The Grammar of Form

Michael Levin's Bioelectric Intelligence and the Closure Framework: How Cells Collectively Build Bodies They Have Never Seen

CF Dietz

> *Bioelectricity is the cognitive glue that allows larger-scale systems to operate in spaces that their parts cannot operate in alone. Just as electrophysiology binds neurons into behavioral intelligence, somatic bioelectricity binds cells into morphogenetic intelligence.*
> Michael Levin, Lifespan.io interview, 2025

> *Every finite closure generates remainder. The remainder is not noise. It is the proof that the grammar is finite.*
> CF Dietz, Consciousness, Closure, and the Cosmos, 2026

Abstract

Michael Levin is Professor at Tufts University and Director of the Allen Discovery Center, working at the intersection of developmental biology, neuroscience, cognitive science, and synthetic biology. His research demonstrates, with experimental precision, that developing organisms do not build their bodies by executing genetic programs. They navigate morphogenetic space: they actively seek target body forms the way brains seek behavioral goals, using bioelectric patterns across cell collectives as the medium of morphogenetic memory and instruction. His planarian experiments, in which he reprogrammed the body plan of flatworms by altering bioelectric signals without changing any DNA, are the most dramatic available demonstration of downward causation from a higher-level organizational closure to the molecular and cellular levels below it. This paper argues that Levin's bioelectric intelligence and the closure framework developed in Consciousness, Closure, and the Cosmos are convergent at the deepest level of biological organization. The bioelectric pattern that guides morphogenesis is a higher-level closure regime that sets boundary conditions for the cellular and molecular closures below it: determining which cells become eyes, which become gut, which become brain, not by specifying molecular pathways but by constituting a morphogenetic grammar that cells interpret and enact. Levin's cognitive light cone, his account of how agents at every scale navigate their own problem spaces, is the closure framework's account of nested closure regimes each constituting facts at their own level while using the remainder generated at lower levels as the resource for higher-level organization. And Levin's vision of an anatomical compiler, a system that communicates large-scale form goals directly to cells, is the vision of being able to write directly to the higher-level morphogenetic closure rather than to the molecular implementation below it.

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1. The Worm That Built the Wrong Head

A planarian flatworm can be cut into pieces and each piece will regenerate a complete worm. Cut it crosswise and the front piece will grow a new tail. The back piece will grow a new head. Cut it lengthwise and each half will regenerate a complete bilateral worm. The regenerative capacity is extraordinary: each fragment somehow knows what kind of worm it should become and builds exactly that, with correct proportions, correct anatomy, correct functionality. The genome encodes the molecular components but not the head-to-tail ratio, not the organ placement, not the final body plan. Something else is carrying the morphogenetic goal.

Michael Levin and his colleagues discovered what that something is. They blocked a specific class of ion channels in planarian tissue, disrupting the bioelectric patterns that normally propagate across cell collectives. The genetic content of the tissue was unchanged. The molecules were all present. But when the bioelectric pattern was disrupted, the regenerating fragments built a two-headed worm: heads at both ends, no tail. When the bioelectric disruption was removed months later, the worms began regenerating normally again, building correctly proportioned worms with one head and one tail, even though no genetic change had occurred at any point.

Then came the result that transformed the paper from striking to transformative. By applying specific bioelectric signals to planarian tissue, Levin's team induced the worms to grow the heads of other planarian species, with no genetic change. The body's bioelectric memory could be rewritten to target a different morphogenetic form, and cells that had never encountered that form would build it correctly.

This is not a molecular biology result. It is a result about levels of organization. The genome encodes the molecular toolkit. The bioelectric pattern is a higher-level organizational closure that determines how that toolkit is deployed across the body's space and time. Changing the bioelectric pattern while leaving the genome intact is changing the higher-level closure while leaving the lower-level components unchanged. Different higher-level closure, different body. Same molecules, different form. Noble's downward causation, demonstrated not in the heartbeat but in the entire body plan. The closure framework calls this a higher-level closure setting boundary conditions for the molecular closures below it. Levin calls it morphogenetic intelligence. They are describing the same structural fact about how organized biological systems work.

2. Levin's Four Claims

Levin's research program has four interconnected claims, developed experimentally and theoretically across his work at Tufts.

2.1 Bioelectricity Is the Cognitive Glue of Morphogenesis

Every cell in an organism maintains electrical potentials across its membrane through ion channels, the same molecular machinery that neurons use for electrochemical signaling. In non-neural tissue, this bioelectric activity is not idle. It propagates across cell collectives through gap junctions, creating spatial patterns of electrical potential that span organs and even whole organisms. Levin's central claim is that these bioelectric patterns are the medium through which

the organism stores and transmits morphogenetic information: the memory of what body form to build, maintained in the electrical state of the tissue rather than in any genetic sequence.

