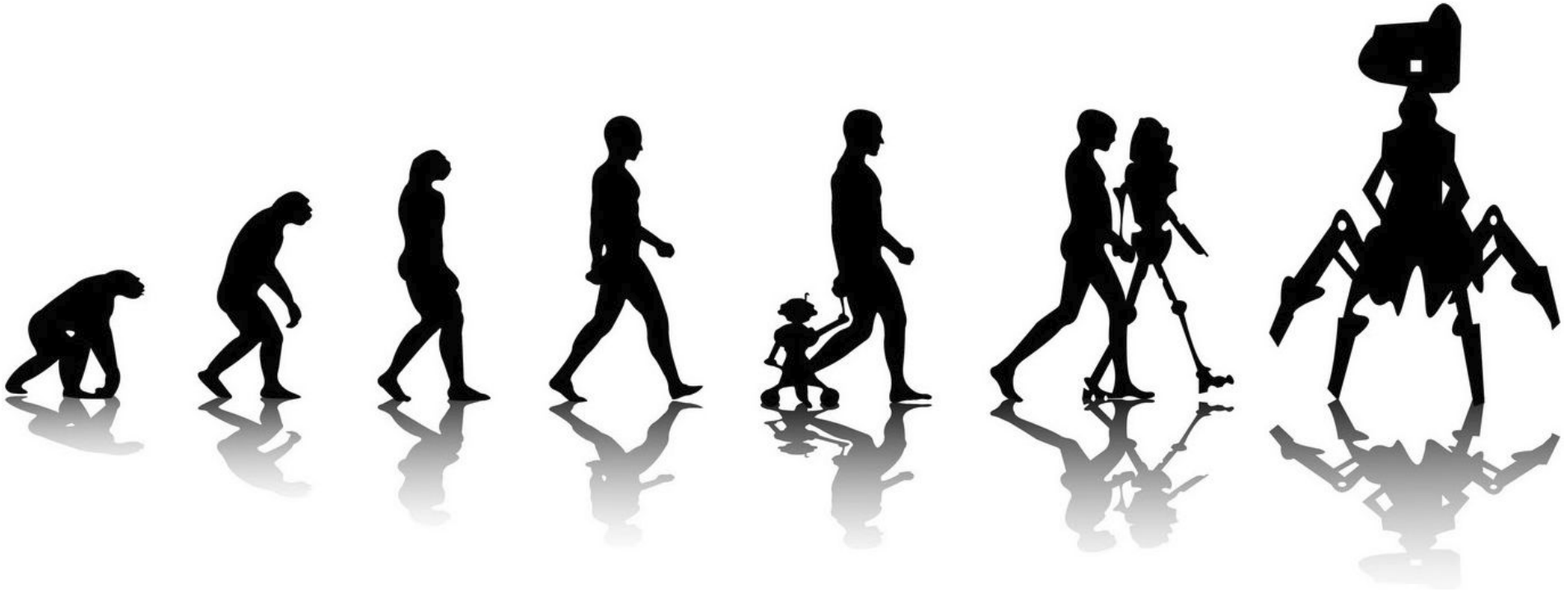


Modern Robotics: Evolutionary Robotics

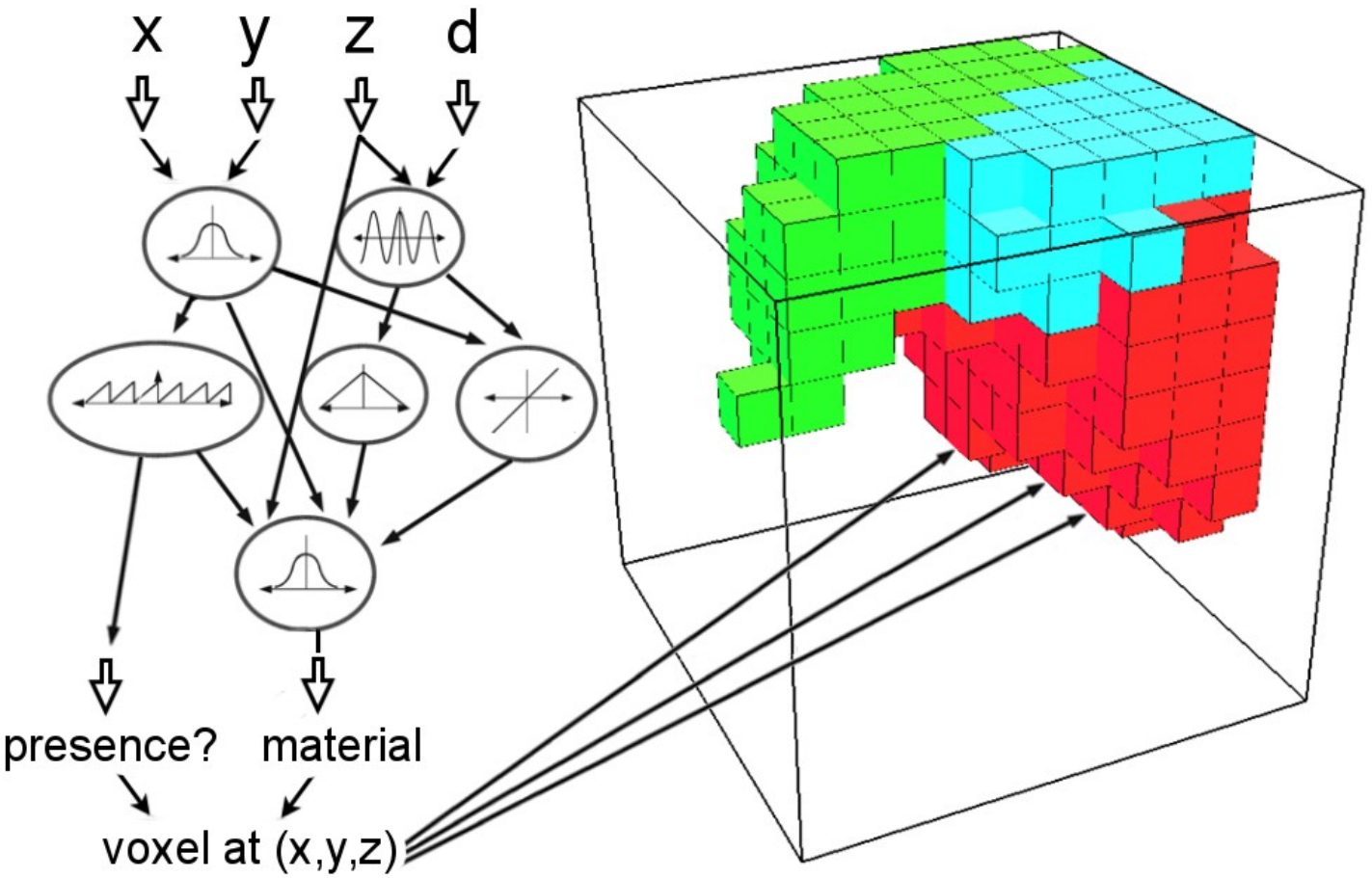
COSC 4560 / COSC 5560

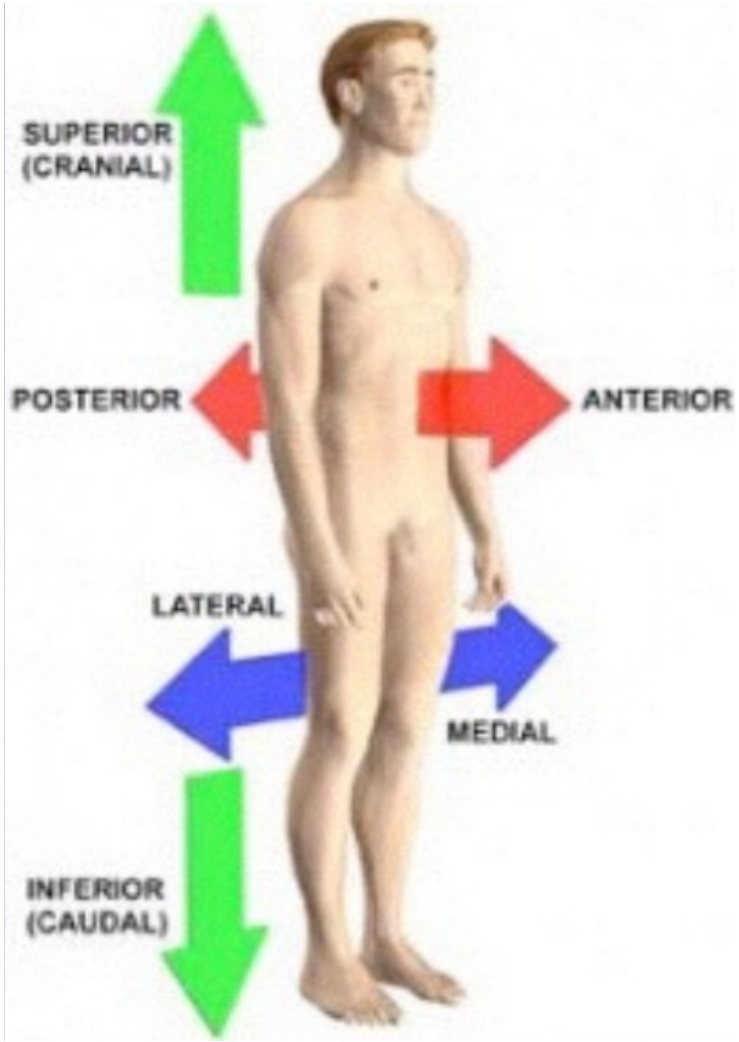
Professor Cheney

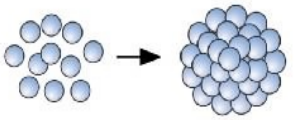
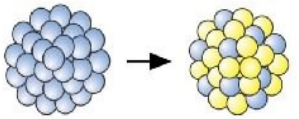
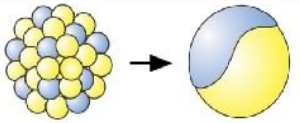
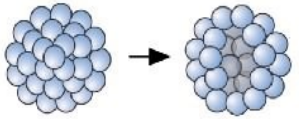
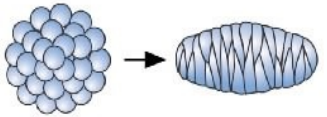
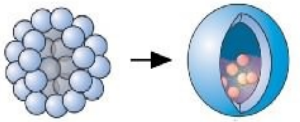
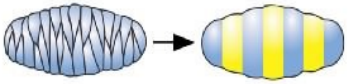
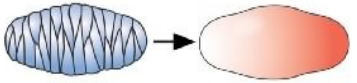
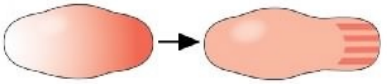
3/21/18

Evolution of Development

CPPNs: “Regularity without Development”



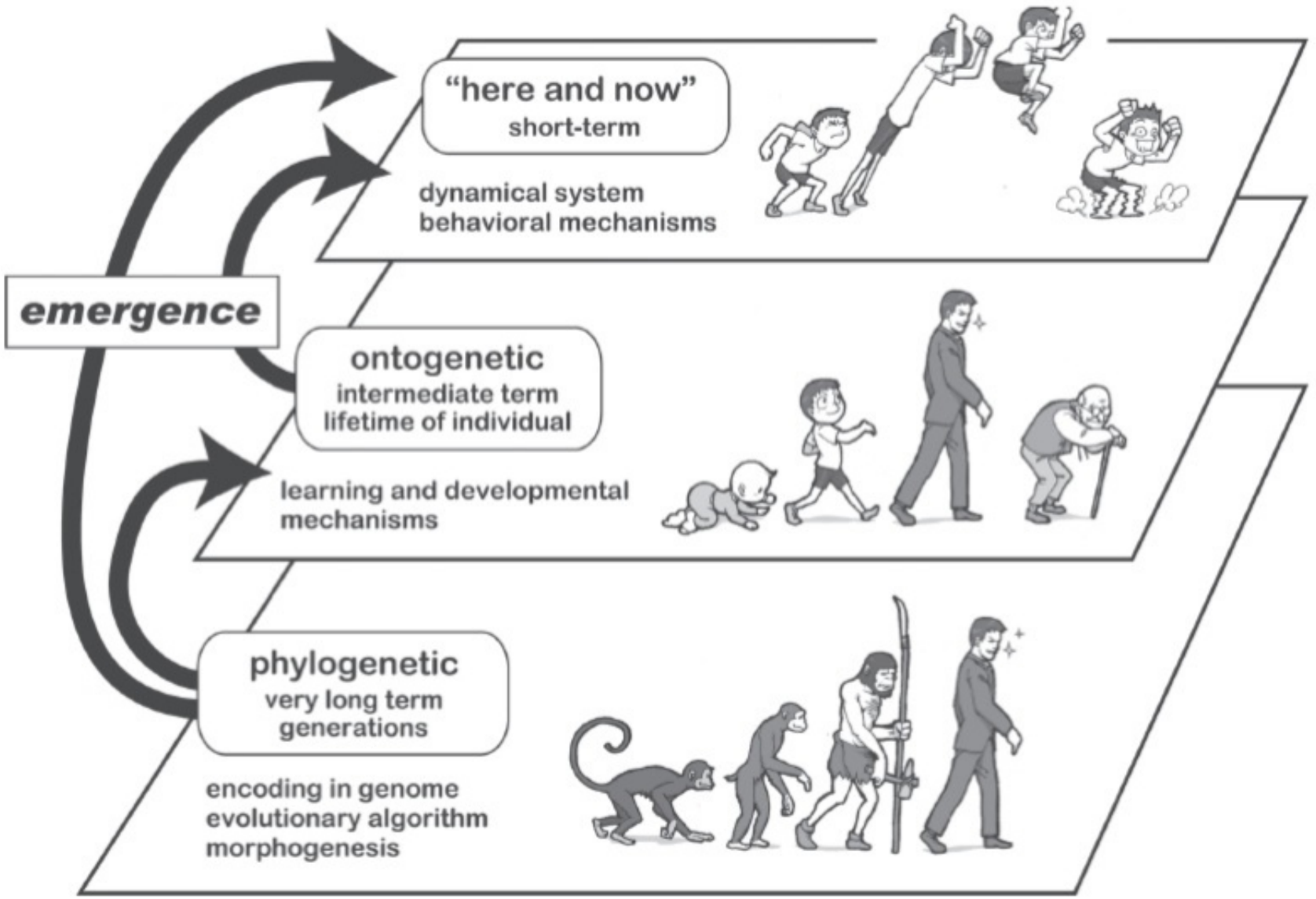

SUPERIOR
(CRANIAL)
POSTERIOR
ANTERIOR
LATERAL
MEDIAL
INFERIOR
