Protocoling as a Design Theory

From Interaction to Infrastructure

Designing conditions for desirable emergence

Chapter 1:

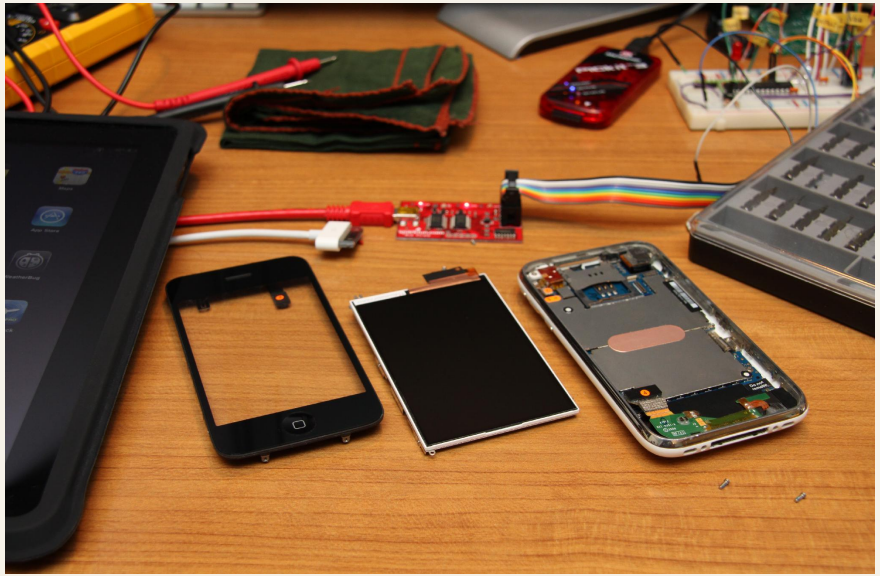
Design Paradigm Shift

The design material is becoming agential.

Classical engineering specifies components

**Dimensions, tolerances and interfaces
can be specified tightly.**

This gives the designer substantial control over how parts relate to the whole.



Example: iPhone disassembly | Yutaka Tsutano, CC BY 2.0

Classic engineering VS Emergent engineering

CLASSIC ENGINEERING

reliable parts
restricted degrees of freedom
known performance target

VS

EMERGENT ENGINEERING

adaptive participants
constraints and feedback
contingent collective outcome

The design problem changes when the “components” can sense and revise.

Evidence: Krakauer, Emergent Engineering (2019)

Two engineering logics

DIMENSION	CLASSICAL	EMERGENT
PARTS	specified components	adaptive participants
SETTING	bounded conditions	open, changing context
LEVER	component behavior	constraints and feedback
TARGET	known performance	capacity to adapt
TEST	fit to specification	behavior across contexts

Comparison: author's synthesis after Krakauer, Emergent Engineering (2019)

Krakauer names emergent engineering

PAPER / SOURCE

David C. Krakauer · 2019

Why does engineering that succeeds with tightly controlled artifacts struggle with adaptive biological and social systems?



EMERGENT ENGINEERING:
REFRAMING THE GRAND CHALLENGE
FOR THE 21ST CENTURY

David C. Krakauer, SFI
Santa Fe Institute, 2019

373

How can human society have reached the moon, harnessed the unobservable mechanics of the atom, continued to build computers that become exponentially faster and cheaper each year, and yet have operated so poorly in establishing stable economies, reducing the incidence of conflict and disease, and discovering and manufacturing effective biomedical drugs? It is certainly not through lack of interest, resources, effort, and intelligence.

The war on cancer, the pursuit of greater economic equality and financial stability, the creation of online safety and security, and the invention of new nontoxic and effective pharmacological drugs have absorbed astronomical sums of money into both research and development—and yet in so many cases they have foundered and failed through the misapplication of previously highly successful ideas of engineering and design to complex systems.

