Annals of
Reviews and Research

Review Article
Volume 15 Issue 1 - March 2026
DOI: 10.19080/ARR.2026.15.555902

Ann Rev Resear

# Sudoku Brought to Life: Constraint-Based Resolution in Embryogenesis

**Brian McCully***

*Locum Consultant in Obstetrics & Gynaecology, Australia*

**Submission**: March 10, 2026; **Published:** March 18, 2026

***Corresponding author:** Brian McCully, Locum Consultant in Obstetrics & Gynaecology, Australia

**Summary**

Embryonic development is often described as a genetic "program," implying that organic form arises from pre-specified instructions. However, the directionality and performance of development can arise without centralized control. This perspective proposes that embryogenesis is more eloquently understood as a process of sequentially resolving constraints within a dynamic, self-organizing system. At each stage, stabilized conditions limit subsequent possibilities and channel future developmental trajectories. Embryogenesis can therefore be understood as an emergent process shaped by the progressive resolution of biological constraints within a dynamic system rather than the execution of a fixed, prewritten genetic blueprint.

**Keywords:** Embryogenesis; Constraint-based development; Self-organization; Developmental systems biology; Morphogenesis; State-dependent transitions; Evolutionary plasticity; Emergent biological order

## Introduction

### Order Without Design: A Constraint-Based View of Problem Solving

When one begins a Sudoku puzzle, the completed grid can seem unattainable. How can one conceive an endpoint when only a sparse scattering of numbers is initially presented? Progress depends on identifying an appropriate starting point, often limited to a single choice. Once solved, further possibilities emerge. Each progressive choice reshapes the field of subsequent decisions, progressively narrowing the remaining options until the puzzle is complete. Simplified constraint-solving systems, such as Sudoku, illustrate how ordered outcomes can emerge from rule-based limitation without programmed oversight. Each placement must satisfy existing constraints, and every resolved position alters the conditions governing subsequent steps. The puzzle does not require anticipating the final configuration; order emerges because earlier states progressively constrain and enable future options. Constraint-driven progression of this kind is a defining feature of self-organizing systems. Initial conditions impose limitations that determine which transitions are possible, and each successful transition modifies the environment in which subsequent events occur. Directionality arises not from foresight but from the systematic reduction of degrees of freedom as compatible states accumulate [1,3]. From this perspective, embryogenesis unfolds through sequential constraint resolution, in which each resolved state reduces possibilities and directs subsequent development with increasing inevitability [4]. This article explores embryogenesis through the lens of constraint-based self-organization, proposing that developmental order emerges through sequential resolution of biological constraints rather than execution of a predetermined genetic program.

### Embryogenesis as a Constraint-Based System

Embryonic development is often described as the execution of a genetic blueprint, a framing that implies programmed pre-specification. The apparent inevitability of organic design reinforces this impression: from a single cell, tissues differentiate in coordinated sequence, body axes emerge, and complex organ systems take shape with striking predictability [5,6]. Yet this order does not necessarily imply foresight. Development does not follow stored directives but emerges from continuous local interactions among genes, cells, and their physical and biochemical environment [5-7]. The organism arises through the unfolding of a dynamic system whose behaviour is shaped by evolving constraints. Each developmental stage represents a resolution of an existing biological circumstance or limitation. Every successful transition reshapes the constraints governing subsequent events, progressively enabling certain growth trajectories while excluding others. At any given moment, cellular possibilities are bounded by the current biological state. Gene expression patterns, signalling gradients, metabolic conditions, mechanical forces, and spatial relationships together define a landscape of permissible choices

[6-8]. As each developmental event alters this landscape, the field of possible futures is reorganized, enabling some states while precluding others. Progression, therefore, reflects a structured narrowing of possibilities rather than movement toward a predetermined goal.

This perspective places embryogenesis within the broader class of constraint-driven systems. In this context, order emerges not because an endpoint is specified in advance, but because each stabilized state reshapes the range of transitions that can follow. As alternatives are progressively excluded, developmental trajectories become increasingly channelled or fixed, creating reliable pattern repetition over time [4-7]. Constraint-driven progression thus generates a directional and seemingly inevitable outcome independent of centralized control. Embryonic development, therefore, unfolds within a dynamic and continuously evolving field of biological constraints that determine which transitions are possible at each moment. These arise from the interaction of genetic, epigenetic, biochemical, mechanical, and metabolic factors, each of which simultaneously enables and restricts future states [6-8]. Developmental progression reflects the stepwise resolution of these interlocking limitations rather than the execution of a predetermined plan. In this framework, cell fate is determined by the landscape in which the cells exist and by the progressive elimination of possibilities that are no longer compatible with the cell’s current condition.

