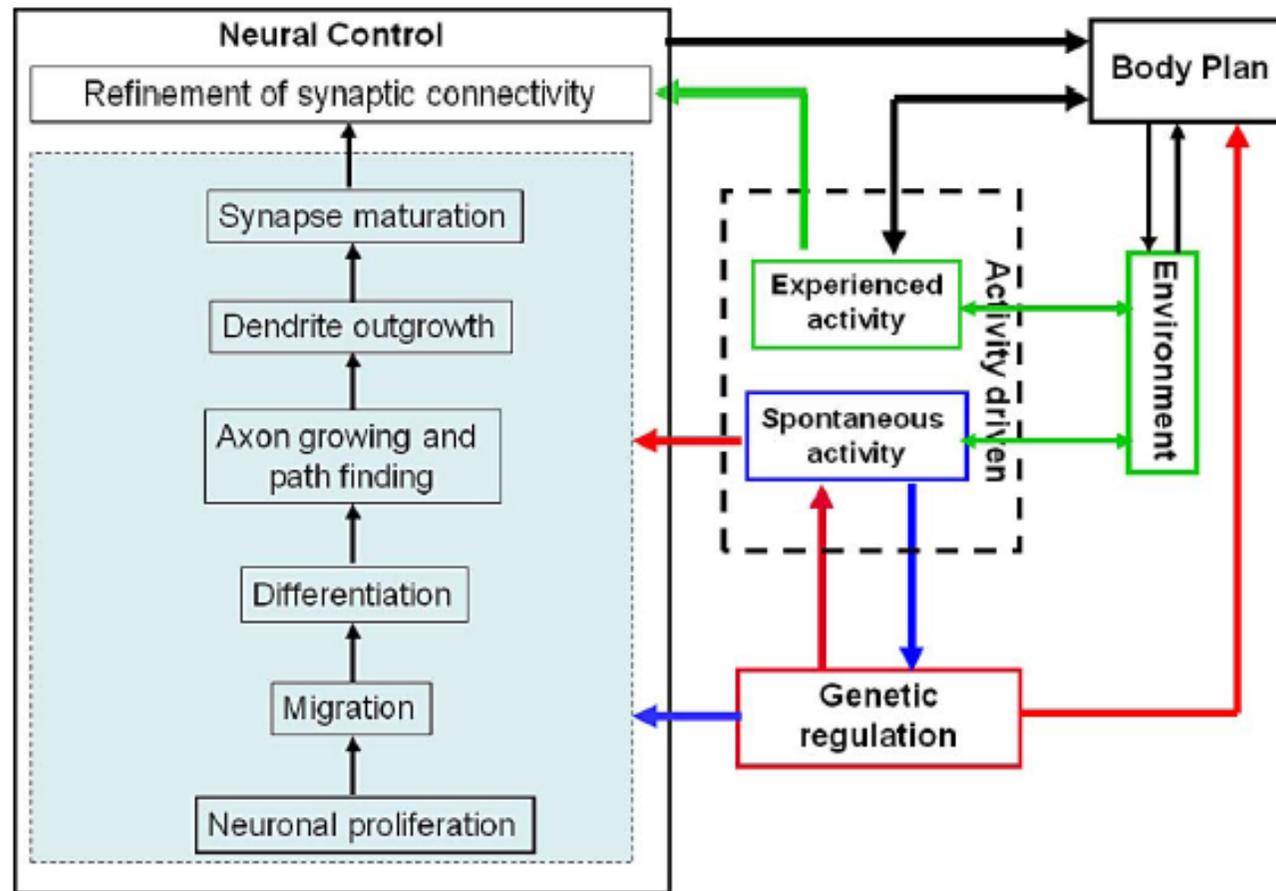
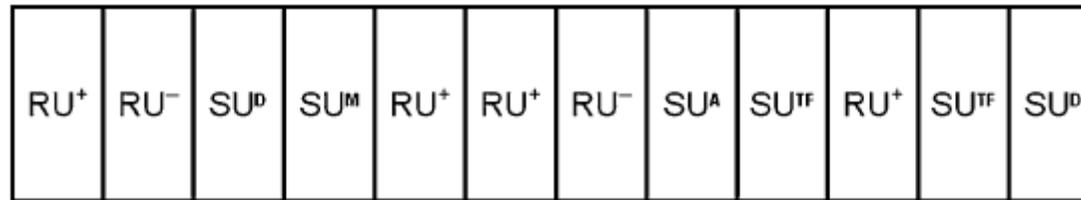


Fig. 16. Main processes in neural development driven by genetic and environmental control situated in a physical environment together with the development of the body plan.

