Electronic Supplementary Material (ESI) for Integrative Biology.

Supplemental Figure Legends

Supplemental Fig. 1: pattern regulation is a closed loop system

Current approaches in this field largely treat morphogenesis as a feed-forward process, where gene-regulatory networks specify effector proteins, whose activity (physical interactions) result in complex pattern formation by emergence. Importantly however, there is a feedback loop in many species. This allows unpredictable environmental events (such as amputation of specific body regions or deformation) to trigger remodeling events that correct back to the target morphology. An important goal of this field in the future is to understand what algorithms and mechanisms guide this error-correcting closed loop process.

Supplemental Fig. 2: Levels of organization: isomorphism between developmental bioelectricity and information processing in the brain and in artificial systems.

Geometric memory (e.g., of a path through a maze) in the brain (A) is implemented by memory encoded as stable bioelectrical states in the brain (D), which in turn are maintained by connectivity and electrical communication among the brain cells (G), which in turn are generated by ion channel and gap junctional proteins (J).

Pattern memory (the shape that is regenerated after a salamander's limb is amputated and that serves as a stop condition for further growth) (B) is likewise implemented by information encoded in gradients of electrical potential in the tissue (E), which are maintained by Vmem potentials of specific cells throughout the body (H), which in turn are generated by ion channel and gap junctional proteins (K).

In artificial cybernetic systems, specific patterns (C) can be remembered and processed by artificial neural net representations (F), which are built up from electrical circuits consisting of transistors (I); interestingly, gap junctions act much like transistors (L) because they regulate their permeability (current) based on voltage applied across them. Graphics by Alexis Pietak.

Supplemental Fig. 3: A network view of how bioelectric states encode anatomy

(A) During normal regeneration, an electrical network can store the memory of a spatial pattern (represented here by a Hopfield network that has been trained to recognize a specific letter's shape). Such networks have the property that memories are attractors in the energy landscape, and when perturbed away from this lowest-energy state (such as when presented by a damaged or incomplete pattern), they can return to the attractor state by reconstructing the whole pattern. In vivo, the networks implemented by bioelectric signaling likewise remember the entire correct pattern despite damage and return to the stable correct state (the target morphology attractor), as is seen in planaria where each fragment can regenerate the entire worm.

(B) However, a network could have more than one stable attractor, representing in artificial networks diverse memories of different shapes. As shown in planaria, animal bodies can be permanently shifted (by a transient physiological perturbation of network state) to a different attractor, corresponding to a 2-headed flatworm. These animals persistently recover the new (different) pattern when cut in the future, because the whole network is stuck in an attractor that corresponds to a different anatomical outcome.

(C) This suggests the possibility to develop rational interventions, such as patterned light delivery, to directly re-write the memories of such bioelectric networks, causing them to rebuild anatomies with different desired structures. Graphics by Alexis Pietak.