(CAUDAL)

DPM	molecules	physics	evo-devo role	effect
ADH	cadherins	adhesion	multicellularity	
LAT	Notch	lateral inhibition	coexistence of alternative cell states	
DAD	cadherins	differential adhesion	phase separation; tissue multilayering	
POL_a	Wnt	cell surface anisotropy	topological change; interior cavities	
POL_p	Wnt	cell shape anisotropy	tissue elongation	
ECM	chitin; collagen	stiffness; dispersal	tissue solidification; elasticity; EMT	
OSC	Wnt + Notch	synchrony of oscillatin	morphogenetic fields; segmentation	
MOR	TGF-β/BMP; FGF; Hh	diffusion	pattern formation	
TUR	MOR + Wnt + Notch	dissipative structure	segmentation; periodic patterning	

[Newman and Bhat, 2008]

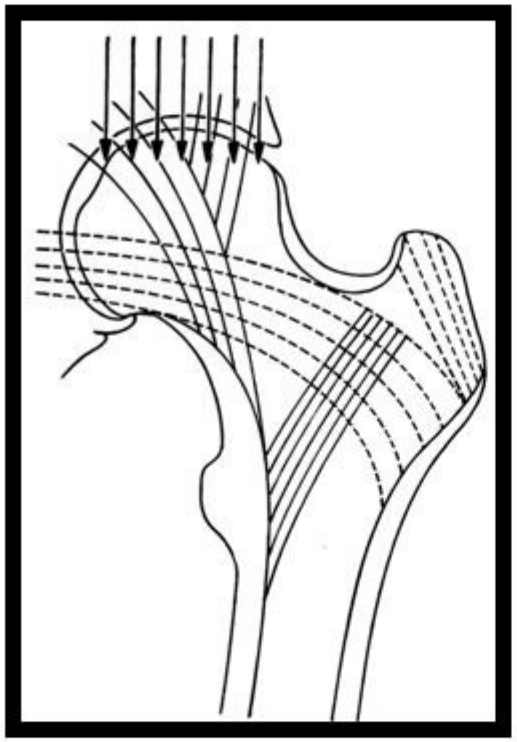
What does physical development buy us?