GRN Model for Neural and Morphological Development



RU⁺: Activating regulatory unit

RU⁻: Inhibitory regulatory unit

SU^D: Cell division

SU^M: Cell migration

SU^A: Axon growth

SU^{TF}: Producing transcription factor

Fig. 17. Example of chromosome for neural development.

$$\gamma_{i,j} = \max(\epsilon - |\text{aff}_i^{\text{TF}} - \text{aff}_j^{\text{RU}}|, 0). \quad (20)$$

$$\alpha_k = 100 \sum_{j=1}^N h_j a_j (2s_j - 1) \quad (21)$$

$$A = \beta \frac{2}{1 + e^{-20 \cdot f \cdot \alpha}} - 1 \quad (22)$$

$$\mathbf{u}_i(t) = \mathbf{u}_i(t-1) + 0.1 D_i^f (\mathbf{G} \cdot \mathbf{u}_i(t-1)) \quad (23)$$

$$\mathbf{u}_i(t) = \min((1 - 0.1 D_i^c) \mathbf{u}_i(t), 1) \quad (24)$$

GRN Model for Neural and Morphological Development

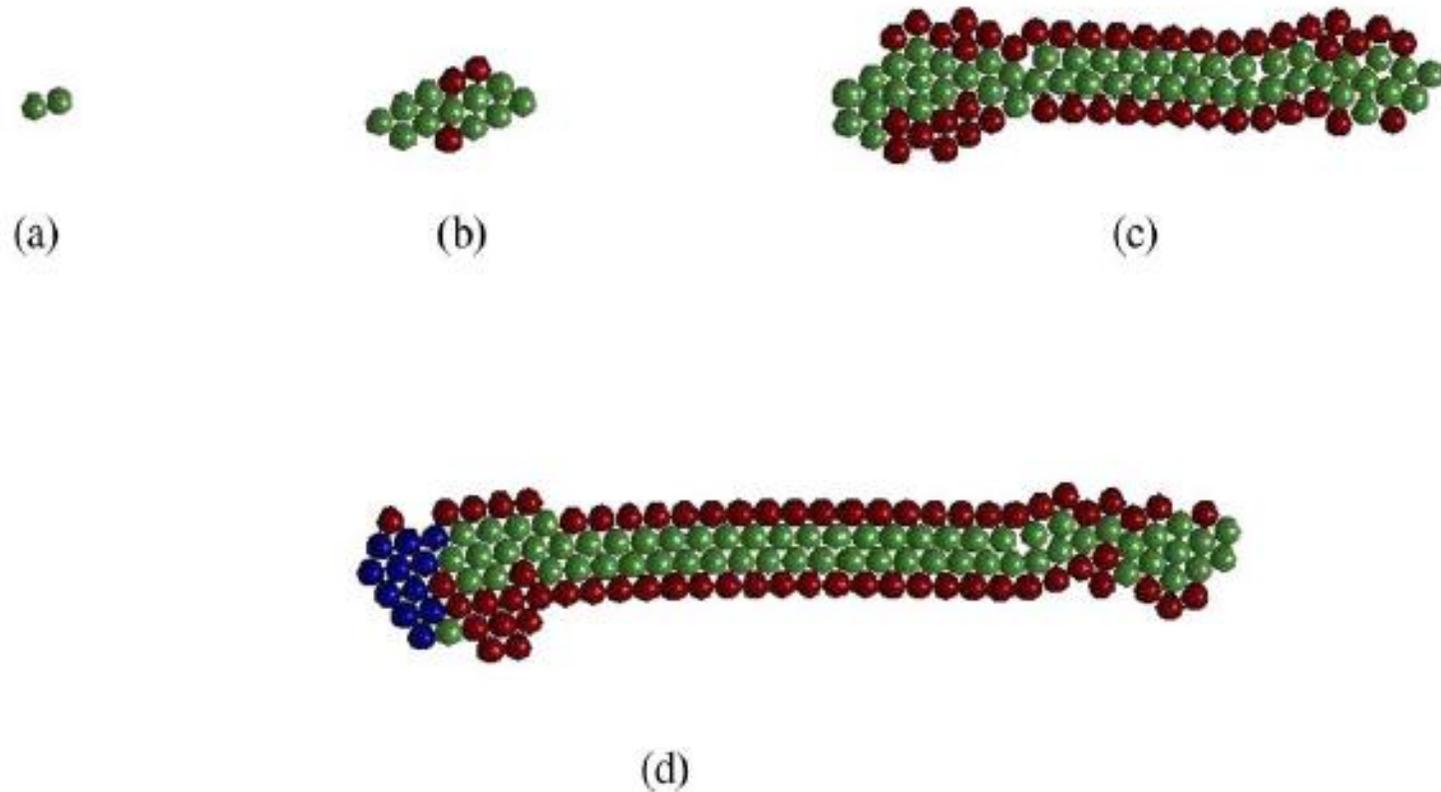


Fig. 18. Self-stabilized cellular growth under the control of a GRN model presented in [82]. (a) System is initialized with two cells. (b)–(c) System grows as cells divide. (d) Growth is self-stabilized dynamically, where