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EMBRYONIC DEVELOPMENT AS EMERGENT PROCESSES

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Abstract: This paper argues that embryonic development is best understood through the lens of process philosophy rather than traditional substance metaphysics. Drawing on both contemporary developmental biology and process thought, I demonstrate how key phenomena in embryogenesis—including morphogenesis, cellular differentiation, and organismal integration—align naturally with process-philosophical principles. Through critical engagement with major figures in developmental biology and philosophy of biology, including Turing's mathematical theory of morphogenesis and autopoietic approaches to biological organization, I show how persistent difficulties in developmental biology stem from implicit substance-metaphysical assumptions and demonstrate how a process framework better captures the dynamic, relational nature of development. Furthermore, I argue that this perspective provides novel insights into emergence in biological systems while resolving longstanding theoretical difficulties in developmental biology. This theoretical framework has important implications for both biological understanding and experimental practice.

1. Introduction

The study of embryonic development has long wrestled with fundamental questions about the nature of biological organization, causation, and becoming. How does complex form emerge from apparent simplicity? What guides the progressive differentiation of cells and tissues? How do parts and whole relate in the developing organism? Traditional approaches, grounded in substance metaphysics, have struggled to provide satisfactory answers to these questions.¹ This paper argues that process philosophy offers a more

¹ See Pellegrin (1986). Pellegrin's detailed analysis of Aristotelian biology provides essential historical context for understanding contemporary approaches to biological classification and development. His work reveals how substance-metaphysical assumptions have shaped biological thinking from its origins, while also identifying aspects of Aristotle's thought that point beyond these limitations.

adequate conceptual framework for understanding embryonic development.

Substance metaphysics,² originating with Aristotle's foundational work in the *Metaphysics* and *Categories*, treats reality as composed of enduring things with properties.³ While Aristotle himself offered sophisticated accounts of biological development in works like *De Generatione Animalium*,⁴ his metaphysical framework—particularly the primacy of substance over process—has led modern biology toward increasingly reified conceptions of biological entities and causes.

This substantialist influence manifests in genetic determinism (Davidson, 2006), mechanistic reductionism (Bechtel & Richardson, 1993), and the search for master control genes (Gehring, 1998). The Aristotelian notion of

² Furth (1988) examines how Aristotle's ideas about reality shaped early biology - showing both what these ancient concepts helped explain and where they fell short. His work helps us understand modern debates about how living things develop and organize themselves. While many of Aristotle's basic assumptions still influence biology today, some of his insights about biological development went beyond these traditional limits

³ Shields (2014) demonstrates how ancient ideas shaped biology's foundations - but more importantly, points toward fresh ways of thinking. His analysis of Aristotle's theory of soul shows that while concepts of form and matter have long influenced how we understand living things, we need not remain bound by these traditional frameworks. By examining how these classical ideas both helped and limited biological understanding, Shields opens pathways to more dynamic and flexible approaches to studying life's organization

⁴ Gotthelf (2012) bridges ancient and modern views of how living things develop, revealing key insights through his analysis of Aristotle's biology. While he shows us how traditional substance-based thinking emerged, his work's real value lies in uncovering ideas that could help us move past these old constraints. By examining Aristotle's biological insights carefully, Gotthelf helps identify concepts that might guide new approaches to understanding life and development.

substantial form finds contemporary expression in the concept of genetic programs, while his emphasis on intrinsic natures resonates with modern genetic determinism. While these approaches have yielded important insights, they consistently fall short of capturing the dynamic, integrated nature of development.⁵

This paper proceeds as follows. First, I establish the core principles of process philosophy and demonstrate their relevance to biological development. Second, I examine key mathematical and theoretical foundations, particularly Turing's theory of morphogenesis and autopoietic approaches to biological organization, showing how these frameworks align with and support process-philosophical perspectives. Third, I analyze the process nature of embryonic development, focusing on continuous becoming, relational development, and emergence. Fourth, I critically engage with alternative frameworks including genetic determinism, mechanistic approaches, and systems biology, demonstrating how their limitations stem from substance-metaphysical assumptions. Fifth, I explore the implications of a process-philosophical approach for both theoretical understanding and experimental practice in developmental biology. Finally, I outline future directions for research, including needed theoretical developments, methodological innovations, and potential applications. Throughout, I demonstrate how process philosophy provides a more adequate framework for understanding embryonic development while maintaining rigorous connections to experimental practice through integration with mathematical approaches and empirical research.