Levin calls bioelectricity the cognitive glue: the physical medium that allows individual cells, each acting on its local chemical environment, to collectively navigate the high-dimensional space of possible body forms toward a specific target. Just as neurons use bioelectricity to collectively produce behavior in 3D physical space, non-neural cells use bioelectricity to collectively produce form in anatomical morphospace. The molecular machinery is identical. What differs is the problem space being navigated and the timescale of navigation.

2.2 Morphogenesis Is Goal-Directed Navigation, Not Program Execution

The standard view of development treats morphogenesis as the execution of a genetic program: the genome encodes instructions that cells execute sequentially to produce the body plan. Levin's research falsifies this view. Bodies do not execute programs. They navigate toward target morphologies. When a salamander limb is amputated at any position, the regenerating tissue does not execute a fixed routine for building a limb. It produces exactly the right amount and type of tissue needed to complete the limb from the current state, stopping when the correct limb is achieved. This requires the regenerating tissue to know what a correct limb is and to evaluate its current state against that target. That is goal-directed navigation, not program execution.

The target morphology is stored in the bioelectric memory of the tissue. The bioelectric pattern represents the morphogenetic goal state toward which the tissue is driving. Cells read this bioelectric state and adjust their behavior, division, differentiation, and migration, to minimize the distance between current morphology and target morphology. The process is fundamentally homeostatic: the same Test-Operate-Exit loop that cells use to maintain their molecular state is scaled up by bioelectric networks into anatomical homeostasis, maintaining the body form.

2.3 The Cognitive Light Cone: Every Agent Has a Scale

Levin's Technological Approach to Mind Everywhere, the TAME framework, addresses a question that developmental biology has avoided: what is an agent, and how does agency scale? His answer is precise. The minimal component of agency is homeostasis: the ability to maintain a setpoint, measure the current state, and act to reduce the difference. A single cell executing this loop has agency at the cellular scale. A bioelectric network binding many cells executes the same loop at the scale of a tissue or organ. A brain binding many neural networks executes it at the scale of behavior in physical space.

Each agent has what Levin calls a cognitive light cone: the spatio-temporal scale of the goals it can pursue and the problem space in which it operates. A cell's cognitive light cone spans molecules and seconds. A tissue's cognitive light cone spans millimeters and hours. A brain's cognitive light cone spans meters and years. The cognitive light cone is not fixed: it expands as bioelectric connectivity binds lower-level agents into higher-level collectives. Evolution has repeatedly expanded cognitive light cones by developing new forms of bioelectric coupling that allow lower-level agents to become components of higher-level ones.

2.4 The Anatomical Compiler: Writing Directly to Morphogenetic Memory

Levin's most visionary claim is that mastering bioelectric communication will allow us to write directly to the morphogenetic closure: to specify target body forms at the level of large-scale anatomy and let the bioelectric system communicate those goals to cells, which will then autonomously build the specified form using whatever molecular pathways are available. He calls this an anatomical compiler, analogous to a software compiler that translates high-level instructions into low-level machine code without requiring the programmer to specify each machine instruction.

The anatomical compiler vision is grounded in experimental demonstrations. Levin's team has suppressed cancer by using bioelectric signals to impose normal tissue-level goals on cells with cancerous genetics. They have induced regeneration of entire limbs in animals that normally cannot regenerate. They have produced xenobots: living machines built from frog cells that spontaneously self-organize into forms that no frog has ever had, navigating morphogenetic space toward novel targets specified by the bioelectric context rather than by any genetic program. The anatomical compiler is not a metaphor. It is an experimental program with demonstrated results.

3. What Levin Needs

Levin's research is among the most experimentally audacious and conceptually ambitious in contemporary biology. His demonstrations are controlled, replicated, and increasingly influential across developmental biology, regenerative medicine, and cognitive science. His TAME framework provides the most empirically grounded account available of how agency scales from single cells to complex organisms.

There are two gaps that Levin's framework does not fully close. The first is structural: why does bioelectric coupling produce higher-level agency rather than merely more complex molecular behavior? Levin demonstrates that it does and specifies the mechanism: gap junctions propagating electrical potentials across cell collectives. But he does not have a philosophical account of why any coupling of lower-level agents into bioelectric networks would produce a higher-level agent with its own goals and problem space rather than just a more complex version of the lower-level agents.