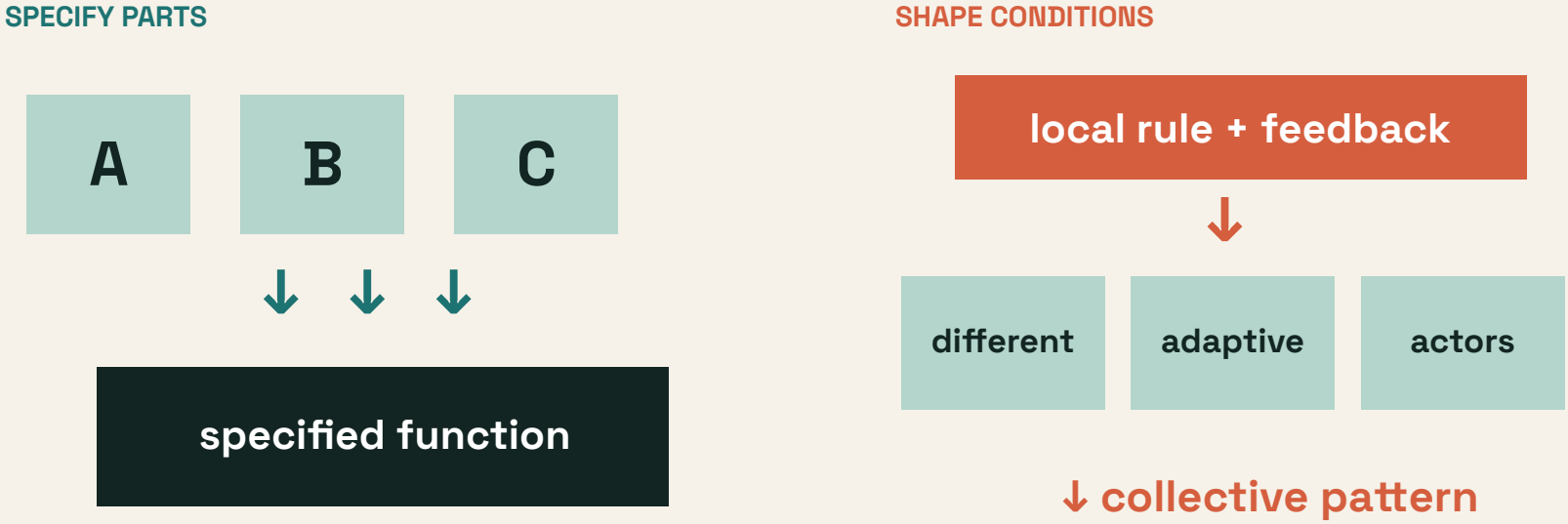
There is an urgent need for novel concepts directed at achieving an evolutionary and emergent engineering, and it is our contention that they are likely to come from the domains of biological and social life—not from the deterministic world of designed mechanical artifacts.

A History of Success and Failure:
The Siren Song of the Grand Challenge

There are a handful of technology projects of such sheer audacity and scale that they have become bywords for human ambition, ingenuity, and impact. Included among these projects should certainly be numbered the Apollo Program, the Manhattan Project, CERN

First page: Krakauer, Santa Fe Institute (2019), pp. 373–376

Where the intervention sits



Author's schematic, informed by Krakauer (2019)

Emergent engineering

Minimal mechanism + maximal adaptive system

A designed intervention recruits capacities the system already has.

Design moves toward the conditions in which local action unfolds.

Source: Santa Fe Institute / David C. Krakauer, 2019

Passive material VS Agential material

PASSIVE MATERIAL

Properties are specified and shaped by an external designer.

Design lever: shape and assemble

VS

AGENTIAL MATERIAL

Cells sense, respond and pursue local goals within their context.

Design lever: engage competencies

The distinction concerns the material's capacities, not its moral status.