⁵ Lennox (2001) offers vital historical insights into today's debates about biological development through his deep analysis of Aristotle's work. He reveals a dual legacy: while Aristotle's biological thinking was remarkably sophisticated, it was also constrained by fundamental assumptions about substances. Understanding both this sophistication and these limitations helps us better grasp how biological thought has evolved and why certain debates persist in contemporary science

2. Theoretical Framework: Process Philosophy and Biology

Process philosophy, developed by thinkers from Heraclitus to Whitehead (1929), holds that reality is fundamentally processual rather than substantial. Following Rescher (1996), we can identify several key process principles particularly relevant to developmental biology. At its core, process philosophy asserts the primacy of becoming over being, recognizing that reality consists fundamentally of processes rather than static substances. This principle finds particular resonance in developmental biology, where constant change and transformation characterize all aspects of embryonic development.

The relational nature of reality forms another crucial principle, with relations being constitutive rather than merely external connections between pre-existing substances. In developmental contexts, this manifests in the intricate web of interactions that constitute cellular and tissue development. Emergence represents a third key principle, understood not as the addition of new substances but as the manifestation of genuine novelty through process. This connects directly to the emergence of new cellular types and tissue organizations during development.

Process philosophy further emphasizes the integration of multiple scales and levels, refusing to privilege any particular level of organization as fundamentally real. This multi-scale integration characterizes embryonic development, where molecular, cellular, and tissue-level processes interact continuously. The context-dependence of entities and processes represents another crucial principle, recognizing that nothing exists in isolation from its environmental relations. Finally, process philosophy emphasizes dynamic stability over static persistence, understanding stability itself as an achievement of continuous process rather than an inherent property of substances. Biology has seen recurring process-oriented approaches, from von Baer's epigenetic vision to Waddington's developmental landscapes. Contemporary biology increasingly demonstrates the validity of process-philosophical principles through its emphasis on

systems-level integration, as elaborated in Noble's (2006) work on biological organization. The recognition of dynamic gene regulatory networks, detailed extensively by Davidson (2006), represents another manifestation of process thinking in modern biology. West-Eberhard's (2003) work on developmental plasticity further reinforces the process perspective, demonstrating how organismal development responds dynamically to environmental conditions.

Environmental responsiveness, extensively documented by Gilbert and Epel (2009), provides another key example of process-philosophical principles in action within contemporary biology. Their work demonstrates how organisms actively engage with and respond to their environments throughout development, rather than simply executing predetermined genetic programs. The phenomenon of emergent self-organization, analyzed in depth by Kauffman (1993), represents perhaps the clearest manifestation of process-philosophical principles in contemporary biological thinking. His work shows how complex biological order can emerge from the dynamic interaction of simpler components without central direction. While process philosophy provides crucial conceptual resources for understanding biological development, its insights must be integrated with rigorous mathematical and experimental approaches to yield productive scientific frameworks. The convergence between process-philosophical principles and contemporary biological understanding suggests the possibility of more formal integration. This potential becomes particularly apparent in mathematical approaches to morphogenesis and theories of biological organization. As we will see in the following section, Turing's mathematical treatment of pattern formation and the theory of autopoiesis provide crucial bridges between process-philosophical insights and empirical biological research. These frameworks demonstrate how process-based thinking can generate precise, testable models of developmental phenomena while maintaining sensitivity to the dynamic, integrated nature of biological processes.

3. Mathematical and Theoretical Foundations

The process-philosophical approach to development requires rigorous mathematical and theoretical frameworks to translate its insights into testable scientific hypotheses. Two frameworks in particular stand out for their ability to capture the processual nature of development while providing precise analytical tools: Turing's mathematical theory of morphogenesis and the theory of autopoiesis. These approaches, though developed independently of process philosophy, demonstrate remarkable alignment with process-philosophical principles while offering formal methods for analyzing developmental phenomena. Together, they provide essential theoretical bridges between philosophical insights and empirical research, showing how process-based thinking can generate precise, testable models of developmental processes.

While these frameworks emerged from different intellectual traditions—Turing from mathematics and computing, autopoiesis from systems theory and biology—they share a fundamental concern with how pattern and organization emerge from process. Their continued relevance and recent experimental validation suggest that they capture something essential about the nature of biological development. Moreover, their success in predicting and explaining developmental phenomena provides crucial support for process-philosophical approaches to understanding biological organization. Turing's (1952) groundbreaking paper "The Chemical Basis of Morphogenesis" provided a mathematical framework for understanding pattern formation in developing systems. His demonstration that interaction between two diffusing substances could generate stable spatial patterns from initial homogeneity represents a crucial bridge between chemical and biological processes. From a process-philosophical perspective, Turing's work carries particular significance in its demonstration of how spatial patterns emerge from temporal processes. His mathematical analysis reveals how complex spatial organization can arise

from purely local interactions, providing a formal framework for understanding biological becoming.