Developmental biology exhibits this principle across molecular, cellular, and tissue scales. The fertilized egg does not encode a finished organism but establishes a set of starting constraints, including cytoplasmic asymmetries, maternal transcripts, polarity cues, and epigenetic states [6-9]. These factors do not specify outcomes; rather, they define the initial solution space within which development can proceed. Major morphogenetic events further demonstrate this process. Gastrulation, for example, the process by which the epiblast becomes structured into a three-layered embryo, precedes organogenesis not by design, but because it creates the spatial and signalling environments required for subsequent differentiation [6,9]. Tissues that did not previously influence one another become neighbours, whereas others remain separated, thereby reshaping potential signalling interactions and the conditions that determine ongoing transition.

Mechanical and physical forces add further direction. Tissue tension, differential growth, adhesion properties, extracellular matrix composition, and fluid pressures all influence morphogenesis. The folding of the neural tube, branching of the lungs, and looping of the gut emerge from growth patterns governed by physical and mechanical states, not by foresight [10,11]. Structure comes from what is possible in the system at that time. Metabolic conditions impose additional constraints. Oxygen availability, mitochondrial function, redox balance, and substrate use influence gene expression and differentiation potential [12-14]. Metabolic state functions not merely as an energy supply system but as a regulator that determines which gene-expression states are biologically stable, thereby shaping the developmental landscape by permitting some cellular transitions while repressing others. Early embryonic environments are often characterized by restrained metabolic activity, a state that may help preserve genomic and epigenetic integrity by limiting oxidative stress [12,13]. As perfusion increases and metabolic states shift, new developmental transitions become possible. Energy availability thus acts as a gatekeeper, regulating when particular cellular states can be stably achieved.

As development advances, these constraints accumulate, progressively narrowing the range of possible future states. This accumulation of restrictions gives development its characteristic directionality and irreversibility. Once a structure, such as a limb bud, forms, the system enters a new state in which certain trajectories are no longer available [5,6]. Directionality, therefore, emerges naturally from state-dependent limitation rather than from goal-oriented processes. The recurring developmental pattern of growth followed by regression reflects the same dynamic. Temporary structures such as interdigital webs, embryonic ducts, or excess neuronal connections can be understood as intermediate stable configurations that enable later reorganization [6,9]. These structures make subsequent developmental states accessible. Taken together, these interacting mechanisms show that embryogenesis unfolds through the dynamic interplay of constraints that both enable and restrict change. Each stage represents a transition to a new stable configuration that reshapes the biological landscape within an ever-narrowing corridor of biologically permissible change. Embryogenesis thus progresses through sequential constraint satisfaction. Directionality and refinement of form arise because each state restricts and channels the next, producing order and complexity through iterative, local interactions. Early states allow broad developmental flexibility, whereas later states reflect increasing commitment. This progressive reduction in degrees of freedom accounts for the characteristic irreversibility of differentiation and its sensitivity to disruption at critical points [4,6].

## Constraint-Based Systems Across Domains

The constraint-based dynamics described in embryogenesis reflect a broader organizing principle observed across natural systems. Chemical systems provide a foundational illustration. Reactions do not proceed with intention; they occur because particular molecular configurations are energetically favourable under given environmental conditions. Bonds form, break, and rearrange in accordance with thermodynamic gradients and kinetic constraints [15,16]. Structures that achieve relative stability persist, whereas unstable arrangements decay or transform. Importantly, each reaction modifies the chemical environment in which subsequent reactions occur. The products of one interaction become the constraints that shape the next, such that chemical pathways unfold through the sequential

How to cite this article: Brian M. Sudoku Brought to Life: Constraint-Based Resolution in Embryogenesis. Ann Rev Resear. 2026; 15(1): 555902. DOI:10.19080/ARR.2026.15.555902

modification of which configurations remain possible. Order in chemical systems therefore emerges from iterative local interactions that progressively restrict and redefine future states [15,16]. Embryogenesis extends this principle of constraint propagation to living systems.

This principle is also evident in protein folding. A polypeptide chain lacks a blueprint for its final three-dimensional structure and does not aim for a predetermined conformation. Instead, local interactions among amino acid residues guide folding across an energy landscape in which only specific conformations are stable [17,18]. As regions of the molecule acquire structure, they constrain the conformations available to remaining segments, progressively narrowing the field of possibilities until a functional form emerges. The final structure is not imposed externally but results from the cumulative resolution of local energetic and spatial constraints. Embryogenesis operates according to analogous principles, though at vastly greater spatial scales and levels of organizational complexity. The same logic of constraint propagation applies: successive interactions reshape the landscape of possible future states, and stability within prevailing genetic, biochemical, mechanical, and metabolic conditions determines which configurations are most favourable and are most likely to persist [7,8]. Biological order, therefore, emerges without centralized control. Complexity arises because each resolved interaction modifies the conditions under which subsequent events occur. Embryogenesis thus represents these principles operating at a scale where chemistry, information flow, and physical form converge to create a living, sustainable organism.