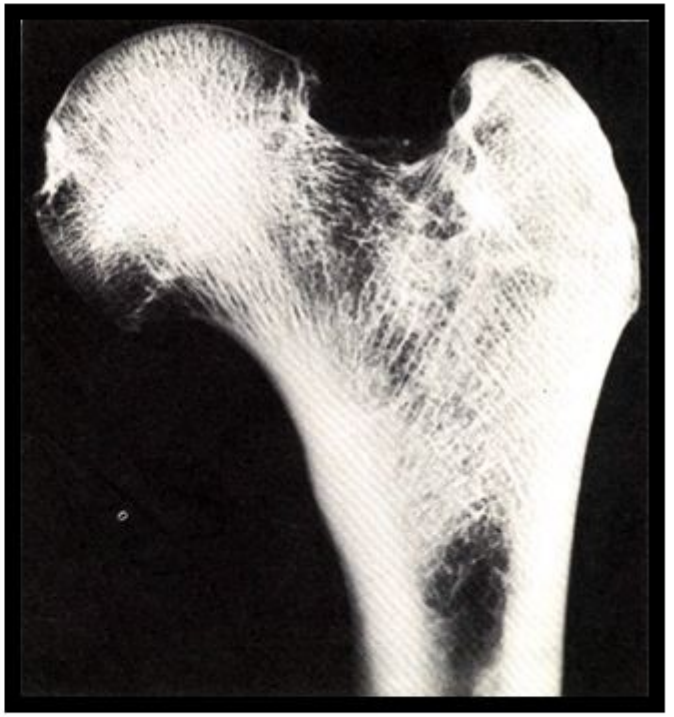
Is it worth the cost?


"here and now"
short-term
dynamical system
behavioral mechanisms
emergence
ontogenetic
intermediate term
lifetime of individual
learning and developmental
mechanisms
phylogenetic
very long term
generations
encoding in genome
evolutionary algorithm
morphogenesis

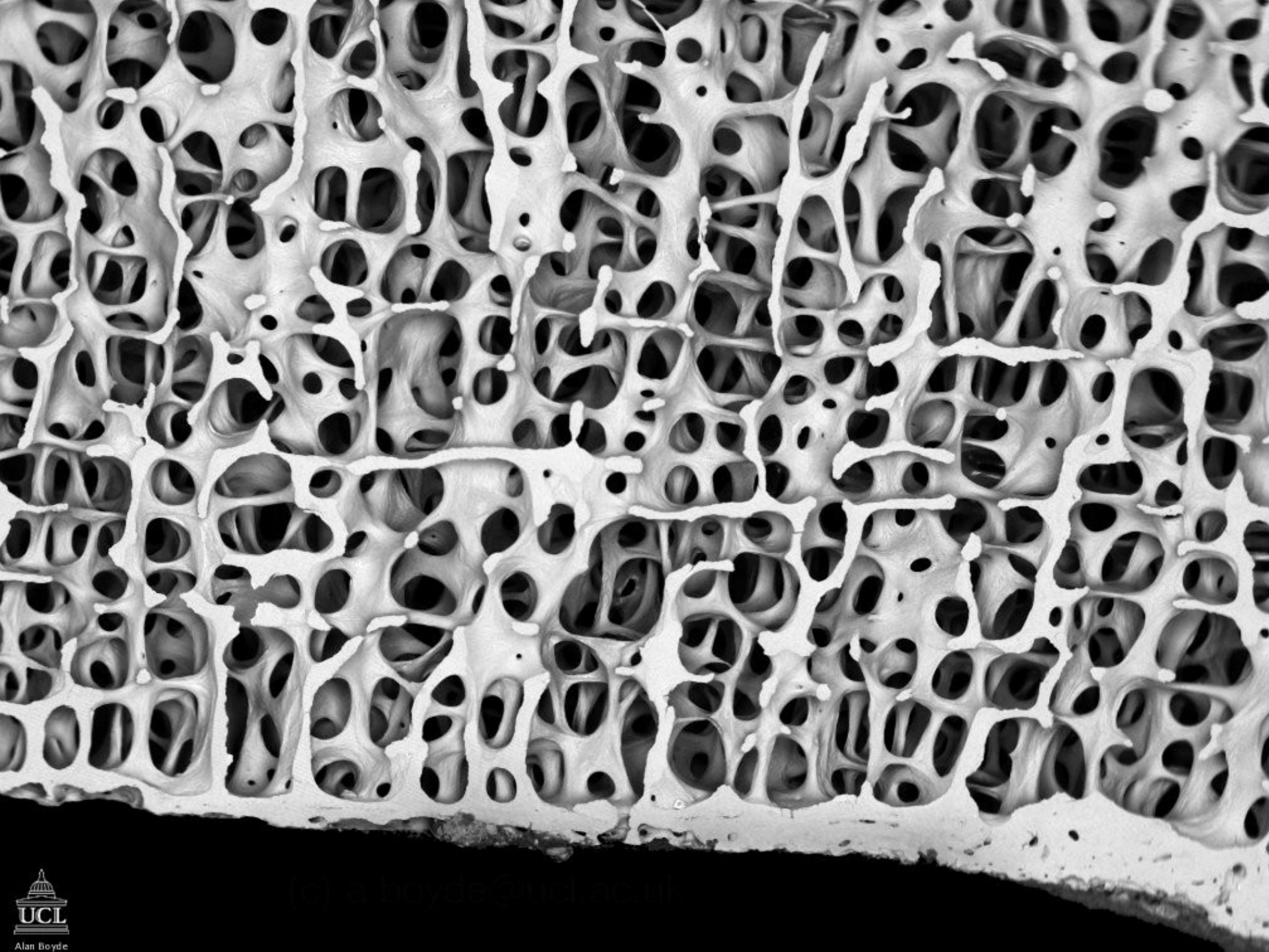
Wolff's Law

"Every change in the form and function of bones, or of their function alone, is followed by certain definite changes in their internal architecture and equally definite secondary alteration in their external conformation, in accordance with mathematical laws." Julius Wolff (1892)





Human Anatomy, Second Edition, C.V. Mosby Company, 1976



UCL

Alan Boyde

Evo-devo *in silico*: a Model of a Gene Network Regulating Multicellular Development in 3D Space with Artificial Physics

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Co-evolution of Morphology and Control of Soft-bodied Multicellular Animats