Recent work has substantially confirmed and extended Turing's insights. Kondo and Miura (2010) have identified actual Turing patterns in biological development, providing empirical validation for his theoretical predictions. Howard et al. (2011) have extended Turing's framework to tissue mechanics, demonstrating its applicability beyond chemical diffusion to mechanical processes in development. Raspopovic et al. (2014) have shown how Turing mechanisms contribute to organ development, particularly in digit formation. Marcon and Sharpe (2012) have integrated Turing's insights with modern understanding of genetic networks, showing how pattern-forming processes interact with genetic regulation.

While Turing's work provides a mathematical foundation for understanding pattern formation, it addresses only one aspect of developmental organization. The emergence of biological form requires not only the generation of spatial patterns but also the maintenance of organizational integrity throughout development. This broader question of biological organization finds its theoretical articulation in the concept of autopoiesis.

Complementing Turing's insights into pattern formation, autopoietic theory addresses the fundamental question of how living systems maintain themselves as coherent entities while continuously exchanging matter and energy with their environments. This theoretical framework, developed by Maturana and Varela (1980), provides essential insights into how developing organisms achieve and maintain their organization through ongoing processes of self-production. This conceptualization aligns naturally with process philosophy while adding important insights about biological organization. The autopoietic perspective reveals development as the progressive elaboration of self-producing systems, where each stage of organization enables and constrains subsequent developments.

Self-production of cellular components represents a fundamental aspect of autopoietic organization in development. Cells continuously synthesize and replace their constituent molecules, maintaining their organization

through constant material flux. This maintenance of organizational closure despite material openness characterizes all living systems, from individual cells to whole organisms. The achievement of dynamic stability through constant renewal, rather than static persistence, exemplifies process-philosophical principles in biological organization.

Thompson (2007) extends autopoietic theory to development through the concept of autonomous systems. His work demonstrates how development expands autopoietic organization across scales, with new levels of autonomy emerging through developmental processes. The integration of multiple autopoietic systems through development creates increasingly complex organizations, while structural coupling between developing systems and their environments guides developmental trajectories. Perhaps most significantly, Thompson shows how cognitive capacities emerge from basic autonomy, providing a bridge between developmental and cognitive biology.

The convergence between Turing's mathematical theory of morphogenesis and autopoietic accounts of biological organization provides robust theoretical support for understanding development as process.⁶ While Turing's work demonstrates how complex spatial patterns can emerge from temporal processes through reaction-diffusion mechanisms, autopoietic theory reveals how living systems maintain their organization through continuous processes of self-production. Together, these frameworks offer complementary perspectives on developmental organization: Turing's mathematics captures the emergence of form through dynamic interaction, while autopoiesis

⁶ Rogers and Schier (2011) shed vital light on morphogen gradients' dynamic role in development, offering important empirical evidence for process-based theories. Their review shows that spatial organization in developing organisms emerges not from fixed positional information, but through ongoing molecular interactions. This work makes clear that developmental patterning is fundamentally a dynamic process - marking a shift away from static models toward understanding development as a continuous flow of molecular events

explains how developing systems maintain their integrity while remaining open to environmental exchange. Both approaches align naturally with process-philosophical principles while providing rigorous theoretical tools for analyzing developmental phenomena. This synthesis of mathematical insight and theoretical biology, grounded in process philosophy, establishes a powerful framework for investigating the dynamic, integrated nature of embryonic development. With these theoretical foundations in place, we can now examine how specific developmental phenomena manifest the processual nature of biological organization in the particular case of embryonic development.

4. The Process Nature of Embryonic Development

Having established both the philosophical framework and mathematical foundations for understanding development as process, we can now examine how these theoretical insights illuminate specific aspects of embryonic development. The convergence of process philosophy with Turing's mathematical insights and autopoietic theory provides powerful conceptual tools for analyzing developmental phenomena. This section applies these tools to three crucial aspects of development: the continuous nature of developmental change, the fundamentally relational character of developmental processes, and the emergence of novel forms and functions.

Traditional developmental biology often presents development as a series of discrete stages, obscuring its fundamentally continuous nature. Similarly, conventional approaches tend to treat developmental entities as distinct substances interacting through external relations, missing the constitutively relational character of development. Finally, standard accounts struggle to explain the genuine emergence of novelty in development. Process-philosophical analysis, supported by mathematical and autopoietic frameworks, helps resolve these difficulties while providing a more adequate understanding of developmental phenomena.