Concept adapted from Davies & Levin, Nature Reviews Bioengineering (2023)

Davies & Levin: agential materials

PAPER / SOURCE

Jamie A. Davies & Michael Levin · 2023

Their review proposes working with the problem-solving capacities of living cell collectives.



Synthetic morphology with agential materials

Jamie Davies[1] and Michael Levin[2*]

[1] Deanery of Biomedical Sciences, and Synthsys Centre for Synthetic Biology, Hugh Robson Building, University of Edinburgh, EH8 9XB, UK

[2] Allen Discovery Center at Tufts University, Medford, MA, USA

* Corresponding Author: michael.levin@tufts.edu

Important note: copyright rules mean that only the version accepted by the journal can be mounted on PURE. The journal worked with us on improving layout and graphic design, so final images will be different from those shown here, though their general content is the same.

Abstract

Bioengineering can address many important needs, from transformative biomedicine to environmental remediation. In addition to practical applications, the construction of new living systems will increase our understanding of biology and nurture emerging intersections between biological and computational sciences. In this Review, we discuss the transition from cell-level synthetic biology to multicellular synthetic morphology. Importantly, we highlight experimental embryology studies, including organoids and xenobots, that go beyond the familiar, default outcomes of embryogenesis, revealing the plasticity, interoperability, and problem-solving capacities of life. In addition to traditional bottom-up engineering of genes and proteins, design strategies can be pursued based on modelling cell collectives as agential materials, with their own goals, agendas and powers of problem-solving. Such an agential bioengineering approach could transform developmental biology, regenerative medicine and robotics, building on frameworks that, include active, computational, and agential matter.

[H1] Introduction

Many problems in biomedicine, from birth defects and traumatic injury, to aging and degenerative disease, could be addressed by answering the fundamental interdisciplinary question of how groups of cells cooperate to build specific anatomical structures. Understanding natural morphogenesis, (the creation or development of anatomical shape), which is, in effect, navigation in morphospace, is key to designing

1

First page: author-accepted manuscript, Edinburgh Research Explorer; published DOI 10.1038/s44222-022-00001-9

From passive to agential material

PASSIVE



retains physical properties

shape and assemble

ACTIVE



changes state under a stimulus

trigger a response

COMPUTATIONAL



processes signals and changes state

program the logic

AGENTIAL



pursues goals with context sensitivity

engage competencies

Greater capacity to act independently →

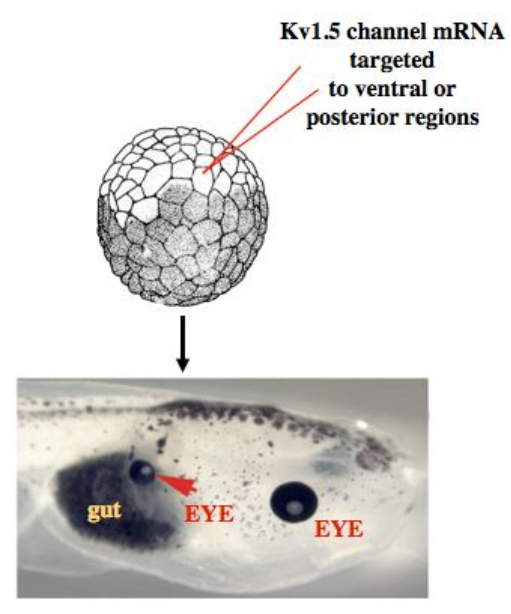
Adapted comparison: Davies & Levin, Nature Reviews Bioengineering (2023), Fig. 3

A signal can recruit cellular work

Bioelectric intervention

An ectopic eye formed in tissue outside the normal eye region.

The intervention changed a developmental signal. The cells carried out the organ-building work.



Experiment: Pai et al., Development (2012) | Image: Levin, Aw & Pai, CC BY-SA 4.0

Game design VS Mechanism design

GAME DESIGN

Design the player's rules, actions and experience within a game.