The second gap is the relationship between morphogenetic intelligence and consciousness. Levin has extended his framework toward what he calls diverse intelligence, the claim that all organized systems from cells to organisms to social groups exhibit forms of intelligence and agency appropriate to their cognitive light cones. He is careful about consciousness, noting that intelligence and agency do not require consciousness. But he does not have a principled account of where in the scaling of cognitive light cones consciousness first becomes relevant, or what the relationship is between morphogenetic goal-directedness and the felt interior of being a goal-directed system.

The closure framework addresses both gaps. The first: bioelectric coupling produces higher-level agency because it constitutes a new level of organizational closure, a closure regime at the tissue or organ level that sets boundary conditions for the cellular closures below it. The higher-level closure does not merely aggregate lower-level behaviors. It constitutes facts at its own

level, the morphogenetic goal states, and uses those constituted facts to set the context within which lower-level closures operate. The second: the relationship between morphogenetic intelligence and consciousness is the relationship between c, the organized content of experience, and C, the bare fact of conscious presence. Levin's morphogenetic agents have c without C: they constitute facts and pursue goals without there being something it is like to do so. The threshold at which C becomes relevant is identified in the Jablonka paper as unlimited associative learning: the level at which closure becomes sophisticated enough to encounter its own remainder as something rather than merely processing it.

4. Two Concepts That Ground Bioelectric Intelligence

The closure framework is introduced here at the minimum level needed to ground Levin's account.

4.1 Closure Regime: What the Bioelectric Pattern Is Structurally

A closure regime is a system that stabilizes some content by drawing distinctions, establishing identity criteria, and maintaining lawful relationships among its elements. It constitutes facts within its scope and generates remainder at its boundary.

The bioelectric pattern that guides morphogenesis is a closure regime in this precise sense. It draws distinctions: between the electrical state that corresponds to head development and the state that corresponds to tail development, between the bioelectric signature of eye tissue and the signature of gut tissue. It establishes identity criteria: the pattern memory that determines what count as valid states for this tissue's morphogenetic identity, the target form toward which the tissue is driving. And it maintains lawful relationships among its elements: the gap junction connections that ensure the bioelectric state of any region is coupled to and constrained by the bioelectric state of neighboring regions, implementing the anatomical coherence of the whole.

Remainder is what the bioelectric closure leaves outside its scope: the molecular details of how cells implement the morphogenetic goals the bioelectric pattern specifies. The bioelectric pattern does not instruct cells to produce specific proteins in specific sequences. It establishes the morphogenetic goal state and leaves the molecular implementation as remainder: the space of possible molecular strategies that could achieve the specified anatomical form. Different cells in different species will use different molecular strategies to implement the same bioelectric instruction. The closure specifies the form. The molecular machinery implements it.

4.2 Nested Closure: Why the Cognitive Light Cone Scales

Levin's cognitive light cone is the closure framework's nested closure hierarchy described in the language of agency and goal-directedness. The single cell is a closure regime navigating molecular space. The bioelectric network binding many cells is a higher-level closure regime navigating morphogenetic space. The neural network binding many cell ensembles is a higher-level closure regime navigating behavioral space. Each higher-level closure uses the outputs of lower-level closures as its elements and sets the boundary conditions within which those lower-level closures operate.

The cognitive light cone expands as new closures form because each new closure constitutes facts at a new scale and pursues goals in a new problem space. A cell collective bound by bioelectric coupling can pursue morphogenetic goals that individual cells cannot represent. A brain bound by neural coupling can pursue behavioral goals that individual cell collectives cannot represent. The expansion of the cognitive light cone is the expansion of what can be constituted as a fact and what can be pursued as a goal: the closure hierarchy climbing one level higher.

This structural account explains why bioelectric disruption of the morphogenetic closure changes the body plan without changing any gene: it is not a molecular manipulation. It is a manipulation of the higher-level closure that sets boundary conditions for the molecular closures below it. Change the bioelectric pattern and you change the morphogenetic goals. Change the morphogenetic goals and the cells, using whatever molecular machinery they have, will build a different body. The closure is not in the molecules. It is in the pattern that organizes how the molecules are used.