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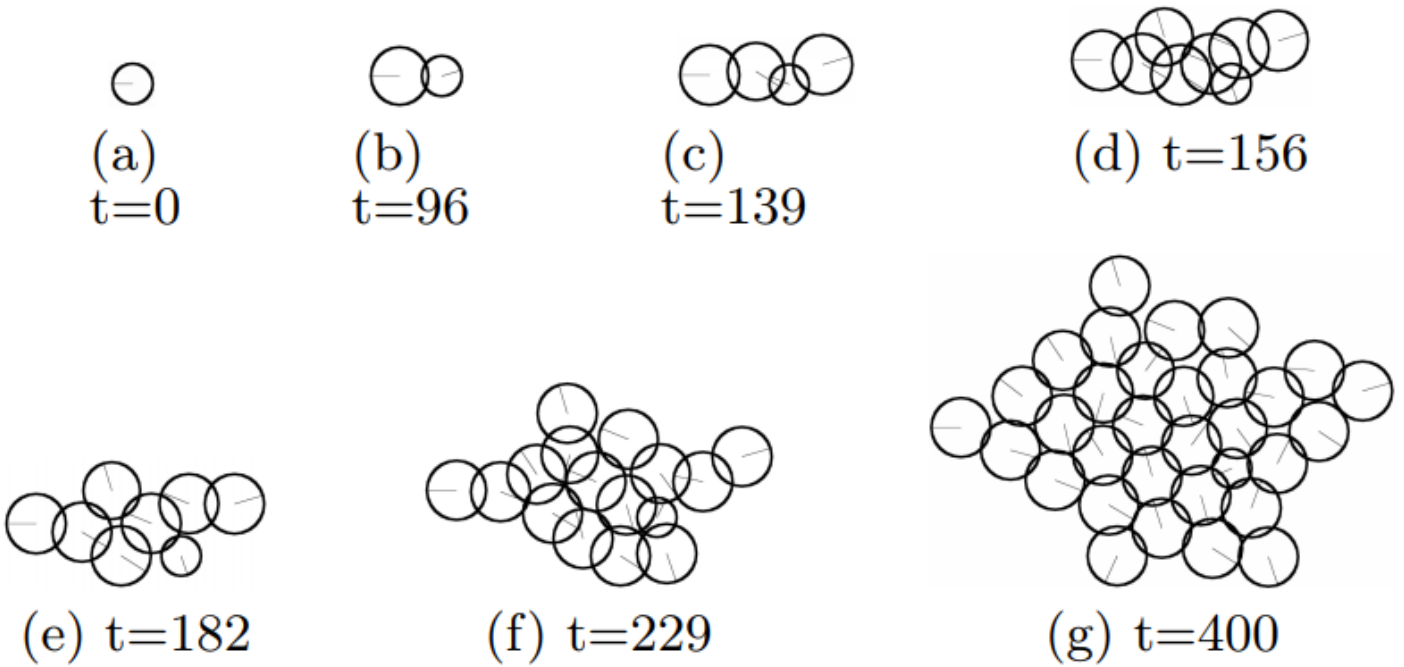
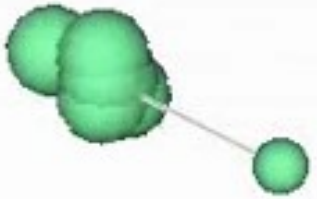
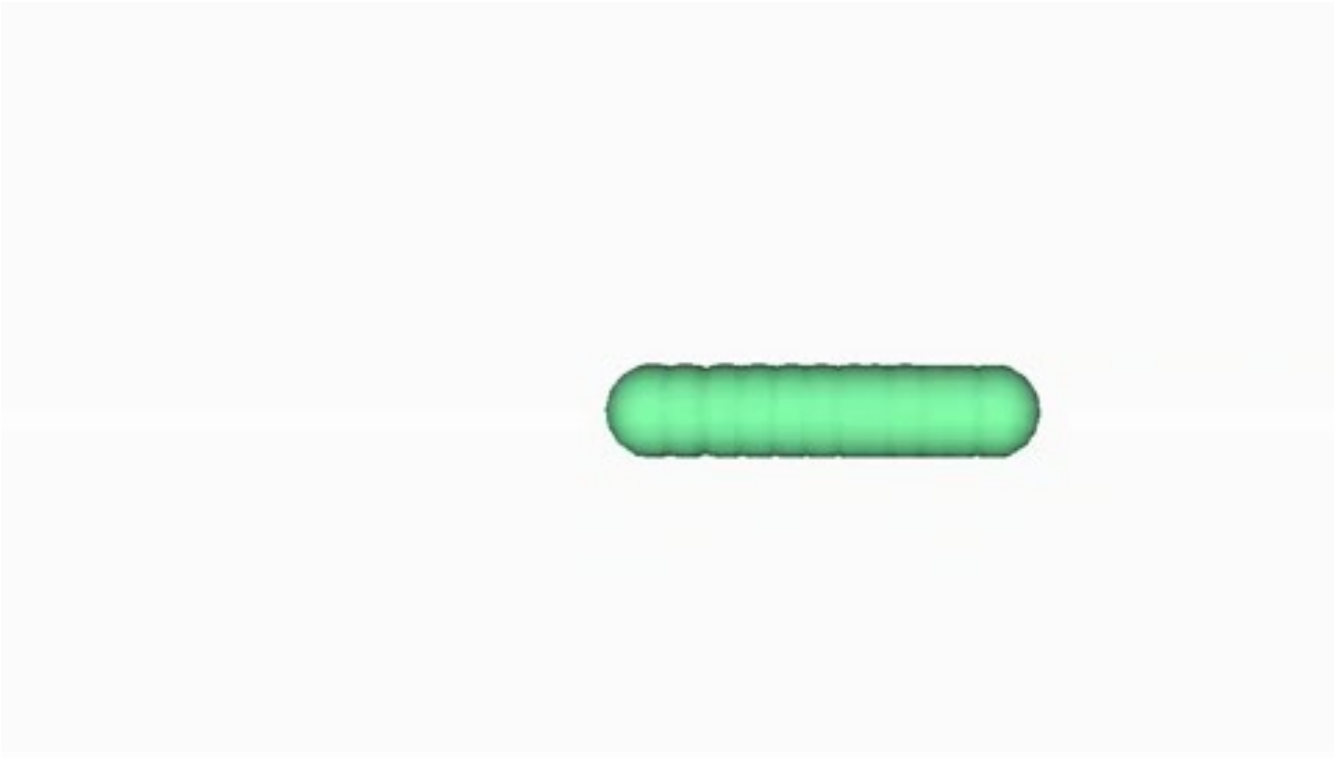


Figure 2: Example of a developmental process. The panels (a-g) show the development of the animat in Fig. 7b, 6a at indicated simulation time steps, (d) shows cells that have just divided, but were not yet pushed away by physical forces, this process took about 30 time steps (e). Cells are represented as circles, short lines indicate the direction of the orientation vector.





Development is guided by diffusive substances, which include not only the three maternal morphogens, but also morphogens which can be produced by cells. In our simplified, grid-less diffusion model, the level of a diffusing product at a given location is a function of distance and the historic concentration of this morphogen at its source.

Cell division occurs when the level of a product coded by the special element associated with this action reaches the threshold of 0.9. Each cell maintains its orientation vector, used to determine the direction towards which a new cell will be placed at division. The daughter cells inherit all the TF concentrations and the direction of the orientation vector from their mothers. At division, the daughter is placed in close proximity to the mother, and the orientation vector of the daughter is rotated proportionally to the activation level of the associated GRN output (maximum expression, 1, corresponds to a rotation angle of 2π). If a mother cell expresses the gene responsible for size increase, the radius of a new cell may be up to 50% larger. We enforced a hard limit for the size of the embryo of 32 cells, with the exception of one series of evolutionary runs in which up to 64 cells were allowed. This limitation can be seen as stemming from the strict limits on the resources available to the embryo.

Special elements, which encode the inputs and outputs of the GRN, are treated like TFs (for inputs) or like if they were regulatory units with one gene (for outputs). The activation of outputs is determined by the concentration of TFs that have affinity to a particular special element. The model includes six cellular actions, associated with outputs: cell division, cell rotation, modification of cell size (which affect development), and three actions that modify oscillation parameters (which affect movement; explained below). Four inputs can be used: a signal of "1" (a TF with a constant maximum concentration; this is similar to a bias input in neural networks), and three substances ("maternal morphogens") diffusing from three sources in the 2-D physical space in which development occurs. Evolution determines what inputs and outputs are actually used in a given GRN.

Product concentrations are updated in discrete time steps. First, activation of each promoter of the given regulatory unit is calculated as a weighted sum of concentrations of products which have affinity to this promoter. Then, the sum of the activities of all the promoters is used to calculate the rate at which products of this regulatory unit are produced or degraded:

$$\Delta L = (\tanh \frac{A}{2} - L)\Delta t \tag{1}$$

where Δt is the time step (0.05 was used), L is the current concentration of the product, and A is the sum of activation of all promoters for this regulatory unit. The formula ensures that all product concentrations remain within $[0, 1)$.

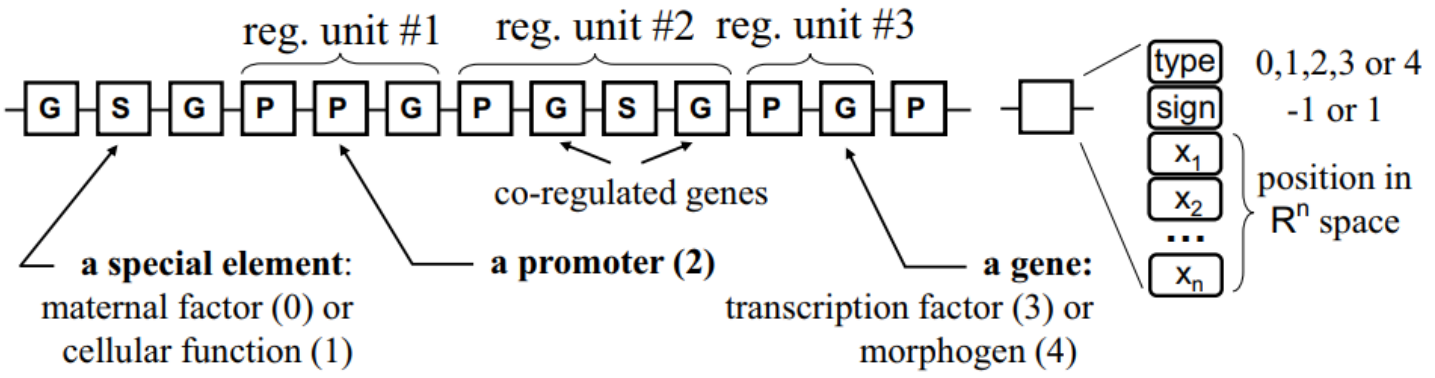


Figure 1: The structure of the genetic elements and the linear genome. Each element consists of a type field (the numbers in parenthesis in the descriptions below the graph indicate types), a sign field, and an ordered set of N real values which is used to determine affinity to other elements; $N = 2$ was used in this paper.