Focus: a playable system

VS

MECHANISM DESIGN

Choose rules and incentives so strategic actors can reach a desired result.

Often called "reverse game theory"

This is a design analogy; game design and game theory are distinct fields.

Sources: Nobel Prize 2007 overview; O'Reilly (2026)

The design move

Designing conditions

for desirable emergence

Outcome remains contingent on how actors respond.

Author's synthesis from Krakauer; Davies & Levin; mechanism design

Agent skills make the shift tangible

SKILL.md

A reusable instruction structure changes what an agent notices, can use and is expected to do.

AI skilling offers a contemporary site for protocoling.

Documentation: OpenAI Agent Skills | Interpretation: author's synthesis

Chapter 2:

Diverse Intelligence and Cognitive Glue

How can bounded actors become a collective?

Diverse intelligence

Heterogeneous actors

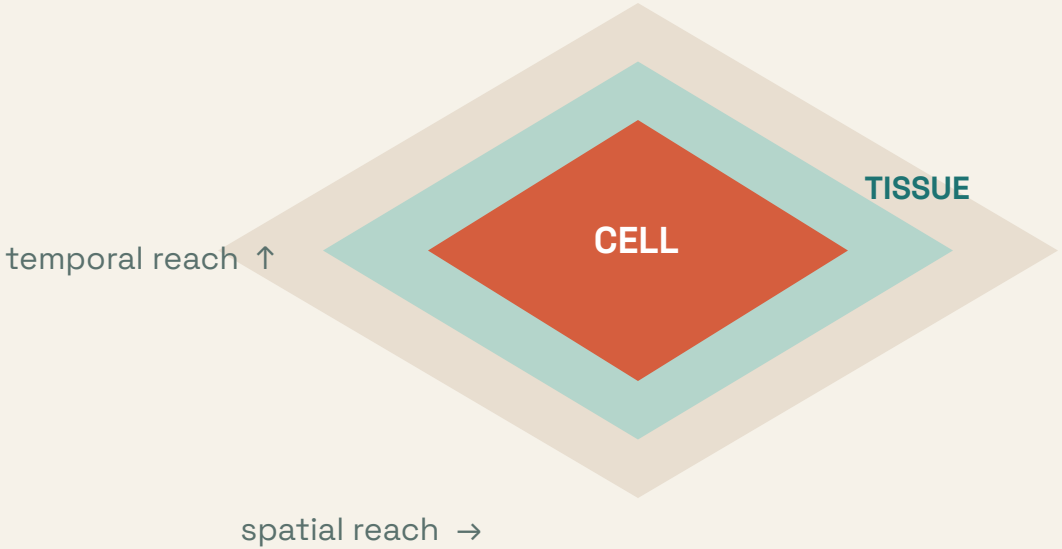
different capacities
different goals
different ways of sensing the world

Coordination does not require identical participants.

Source: Levin's diverse intelligence research | Framing: author's synthesis

Cognitive light cones

How far can a system's goals reach?



Coupling can enlarge the horizon of collective goals.

Editable schematic adapted from Levin (2019), Fig. 2; not the original Guay image

Levin: the computational boundary of a self

PAPER / SOURCE

Michael Levin · 2019

The cognitive light cone asks what scale of goals a system can pursue across space and time.



frontiers in Psychology

HYPOTHESIS AND THEORY
published: 13 December 2019
doi: 10.3389/fpsyg.2019.02688

The Computational Boundary of a "Self": Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition

Michael Levin[1,2]*†

[1] Allen Discovery Center at Tufts University, Medford, MA, United States, [2] Wyss Institute for Biologically Inspired Engineering, Harvard University, Boston, MA, United States

OPEN ACCESS

Edited by:
Robert Prevedel,
University of California, Irvine, United States

Reviewed by:
Clifford Ian Workman,
University of Pennsylvania, United States
Valentina Cuccioli,
University of Parma, Italy