5. Four Claims, One Structure

The vocabulary correspondence between Levin's bioelectric intelligence and the closure framework is the most biologically specific in the series. What Levin calls the bioelectric pattern, the closure framework calls a morphogenetic closure regime: a higher-level organizational closure that sets boundary conditions for cellular and molecular closures. What Levin calls morphogenetic goal-navigation, the framework calls supersession driven by morphogenetic remainder: the tissue updating its organizational state to reduce the mismatch between current form and target form. What Levin calls the cognitive light cone, the framework calls the scope of a closure regime's constitutive capacity: the scale of the facts it can constitute and the goals it can pursue. And what Levin calls the anatomical compiler, the framework calls direct manipulation of the morphogenetic closure: specifying what to constitute at the higher level without specifying how to implement it at the lower level.

5.1 The Planarian Experiment Is Downward Causation

Levin's planarian experiments, in which changing bioelectric signals without changing any DNA produced different body plans, are the most dramatic experimental demonstration of downward causation in the biological literature. Not just Noble's heartbeat demonstration that a higher-level property, cardiac rhythm, emerges from cellular organization. The reverse: that changing the higher-level organizational closure, the bioelectric pattern, changes the outcomes of lower-level molecular processes, the body plan, without touching the molecular machinery that implements those outcomes.

The closure framework names the mechanism: the bioelectric pattern is a higher-level closure that sets boundary conditions for the molecular closures below it. Different boundary conditions produce different molecular implementations of the same cellular machinery. The cells are not executing different genetic programs. They are implementing different morphogenetic goals specified by the higher-level bioelectric closure. Same hardware, different closure, different form. This is precisely the structure that Noble established for biological relativity, that Friston formalized for neural hierarchy, and that the Grammar of Healing demonstrated for cognitive-

biological downward causation. Levin demonstrates it at the developmental level with an experimental system that makes the causal direction unmistakable.

5.2 Morphogenetic Navigation Is Supersession

Levin's account of morphogenesis as goal-directed navigation toward target morphologies, with feedback loops that compare current form to target form and drive developmental processes to minimize the difference, is the closure framework's account of supersession: the process by which a closure updates its organizational state when the mismatch between its current constitution and what it opens onto exceeds the threshold the closure can absorb.

The target morphology stored in bioelectric memory is the identity criterion of the morphogenetic closure: the specification of what this tissue should constitute as its organizational form. The comparison between current morphology and target morphology is the measurement of remainder: the mismatch between what the closure currently constitutes and what its identity criteria require it to constitute. The developmental processes that reduce this mismatch are supersession: the closure updating its organizational state to reduce remainder. The morphogenetic closure supersedes continuously from fertilization to adult form, maintaining the tissue's organizational identity through continuous structural change.

5.3 The Cognitive Light Cone Is the Closure Hierarchy

Levin's cognitive light cone maps directly onto the closure hierarchy. The single cell's cognitive light cone, spanning molecular space and seconds, is the scope of the cellular closure regime: the scale of the facts it constitutes and the goals it pursues. The tissue collective's cognitive light cone, spanning millimeters and hours, is the scope of the morphogenetic closure regime: the higher-level closure that uses cellular outputs as its elements and constitutes anatomical facts. The brain's cognitive light cone, spanning behavioral space and years, is the scope of the cognitive closure regime: the highest-level closure the framework has addressed, constituting facts about the world and pursuing goals in it.

The expansion of the cognitive light cone during evolution is the formation of new levels of organizational closure: each new level binding lower-level agents into a new collective agent with a new problem space. This is the evolutionary history of nested closure hierarchies, which Jablonka's four inheritance systems traced at the timescale of evolutionary change. Levin traces it at the timescale of individual development: the same process of new closures forming from the outputs of existing ones, expanding the scope of what can be constituted and pursued.

5.4 The Anatomical Compiler Is Direct Access to the Morphogenetic Closure

Levin's anatomical compiler vision, the ability to specify target body forms directly without specifying molecular pathways, is the vision of being able to write to the morphogenetic closure without having to specify the implementation in the closures below it. The compiler translates high-level morphogenetic specifications into bioelectric signals that cells interpret and implement using whatever molecular machinery is available.

This vision is grounded in experimental demonstrations of exactly this capacity. Cancer suppression through bioelectric normalization is writing to the tissue-level closure to override the cell-level disruption caused by oncogenic mutations. Limb regeneration through bioelectric intervention is writing to the limb-level closure to specify that a complete limb is the target form. Xenobots are cells that have been given a new tissue-level closure, one that specifies a novel form that no frog has ever built, and that autonomously build toward that form using frog molecular machinery. In each case, the intervention is at the level of the morphogenetic closure, not at the level of the molecular implementation. The closure specifies the goal. The molecules implement it.

6. The Connection to the Suite

Levin's research connects to the series at multiple points simultaneously, which reflects its position at the intersection of every major theme the series has addressed.