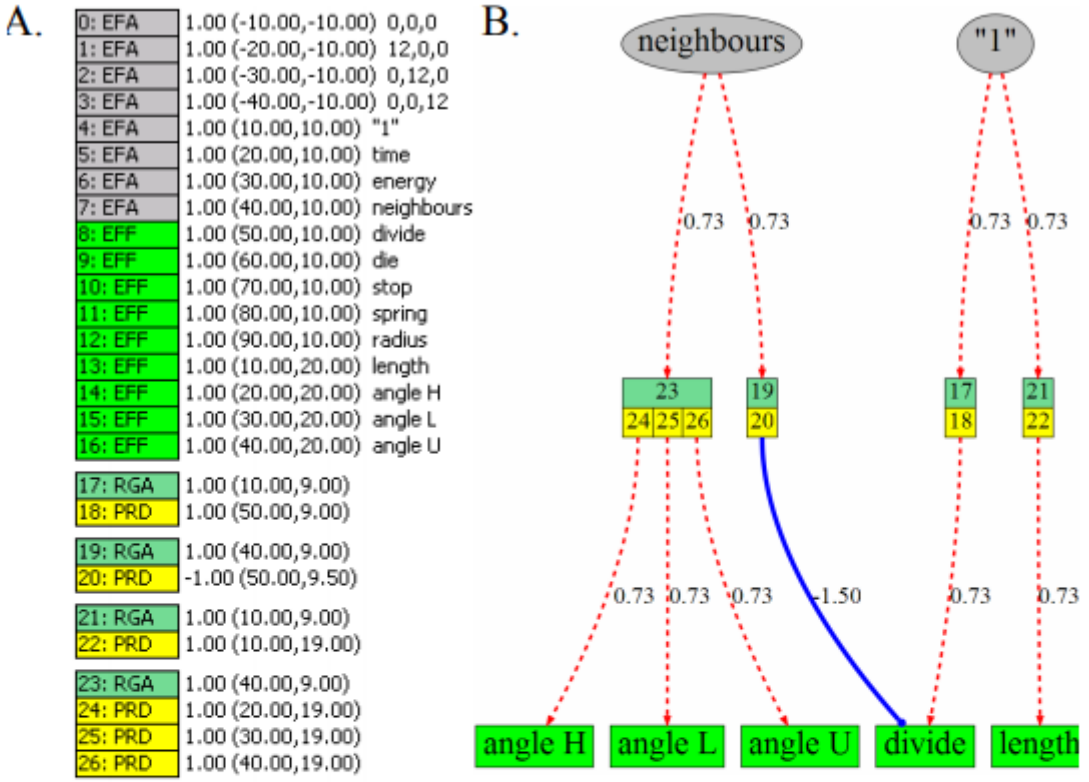


Figure 1: The seed genome (A) and the corresponding gene regulatory network (GRN; B). The genome consists of 27 elements (the value of the modifier, the coordinates in 2D sequence space are listed on the right): 8 external factors (the first 4 are positional factors, with 3 coordinates in 3D developmental space), only 2 of which are connected to the GRN, and 9 effectors, of which only 5 are connected, and 6 genes in 4 regulatory units.

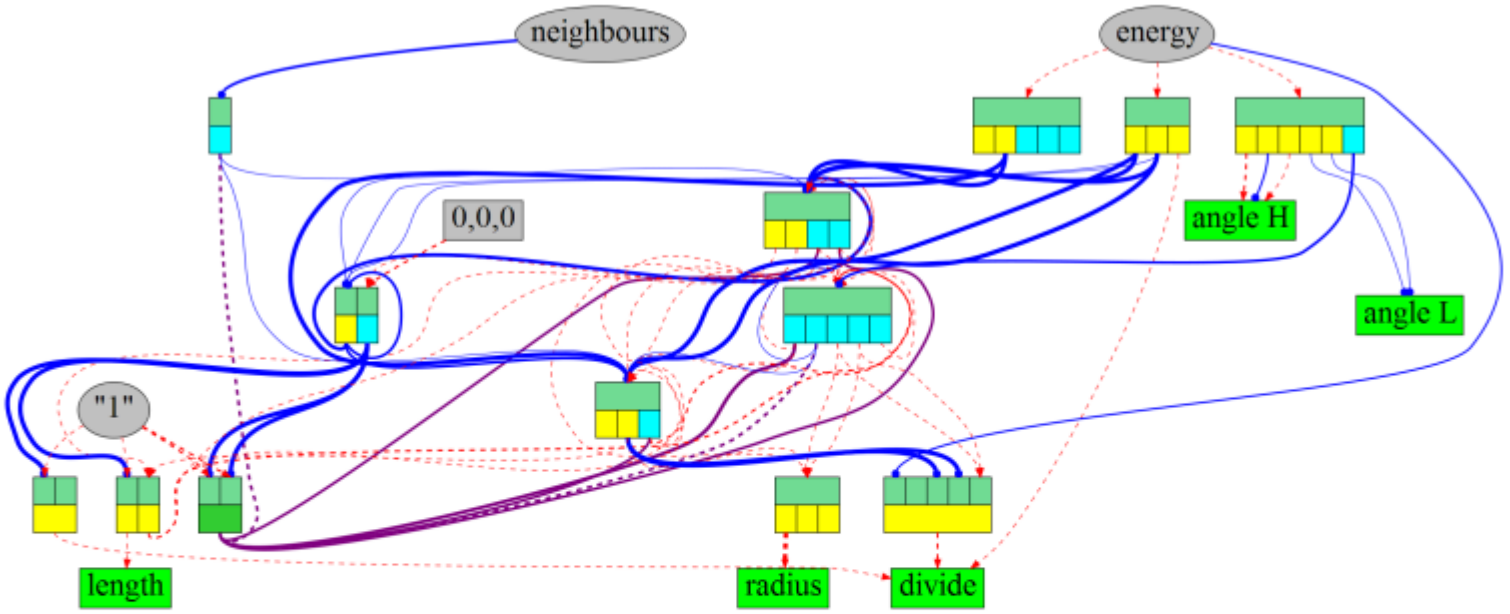


Figure 5: The GRN controlling the development of a asymmetrical dumb-bell shape in Fig. 2B. Dashed lines correspond to excitatory connections.

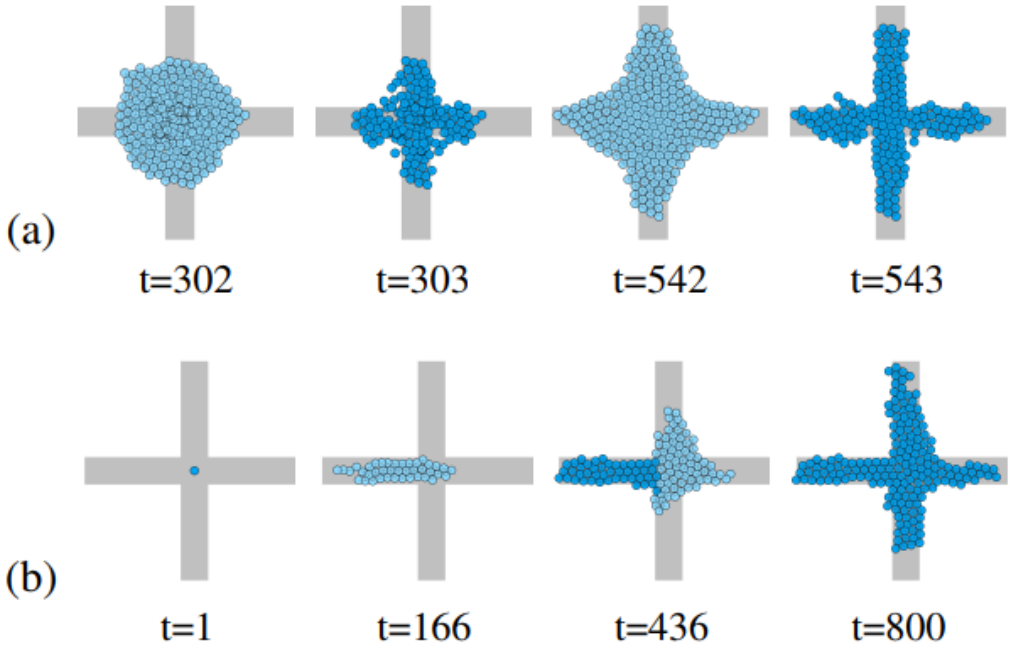


Figure 1: Example snapshots from development of 2 embryos (blue cells) evolved to produce cross shape, overlaid on the target to which embryos would be compared during evaluation (gray). (a) the system allowed for unconstrained cellular divisions whenever an associated output crossed a threshold, the final shape is a result of repeated subtractive process: apoptosis removing excess cells; (b) cell divisions were constrained to non occupied space, evolved shape is a result of an additive assembly. Brightly colored cells have their division signal above the threshold.