***Correspondence:**
Michael Levin
michael.levin@tufts.edu

†ORCID:
Michael Levin
orcid.org/0000-0001-7292-8084

Specialty section:
This article was submitted to Theoretical and Philosophical Psychology, a section of the journal Frontiers in Psychology

Received: 26 August 2019
Accepted: 14 November 2019
Published: 13 December 2019

Citation:
Levin M (2019) The Computational Boundary of a "Self": Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition. Front. Psychol. 10:2688. doi: 10.3389/fpsyg.2019.02688

All epistemic agents physically consist of parts that must somehow comprise an integrated cognitive self. Biological individuals consist of subunits (organs, cells, and molecular networks) that are themselves complex and competent in their own native contexts. How do coherent biological individuals result from the activity of smaller sub-agents? To understand the evolution and function of metazoan creatures' bodies and minds, it is essential to conceptually explore the origin of multicellularity and the scaling of the basal cognition of individual cells into a coherent larger organism. In this article, I synthesize ideas in cognitive science, evolutionary biology, and developmental physiology toward a hypothesis about the origin of Individuality: "Scale-Free Cognition." I propose a fundamental definition of an Individual based on the ability to pursue goals at an appropriate level of scale and organization and suggest a formalism for defining and comparing the cognitive capacities of highly diverse types of agents. Any Self is demarcated by a computational surface – the spatio-temporal boundary of events that it can measure, model, and try to affect. This surface sets a functional boundary - a cognitive "light cone" which defines the scale and limits of its cognition. I hypothesize that higher level goal-directed activity and agency, resulting in larger cognitive boundaries, evolve from the primal homeostatic drive of living things to reduce stress – the difference between current conditions and life-optimal conditions. The mechanisms of developmental bioelectricity - the ability of all cells to form electrical networks that process information - suggest a plausible set of gradual evolutionary steps that naturally lead from physiological homeostasis in single cells to memory, prediction, and ultimately complex cognitive agents, *via* scale-up of the basic drive of infotaxis. Recent data on the molecular mechanisms of pre-neural bioelectricity suggest a model of how increasingly sophisticated cognitive functions emerge smoothly from cell-cell communication used to guide embryogenesis and regeneration. This set of hypotheses provides a novel perspective on numerous phenomena, such as cancer, and makes several unique, testable predictions for interdisciplinary research that have implications not only for evolutionary developmental biology but also for biomedicine and perhaps artificial intelligence and exobiology.

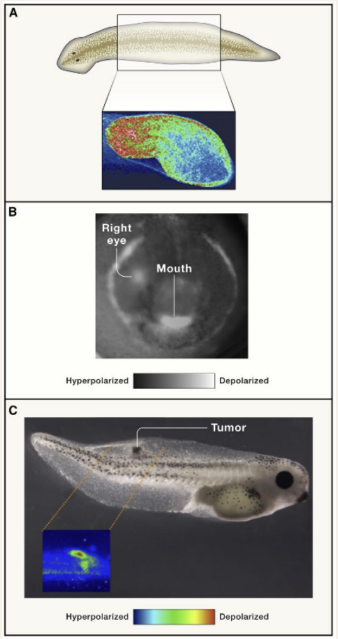
Keywords: development, bioelectricity, gap junctions, primitive cognition, active inference

First page: Frontiers in Psychology 10, 2688. DOI 10.3389/fpsyg.2019.02688

Bioelectricity as cognitive glue

Local cells can respond to shared physiological signals.

These signals help align local activity with larger anatomical patterns.



Evidence: Levin (2023) | Visual: Istpoir, CC BY-SA 4.0

Levin: bioelectric networks as cognitive glue

PAPER / SOURCE

Michael Levin · 2023

This review proposes that electrical networks help coordinate cell-level activity into larger anatomical goals.