The connection to Noble is most direct. Noble established biological relativity: no level of biological organization has privileged causal authority. Levin's planarian experiments make this concrete at the developmental level. The bioelectric closure is causally prior to the molecular level in determining body form. Changing the higher-level closure changes the lower-level outcomes without changing any molecular component. Noble argued this from physiology. Levin demonstrates it from developmental biology with an experimental system that isolates the variables precisely.

The connection to Friston is methodological. Levin's account of morphogenesis as active inference, minimizing the distance between current state and target state, is the free energy principle applied to morphogenetic space. Levin and Friston have explicitly collaborated on papers connecting bioelectric morphogenesis to active inference. The closure framework's account of supersession driven by remainder is the structural description of what both Friston's free energy minimization and Levin's morphogenetic navigation describe mathematically and biologically.

The connection to Maturana is foundational. Autopoiesis is the cellular closure that Levin uses as his starting point: the single cell maintaining its molecular organization through metabolism. Levin extends this upward through bioelectric coupling into the tissue and organismal levels. He is Maturana's biology extended two organizational levels higher, with experimental demonstrations at each level.

The connection to Jablonka is evolutionary. Jablonka's four inheritance systems operate at different timescales and accumulate organizational information differently. Levin's bioelectric patterns are a non-genetic inheritance system operating at the developmental timescale: they are modified by environmental signals, they can be inherited across cell divisions as pattern memories, and they set the context within which genetic information is interpreted. Levin's developmental biology and Jablonka's evolutionary biology are describing the same nested closure structure from different temporal vantage points.

7. The Grammar of Form

A flatworm is cut in half. The two pieces know they are incomplete. They do not consult their genes to find out what to build. They read their bioelectric state, compare it to the morphogenetic memory distributed across the tissue, and build toward the form that memory specifies. The back piece builds a head. The front piece builds a tail. If the bioelectric memory has been rewritten, the pieces build the heads of other species. Same genes. Different memory. Different form.

Michael Levin has spent two decades demonstrating that this is how development works, not only in planarians but in frogs, salamanders, and eventually in synthetic organisms made of cells that have never before been part of anything like what they build. Bodies do not execute programs. They navigate morphogenetic space toward goals stored in bioelectric memory, using their molecular machinery to implement whatever path the higher-level organizational closure specifies.

The closure framework names the structure underlying these demonstrations. The bioelectric pattern is a higher-level closure regime that sets boundary conditions for the molecular and cellular closures below it. Different bioelectric closures specify different morphogenetic goals. The cells, using their molecular machinery as the implementation substrate, build toward the goals the higher-level closure specifies. This is downward causation at the developmental level: not the heartbeat generating from cellular feedback, but the whole body plan determined by the tissue-level closure that decides what form to pursue.

Levin's cognitive light cone is the closure hierarchy in the language of agency and goal-directedness. Every level of biological organization from single cells to whole organisms has its own closure regime, its own problem space, its own goals. The expansion of the cognitive light cone during evolution is the formation of new levels of organizational closure, each binding lower-level agents into higher-level collectives with higher-level goals. And the anatomical compiler is the vision of being able to write directly to the morphogenetic closure: to specify what form to build at the level that matters, without specifying the molecular implementation that will achieve it. The grammar of form is the grammar of how higher-level closures specify what lower levels must build. Levin has been reading it in the bioelectric patterns of developing organisms. The closure framework names what he has been reading.

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Author's Note

This paper is the thirteenth in a series engaging thinkers whose work converges with the closure framework developed in Consciousness, Closure, and the Cosmos. Michael Levin is Vannevar Bush Professor of Biology at Tufts University, director of the Allen Discovery Center at Tufts, and associate faculty at the Wyss Institute at Harvard University. His experimental demonstrations that bioelectric patterns govern body plan determination independently of genetic sequence are among the most important results in contemporary developmental biology. This paper makes a specific claim about the experimental significance of Levin's planarian experiments: they are the most controlled experimental demonstration of downward causation in biological literature, isolating the higher-level bioelectric closure as the causal variable while holding the molecular implementation constant. This is a stronger empirical demonstration of the structural claim made in the Grammar of Healing and in the Noble paper than anything available in the physiology or placebo literatures, because the planarian system allows the level of intervention to be specified with unusual precision. The author welcomes engagement from Levin directly, from developmental biologists, synthetic biologists, and cognitive scientists working on the collective intelligence of biological systems, and from philosophers of biology who find the convergence between bioelectric morphogenesis and the closure framework either illuminating or contestable.