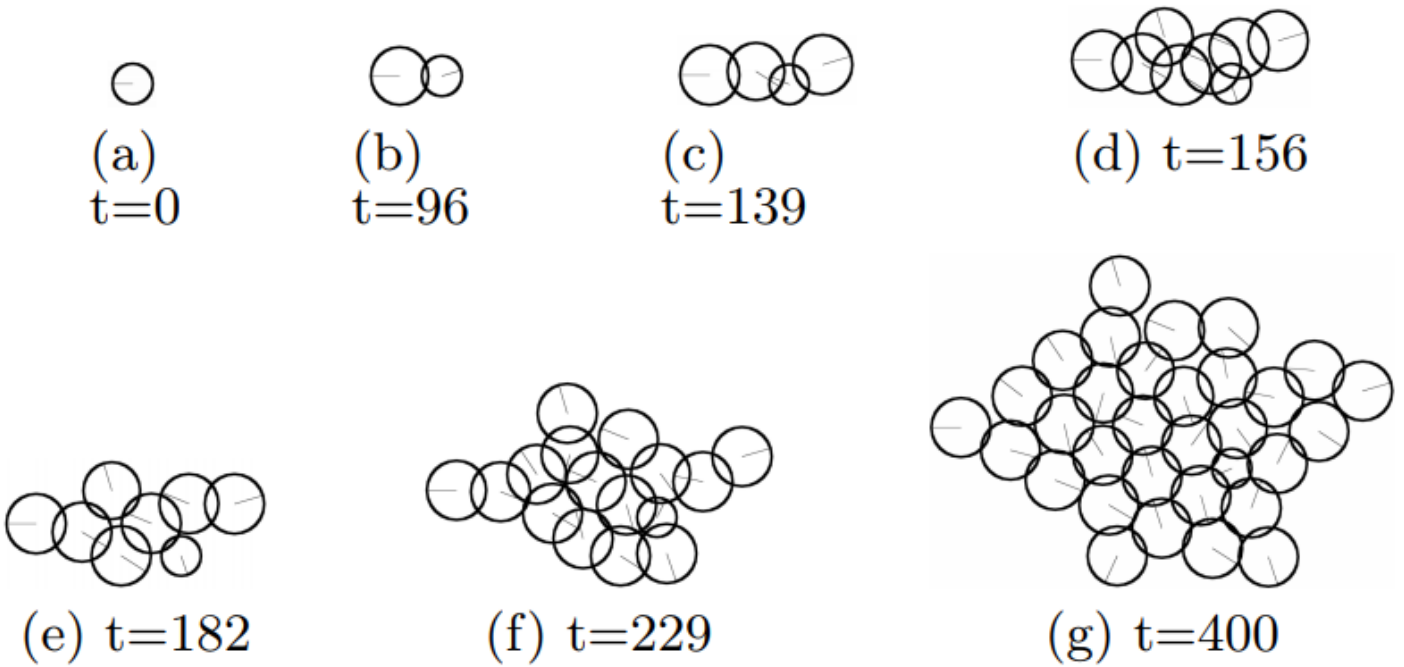


Figure 2: Example of a developmental process. The panels (a-g) show the development of the animat in Fig. 7b, 6a at indicated simulation time steps, (d) shows cells that have just divided, but were not yet pushed away by physical forces, this process took about 30 time steps (e). Cells are represented as circles, short lines indicate the direction of the orientation vector.

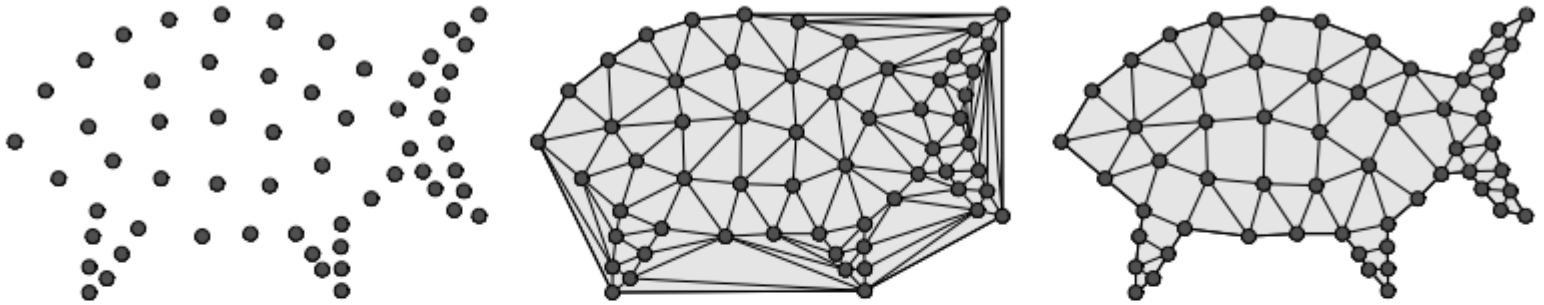
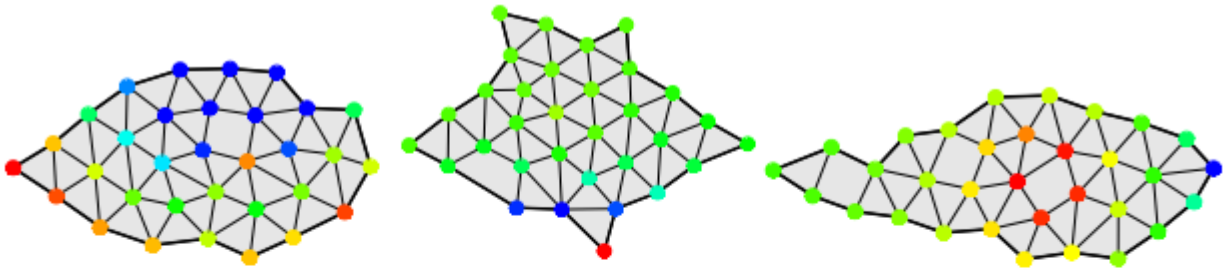
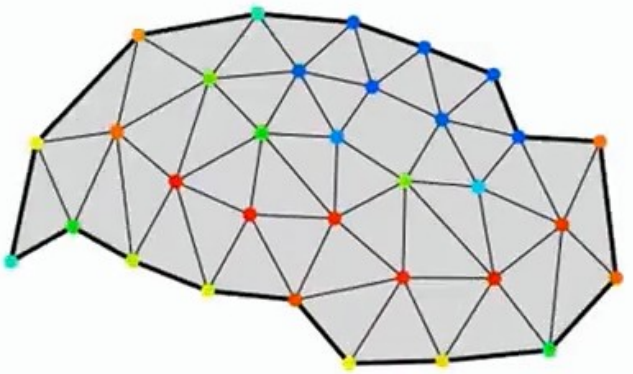


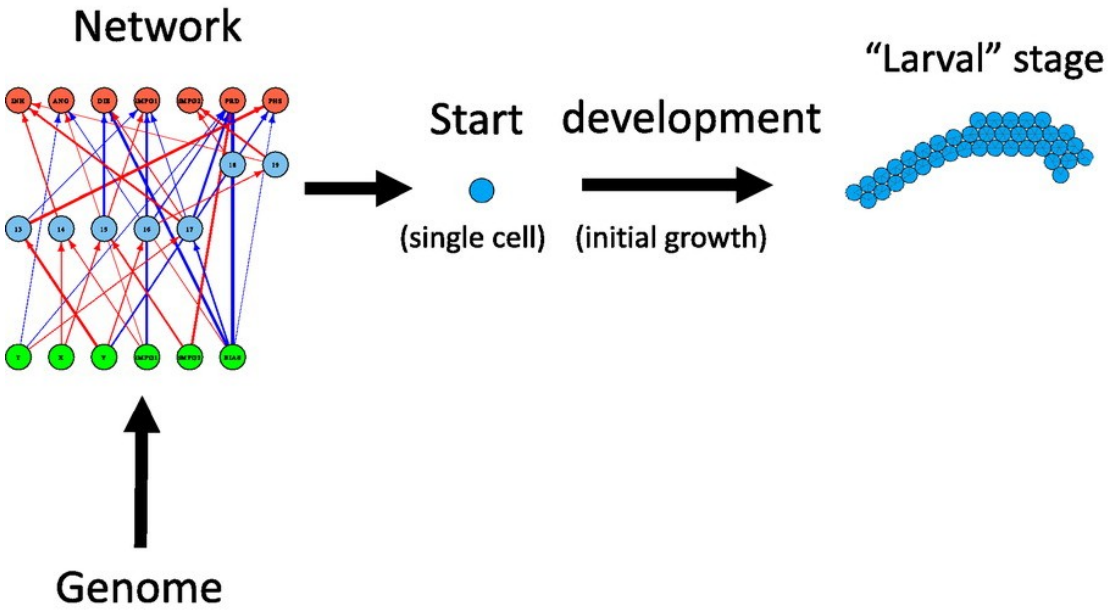
Figure 3: Algorithmic transformation of a set of points into the structure of the animat: (a) cell centers at the end of developmental phase, (b) a Delaunay triangulation, (c) a Gabriel graph (final structure).