Animal Cognition (2023) 26:1865–1891
https://doi.org/10.1007/s10071-023-01780-3

REVIEW

Bioelectric networks: the cognitive glue enabling evolutionary scaling from physiology to mind

Michael Levin[1,2]

Received: 28 November 2022 / Revised: 12 April 2023 / Accepted: 24 April 2023 / Published online: 19 May 2023
© The Author(s) 2023

Abstract
Each of us made the remarkable journey from mere matter to mind: starting life as a quiescent oocyte ("just chemistry and physics"), and slowly, gradually, becoming an adult human with complex metacognitive processes, hopes, and dreams. In addition, even though we feel ourselves to be a unified, single Self, distinct from the emergent dynamics of termite mounds and other swarms, the reality is that all intelligence is collective intelligence: each of us consists of a huge number of cells working together to generate a coherent cognitive being with goals, preferences, and memories that belong to the whole and not to its parts. Basal cognition is the quest to understand how Mind scales—how large numbers of competent subunits can work together to become intelligences that expand the scale of their possible goals. Crucially, the remarkable trick of turning homeostatic, cell-level physiological competencies into large-scale behavioral intelligences is not limited to the electrical dynamics of the brain. Evolution was using bioelectric signaling long before neurons and muscles appeared, to solve the problem of creating and repairing complex bodies. In this Perspective, I review the deep symmetry between the intelligence of developmental morphogenesis and that of classical behavior. I describe the highly conserved mechanisms that enable the collective intelligence of cells to implement regulative embryogenesis, regeneration, and cancer suppression. I sketch the story of an evolutionary pivot that repurposed the algorithms and cellular machinery that enable navigation of morphospace into the behavioral navigation of the 3D world which we so readily recognize as intelligence. Understanding the bioelectric dynamics that underlie construction of complex bodies and brains provides an essential path to understanding the natural evolution, and bioengineered design, of diverse intelligences within and beyond the phylogenetic history of Earth.

Keywords Morphogenesis · Voltage · Development · Regeneration · Basal cognition · Evolution · Behavior · Cells

Introduction: from cells to cognition in the collective intelligence of organisms

All animals with advanced conventional cognitive capacities are the products of a very lengthy evolutionary process of accumulating gradual modifications of early microbial life. Even more remarkably, each of us personally took a journey in which matter acquired mind: we start life as a quiescent oocyte, and slowly remodel into an adult modern human with metacognitive, self-aware capacities and the ability to reason about entire counterfactual universes. How did the information processing capabilities of a single cell (Lyon 2006, 2015), with metabolic and physiological competencies, inflate to that of a human, who can pursue goals of planetary scale whose endpoint may be far after their expected lifespan (Fig. 1)? Taking evolution, and especially developmental biology, seriously means coming to grips with the continuous process of transformation that enables configurations of matter to express increasingly greater degrees and kinds of cognitive capabilities: decision-making, generalization, perception, causality detection, innate responses, learning, and advanced problem-solving. The emerging field of *basal cognition* (Baluška and Levin 2016; Levin et al. 2021; Lyon et al. 2021) strives to understand the evolutionary and embryological origins of our current behavioral capacities, and uncover the physical and computational dynamics by which simple minds emerge from chemistry and scale over time.

✉ Michael Levin
michael.levin@tufts.edu

[1] Allen Discovery Center at Tufts University, 200 Boston Ave., Suite 4600, Medford, MA 02155, USA

[2] Wyss Institute for Biologically Inspired Engineering at Harvard University, Boston, MA, USA

Springer

First page: Animal Cognition 26, 1865–1891. DOI 10.1007/s10071-023-01780-3

Price as a coordinating signal



A shared signal can make dispersed plans mutually compatible.

Different goals. Partial knowledge. One locally actionable cue.

Source: Levin & Lyons, “Cognitive glues…” (2026)

Cognitive glue as compression

Global complexity

shared signal

local action

An actor can participate without understanding the entire system.

Author's theoretical extension of Levin & Lyons (2026)

Bounded reliance

A participant needs to rely on...

the next action

the verification point

the right to contest or revise

A protocol can make that reliance more explicit and bounded.