the cells on light grey color will divide and those in dark will die. A balance of cell division and cell death is accomplished under the control of the GRN.

Conceptual Framework for Coevolving the Development of Robot Hand Morphology and Controller

- It has been found that the morphology of the animal hands has changed a lot to adapt to the needs of the animals during evolution.
- The importance of coevolving the development of hand morphology and control in robotics is twofold.

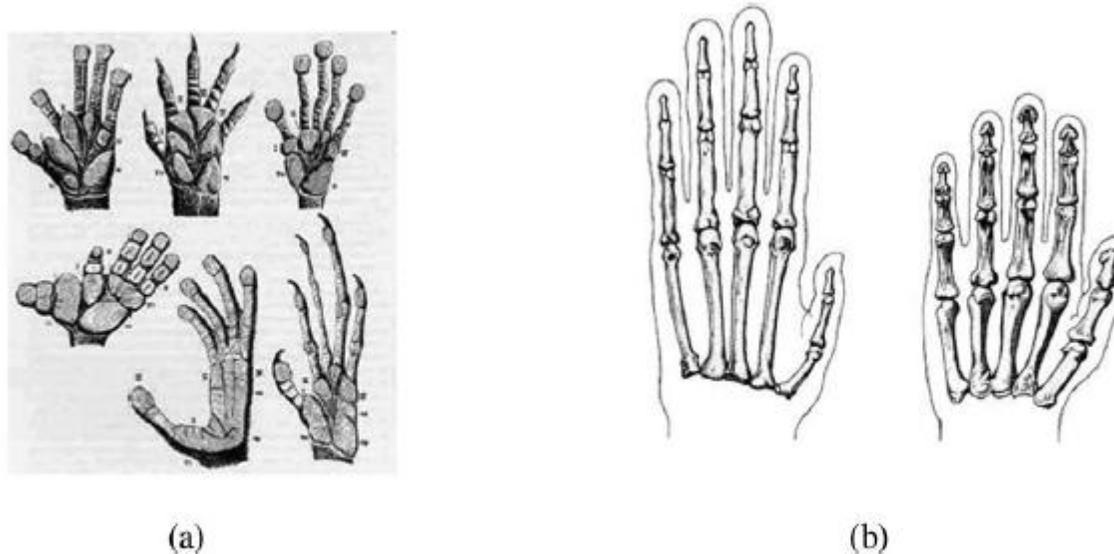


Fig. 21. (a) Examples of primate hands. (b) Differences between a human hand and a chimpanzee hand.

Conceptual Framework for Coevolving the Development of Robot Hand Morphology and Controller

- Existing work focuses on the design of the hand controller for a given morphology [97], which is inefficient when the shape of the objects changes considerably.
- A better approach is to codesign the hand morphology and control in a developmental manner, as illustrated in Fig. 22.