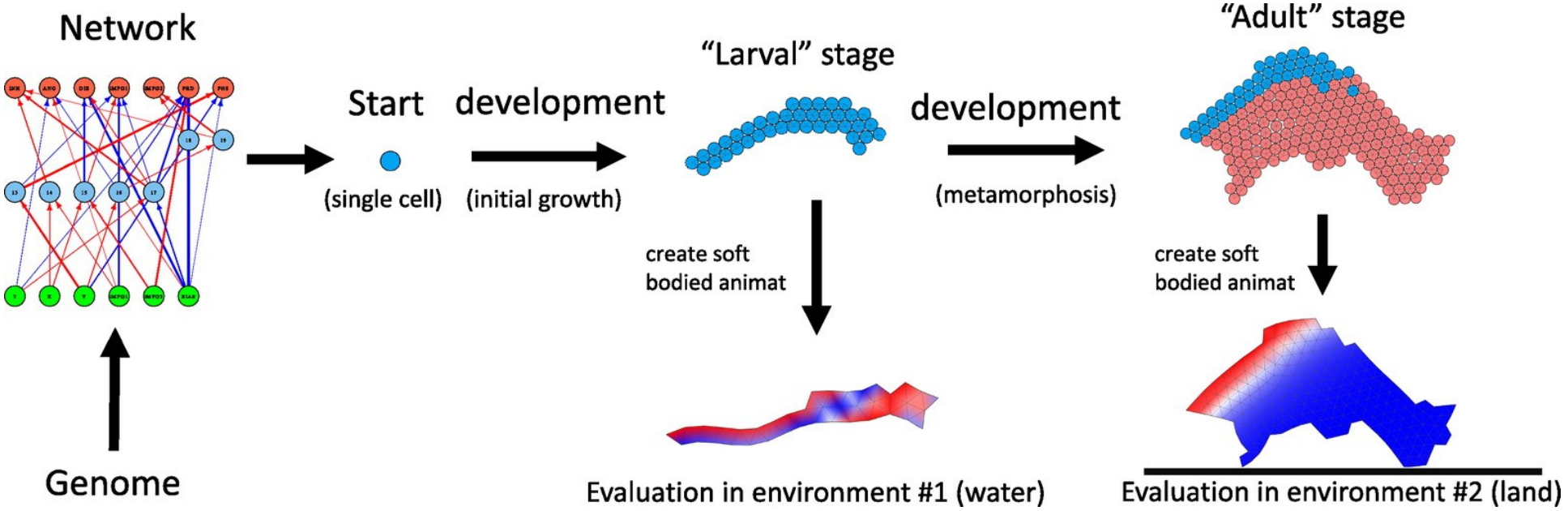


(a) 1.42π (b) 1.27π (c) 0.29π

Figure 7: Example of evolved cell oscillation phase shifts. Panel (a): the individual in Fig. 4a, (b): in Fig. 6a, (c): in Fig. 5a. All animats are displayed in their initial, equilibrium states. Color range is normalized on each picture and the maximum value of phase shift in each individual (corresponding to the red node) is indicated.




Network
Start
development
"Larval" stage
(single cell)
(initial growth)
Genome


Network
Start
development
(single cell)
(initial growth)
"Larval" stage
development
(metamorphosis)
"Adult" stage
create soft
bodied animat
create soft
bodied animat
Genome
Evaluation in environment #1 (water)
Evaluation in environment #2 (land)

Harnessing evolutionary creativity: evolving soft-bodied animats in simulated physical environments

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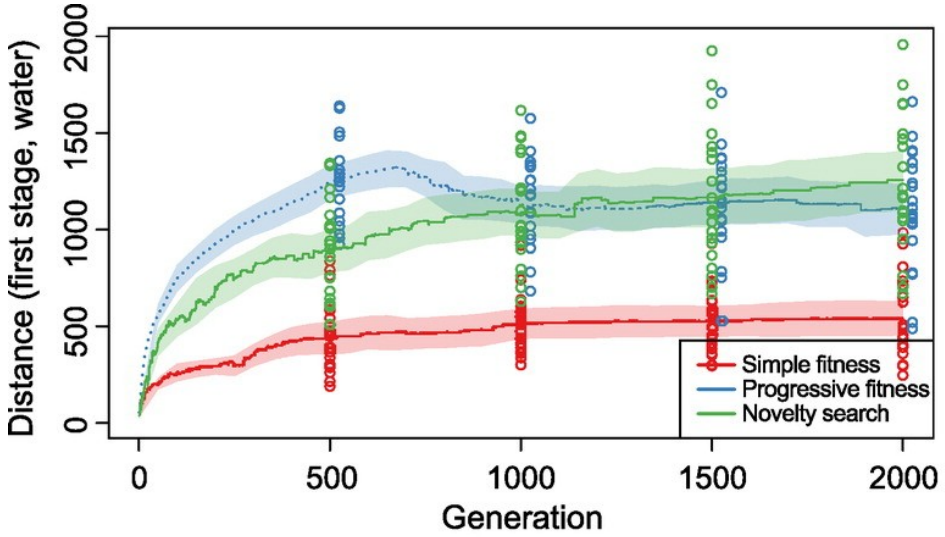
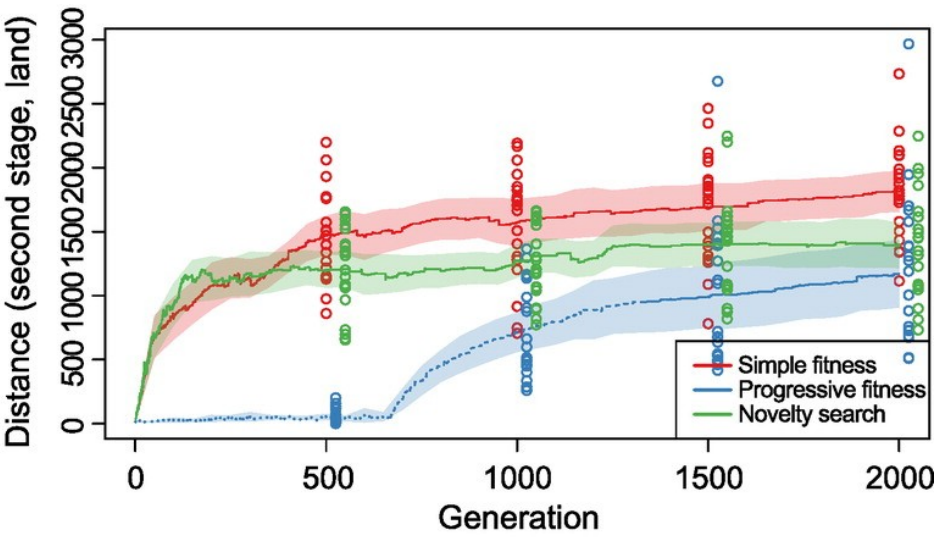
NAGOYA UNIVERSITY

INFORMATION SCIENCE NAGOYA UNIVERSITY

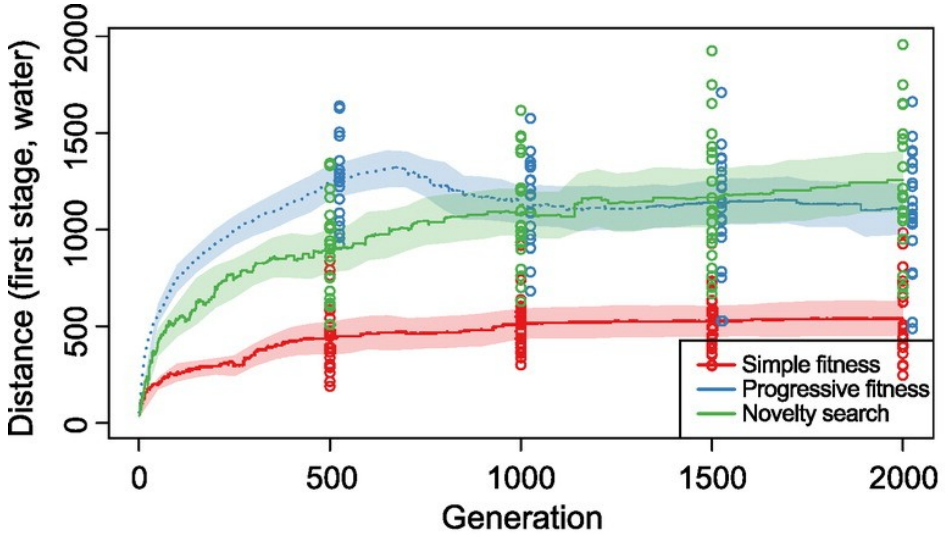
JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE
日本学術振興会