Author's theoretical proposal | No claim that protocols eliminate trust

Chapter 3:

Protocoling

Protocol is the material. Protocoling is the design action.

Protocol: codified interaction

A structure of codified interaction

that shapes local action spaces and enables coordination among heterogeneous actors.

Author's proposed definition

What a protocol shapes

What can an actor...

see? do? access? expect?

signal? commit? contest? revise?

These choices structure local action without specifying every move.

Author's proposed framework

Protocols shape possibility

Auction rules can specify

who bids / what is visible / when bids close

They leave participants to choose how to act.

The protocol changes the distribution of possibilities. It does not guarantee one outcome.

Author's proposed distinction | Auction example is schematic

Protocol is a design material

rules

permissions

signals

commitments

interfaces

feedback

Material: the codified conditions of interaction

Author's conceptual positioning

Protocoling is the design action

Observe / design / enact / revise

Protocoling actively and iteratively changes interaction conditions toward a desired collective possibility.

Material: protocol Action: protocoling Aim: desirable emergence

Author's proposed definition

Chapter 4:

From Interaction to Infrastructure

How repeated interaction becomes a durable coordination structure.

Interaction design and protocoling

INTERACTION DESIGN

How should this encounter work?

PROTOCOLING

How can many encounters remain coordinatable over time?

Author's conceptual distinction

Protocolization

interaction

repetition

convention

codification

standardization

infrastructure

Author's proposed process model

Pak's Merge: a bounded protocol example

The rule

Mass acquired by one collector merges into a changing work.

The trajectory

Collectors decide when, whether and how much to acquire.

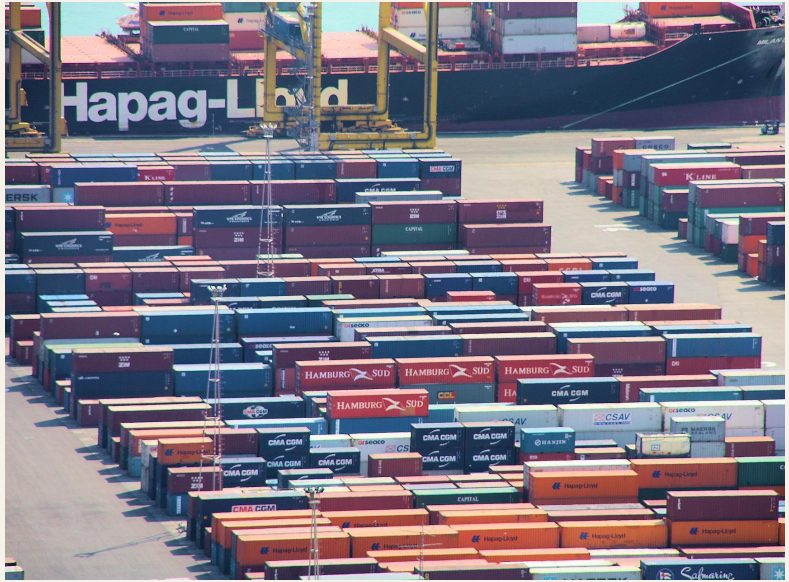
The rule is specified. Collective behavior unfolds through participation.

Source: Nifty Gateway / Gemini (2021) | Theoretical reading: author's

Infrastructure needs durable adoption

Shared expectations need…

adoption
maintenance
interoperability
ways to contest and revise



Example: ISO 668 container dimensions | Image: Marek Ślusarczyk, CC BY 3.0

From interaction to infrastructure

Protocol	material
Protocoling	action
Protocolization	hardening process

What conditions make desirable collective behavior possible?