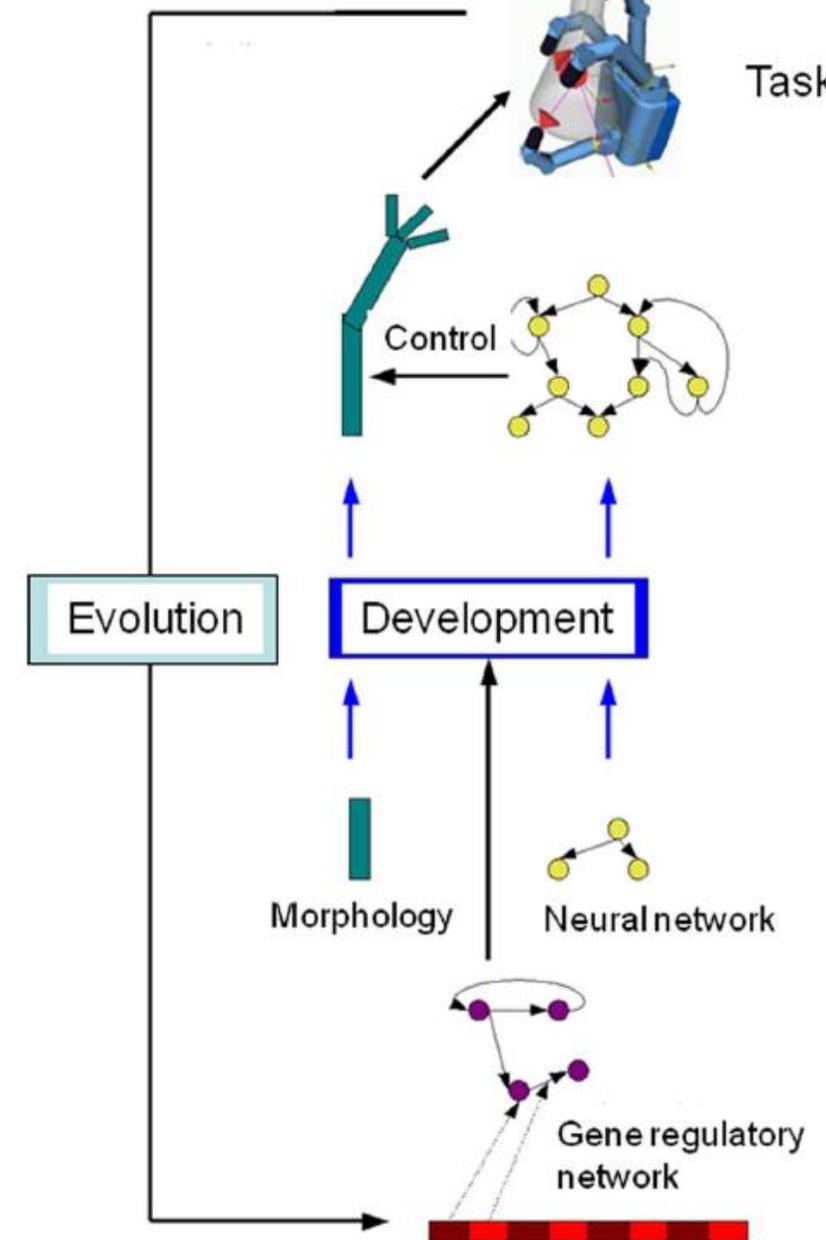


Fig. 22. Conceptual diagram for coevolving the development of hand/arm and control. Adapted from [37].

Concluding Remarks



- This paper suggests a new field of robotics termed *morphogenetic robotics*, which focuses on employing genetic and cellular mechanisms in biological morphogenesis for developing self-organizing, self-reconfigurable, and self-adaptive robotic systems.
- Research on morphogenetic robotics is still in its infancy and therefore many issues remain to be explored.
- 1) Many genetic and cellular mechanisms underlying biological morphogenesis still remain elusive
- 2) The interactions between morphogenetic robotics and epigenetic robotics are largely unexplored.
- 3) Morphogenetic robotics is currently very much limited to computational simulations. → Appropriate hardware for morphogenetic robotics, including programmable materials and adaptable sensors and actuators, is to be studied.



Thanks for listening!