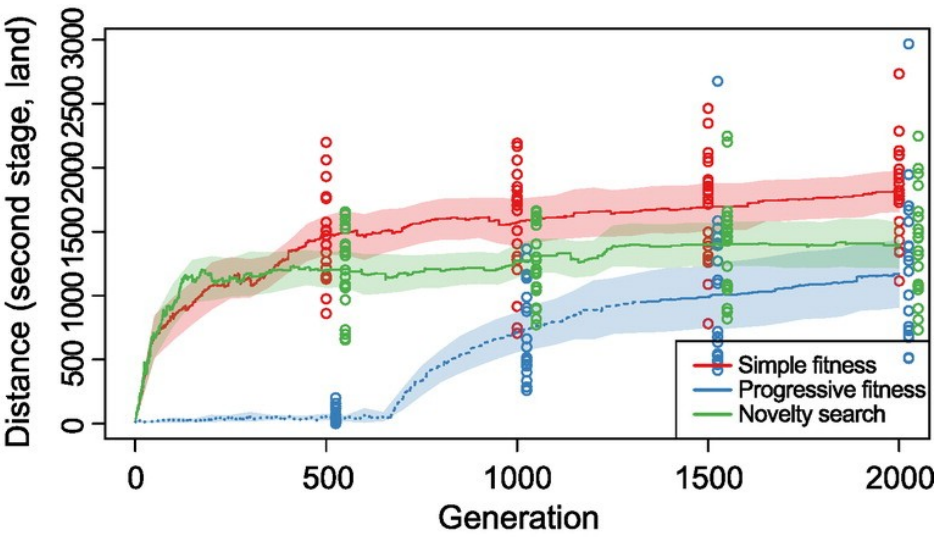
(a) Aquatic larvae



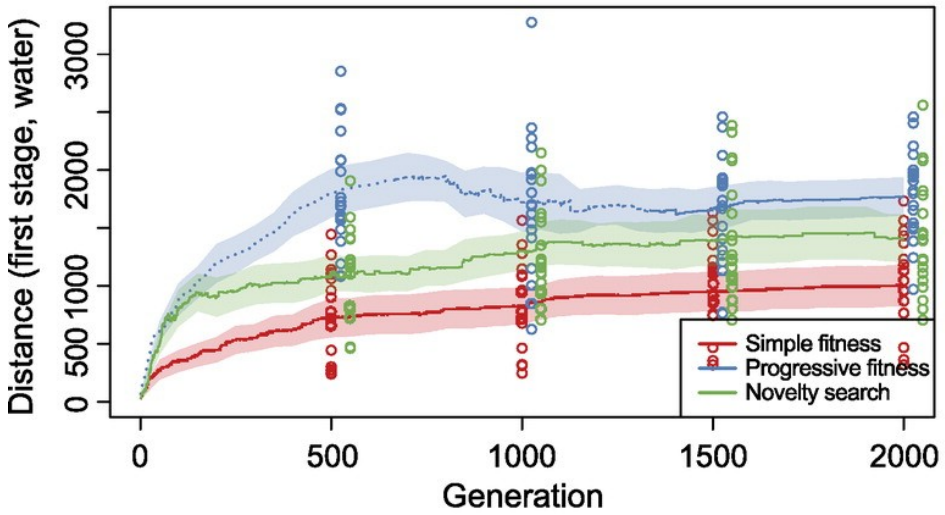
(b) Terrestrial adults



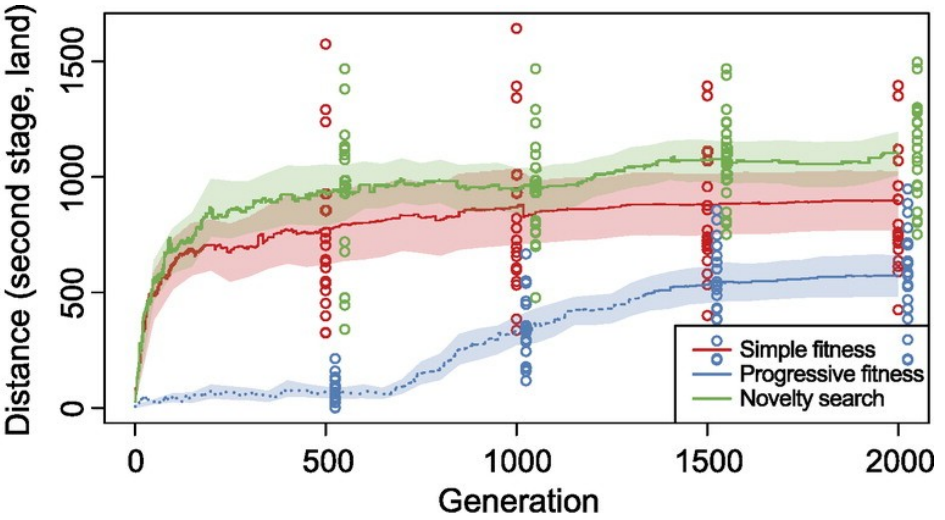
(a) Aquatic larvae



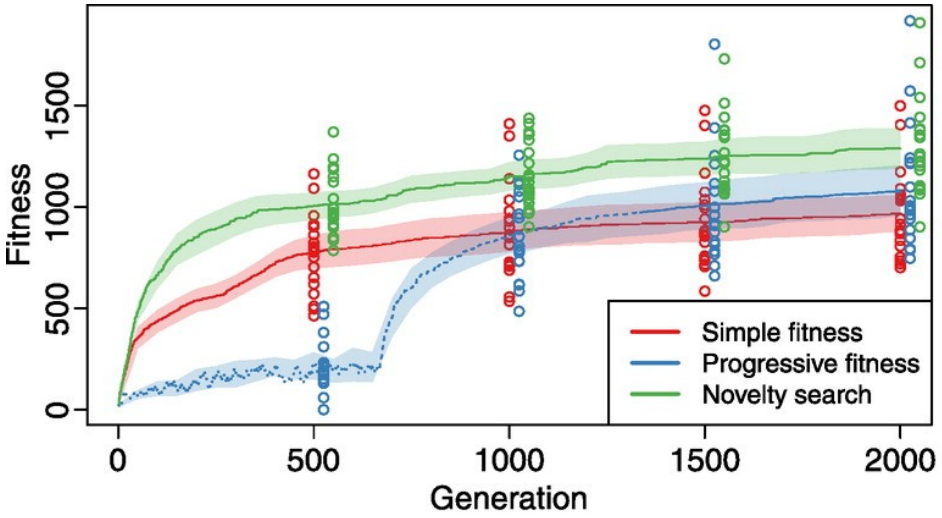
(b) Terrestrial adults



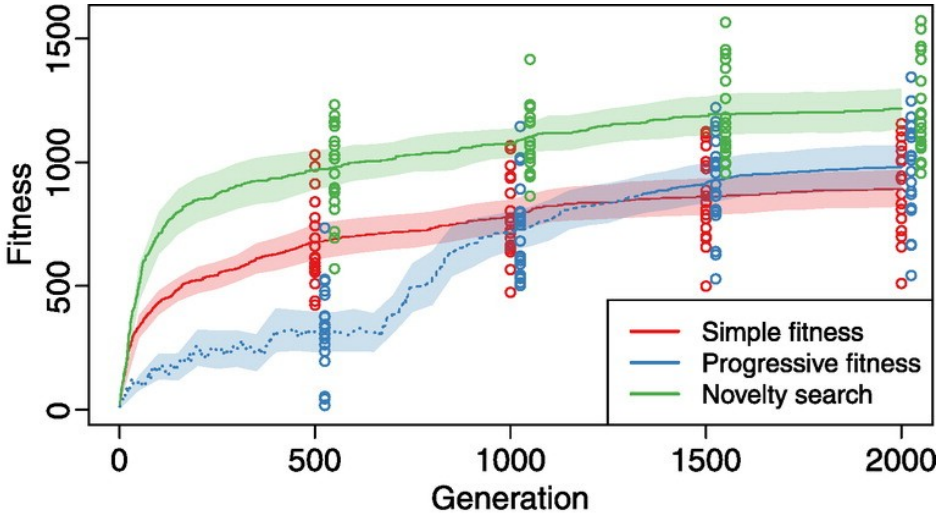
(a) Terrestrial larvae



(b) Aquatic adults



(a) Aquatic larvae and terrestrial adults



(b) Aquatic adults and terrestrial larvae