Author's theory proposal | Sources and visual credits on the next slide

Research foundations · 1

Krakauer · emergent engineering

Krakauer, D. C. (2019). “Emergent Engineering: Reframing the Grand Challenge for the 21st Century.” Santa Fe Institute, pp. 373–376. https://sfi-edu.s3.amazonaws.com/sfi-edu/production/uploads/static_assets/37_Krakauer_Emergent_Engineering_2eea10.pdf

Davies & Levin · agential materials

Davies, J. A., & Levin, M. (2023). “Synthetic morphology with agential materials.” Nature Reviews Bioengineering, 1, 46–59. https://doi.org/10.1038/s44222-022-00001-9

Pai et al. · eye patterning

Pai, V. P., Aw, S., Shomrat, T., Lemire, J. M., & Levin, M. (2012). “Transmembrane voltage potential controls embryonic eye patterning in Xenopus laevis.” Development, 139(2), 313–323. https://doi.org/10.1242/dev.073759

Research foundations · 2

Levin · cognitive boundaries

Levin, M. (2019). “The Computational Boundary of a ‘Self’: Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition.” Frontiers in Psychology, 10, 2688. https://doi.org/10.3389/fpsyg.2019.02688

Levin · bioelectric cognitive glue

Levin, M. (2023). “Bioelectric networks: the cognitive glue enabling evolutionary scaling from physiology to mind.” Animal Cognition, 26, 1865–1891. https://doi.org/10.1007/s10071-023-01780-3

Levin & Lyons · price as cognitive glue

Levin, M., & Lyons, B. (2026). “Cognitive glues are shared models of relative scarcities: the economics of collective intelligence.” Philosophical Transactions of the Royal Society A, 384(2320), 20240528. https://doi.org/10.1098/rsta.2024.0528

Design and case references

Mechanism design

The Royal Swedish Academy of Sciences. (2007). “Mechanism Design Theory” [2007 economic sciences prize overview]. https://www.nobelprize.org/prizes/economic-sciences/2007/9272-the-sveriges-riksbank-prize-in-economic-sciences-in-memory-of-alfred-nobel-for-2007/

“Reverse game theory” phrasing

O’Reilly, T. (2026). “The Missing Mechanisms of the Agentic Economy.” O’Reilly Radar. https://www.oreilly.com/radar/the-missing-mechanisms-of-the-agentic-economy/

Agent skills

OpenAI. (accessed 2026). “Agent Skills.” OpenAI API documentation. https://developers.openai.com/api/docs/guides/tools-skills

Pak’s Merge / container standard

Gemini / Nifty Gateway. (2021). “Pak’s Merge Drop on Nifty Gateway Breaks Records in Largest Ever Public Sale.” https://www.gemini.com/blog/paks-merge-drop-on-nifty-gateway-breaks-records-in-largest-ever-public-sale · ISO. (2020). ISO 668:2020, Series 1 freight containers: Classification, dimensions and ratings. https://www.iso.org/standard/76912.html

Visual and document credits

Yutaka Tsutano. “IPhone disassembled.jpg.” CC BY 2.0. commons.wikimedia.org/wiki/File:IPhone_disassembled.jpg

Michael Levin, Sherry Aw & Vaibhav Pai. “Misexpression of ion channels.crop.png.” CC BY-SA 4.0. commons.wikimedia.org/wiki/File:Misexpression_of_ion_channels.crop.png

Istpoir. “Tissue- and organ-level bioelectric patterns.png.” CC BY-SA 4.0. commons.wikimedia.org/wiki/File:Tissue-_and_organ-level_bioelectric_patterns.png

Marek Ślusarczyk. “Shipping containers at Port of Barcelona.” CC BY 3.0. commons.wikimedia.org/wiki/File:34_Shipping_containers_at_Port_of_Barcelona,_Spain.jpg

Paper pages: Krakauer (2019) SFI original; Davies & Levin (2023) author-accepted manuscript; Levin (2019) Frontiers PDF; Levin (2023) Springer PDF. See the full references on prior slides.

Light-cone and comparison diagrams: editable redraws for this talk.