## Conclusion

Despite the absence of centralized control, embryonic development gives a compelling impression of direction, intention, and design. Structures form in precise locations, organs emerge in coordinated sequence, and the final organism appears as though assembled toward a predetermined goal. This perception arises naturally from the human tendency to interpret ordered outcomes as evidence of planning. Yet the appearance of purpose can emerge from systems governed entirely by local interactions and constraint-based progression [4,7]. In constraint-driven systems, earlier states systematically reduce the range of future possibilities. As alternatives are progressively eliminated, the system's trajectory becomes increasingly channelled, and observers viewing the endpoint retrospectively perceive inevitability and infer intention. Directionality, however, is not imposed from above. It emerges from accumulated restrictions that render certain outcomes far more stable and accessible than others. The embryo does not aim for a body plan; it moves through a landscape in which only particular configurations remain compatible with prior states. Stability is interpreted as purpose when, in fact, it is the natural consequence of systems settling into energetically and regulatorily favourable configurations. In this framework, stability replaces intention as the organizing principle of development [4,19].

Recognizing this enables practical insights. It clarifies why development is simultaneously robust and vulnerable: robust because constraint structures channel trajectories toward stable solutions, and vulnerable because early perturbations reshape the entire landscape of future possibilities [20]. Alteration of initial constraints does not merely affect a single step; it propagates through the system by modifying downstream conditions. Teratogenesis can therefore be understood as a disturbance of the constraint framework rather than a failure of developmental programming [20,21]. From an evolutionary perspective, this framework may also explain how small genetic or environmental modifications can shift developmental landscapes, not by intending new forms, but by altering the constraints under which developmental systems propagate, thereby enabling novel structures to emerge [21,22]. Embryogenesis thus proceeds as a sequential constraint-satisfaction process, analogous to rule-based systems in which each resolved state reduces degrees of freedom and makes subsequent structure increasingly inevitable. The organism is not the execution of a blueprint but the emergent solution of a dynamic system navigating a landscape of permissible states. Like a Sudoku puzzle, which is solved through successive successful solutions, life and biological form emerge as the natural and inevitable configuration patterned by a well-played game of accumulated constraints.

## References

1. Kauffman SA (1993) The origins of order: self-organization and selection in evolution. New York: Oxford University Press.
2. Camazine S, Deneubourg JL, Franks NR, Sneyd J, Theraulaz G, et al. (2001) Self-organization in biological systems. Princeton: Princeton University Press.
3. Deacon TW (2012) Incomplete nature: how mind emerged from matter. New York: W.W. Norton.
4. Waddington CH (1957) The strategy of the genes. London: Allen & Unwin.
5. Gilbert SF, Barresi MJF (2020) Developmental Biology. 12th ed. Sunderland (MA): Sinauer Associates.
6. Wolpert L, Tickle C, Arias AM (2019) Principles of Development. 6th ed. Oxford: Oxford University Press.
7. Newman SA, Bhat R (2008) Dynamical patterning modules: physico-genetic determinants of morphological development and evolution. Phys Biol 5:015008.
8. Forgacs G, Newman SA (2005) Biological Physics of the Developing Embryo. Cambridge: Cambridge University Press.
9. Gilbert SF (2012) Ecological developmental biology: environmental signals for normal animal development. Evol Dev 14(1): 20-28.
10. Heisenberg CP, Bellaïche Y (2013) Forces in tissue morphogenesis and patterning. Cell 153(5): 948-962.
11. Nelson CM (2016) On buckling morphogenesis. J Biomech Eng 138(2): 021005.
12. Leese HJ (2012) Metabolism of the preimplantation embryo: 40 years on. Reproduction 143(4): 417-427.

**How to cite this article:** Brian M. Sudoku Brought to Life: Constraint-Based Resolution in Embryogenesis. Ann Rev Resear. 2026; 15(1): 555902. DOI:10.19080/ARR.2026.15.555902

13. Gardner DK, Harvey AJ (2015) Blastocyst metabolism. Reprod Fertil Dev 27(4): 638-654.

14. Harvey AJ, Kind KL, Thompson JG (2002) REDOX regulation of early embryo development. Reproduction 123(4): 479-486.

15. Atkins P, de Paula J (2014) Physical Chemistry. 10th ed. Oxford: Oxford University Press.

16. Prigogine I, Stengers I (1984) Order out of chaos: man's new dialogue with nature. New York: Bantam Books.

17. Dill KA, MacCallum JL (2012) The protein-folding problem, 50 years on. Science 338(6110): 1042-1046.

18. Dobson CM (2003) Protein folding and misfolding. Nature 426(6968): 884-890.

19. Waddington CH (1942) The epigenotype. Endeavour 1: 18-20.

20. Gilbert SF, Epel D (2009) Ecological developmental biology: integrating epigenetics, medicine and evolution. Sunderland (MA): Sinauer Associates.

21. West-Eberhard MJ (2003) Developmental plasticity and evolution. Oxford: Oxford University Press.

22. Kirschner MW, Gerhart JC (2006) The plausibility of life: resolving Darwin's dilemma. Yale J Biol Med 79: 199-206.

DOI: 10.19080/ARR.2026.15.555902

**How to cite this article:** Brian M. Sudoku Brought to Life: Constraint-Based Resolution in Embryogenesis. Ann Rev Resear. 2026; 15(1): 555902. DOI:10.19080/ARR.2026.15.555902