4.1 Continuous Becoming vs. Discrete Stages

Traditional accounts often present development as a series of discrete stages. While useful for description, this view obscures development's continuous nature. Process philosophy helps reconceptualize developmental "stages" as abstractions from continuous becoming. Drawing on Griesemer's (2000) work on reproduction and Salazar-Ciudad et al.'s (2003) analysis of morphogenetic mechanisms, we can identify several key aspects of developmental continuity.

Cell divisions, far from being instantaneous events, constitute complex processes extending through time. Each division involves continuous reorganization of cellular components, with gradual establishment of new cellular identities occurring throughout the process. The progressive specification of cell fates unfolds through continuous molecular and cellular interactions, while integration with surrounding tissues proceeds through ongoing signaling and mechanical interactions. Environmental factors continuously influence these processes, making development inherently contextual and relational.

Tissue formation proceeds through ongoing cellular dynamics rather than discrete steps. Cell-cell signaling networks operate continuously, creating and maintaining tissue organization through persistent communication.⁷ Mechanical forces transmitted between cells shape tissue development through continuous physical interaction. The modification of extracellular matrix components proceeds

⁷ Bhattacharyya et al. (2006) provide a comprehensive review that illuminates the complex web of molecular interactions driving cellular development. Their analysis of modular interactions reveals that cellular processes are fundamentally relational in nature, offering crucial empirical support for process-based approaches to understanding biological organization. Rather than seeing cells as static structures, their work emphasizes the dynamic relationships between molecular components that shape cellular life.

gradually, creating and maintaining tissue architecture through persistent molecular remodeling. Changes in cell behavior occur progressively rather than suddenly, contributing to the continuous nature of tissue development.

The substance-metaphysical tendency to segment development into discrete stages, while epistemically useful, misrepresents the nature of developmental processes. Such discretization artificially fragments what is actually a continuous flow of interrelated changes. A process-philosophical perspective reveals how apparent developmental stages emerge as temporary stabilizations within continuous becoming, rather than representing ontologically distinct states. This reconceptualization better captures the empirical reality of development, where cellular divisions involve gradual reorganization rather than instantaneous splitting, tissue formation emerges through continuous cellular dynamics rather than step-wise transitions, and organismal form develops through ongoing mechanical and molecular interactions rather than sudden transformations. Moreover, this continuous perspective better accounts for the crucial role of environmental factors, which influence development not at discrete moments but through persistent interaction throughout the developmental process. Understanding development as continuous becoming thus provides not merely a different description but a more accurate representation of developmental reality, one that better aligns with both empirical observation and theoretical understanding of biological processes.

4.2 Relational Development

Development proceeds through complex networks of relations rather than linear causal chains. Recent work has revealed the deeply relational nature of developmental processes at multiple scales. At the molecular level, gene regulatory networks function as dynamic systems rather than linear programs, as demonstrated by Davidson (2006). These networks involve complex feedback loops and context-dependent interactions that cannot be reduced to simple causal chains. Protein-protein interactions form continuous

reaction networks that maintain cellular organization through constant activity, while signaling pathways operate through complex feedback loops that integrate multiple cellular processes.⁸

Cellular relations in development exemplify the deeply interconnected nature of biological processes. Cell-cell communication occurs through continuous exchange of molecular signals, creating dynamic information networks that guide developmental decisions. The work of Pieters and van Roy (2014) has revealed how these communication networks integrate multiple signaling pathways to coordinate cellular behavior. Mechanical forces, as demonstrated by Heisenberg and Bellaïche (2013), shape cellular behavior through continuous physical interactions, creating another layer of relational influence in development. These mechanical interactions work in concert with molecular signaling to guide tissue formation and organ development.

The traditional substance-metaphysical framework, with its emphasis on linear causation, fundamentally misrepresents the relational nature of developmental processes. Development cannot be reduced to simple chains of cause and effect, where one event triggers another in a predetermined sequence. Instead, as revealed by contemporary research, development emerges through dense networks of simultaneous interactions operating across multiple scales. From gene regulatory networks with their complex feedback loops, to protein interaction networks maintaining cellular organization, to intercellular signaling networks coordinating tissue formation, development manifests as an intricate web of relations rather

⁸ Housden and Perrimon (2014) demonstrate that developmental signaling involves intricate patterns unfolding across both space and time. Thus, providing strong evidence for viewing biological organization as a dynamic process rather than a static system. Importantly, they show that cells communicate through continuous, flowing interactions rather than isolated molecular events. Their work supports a shift toward understanding biological processes as ongoing, interconnected flows rather than discrete steps.

than a linear sequence of events. This relational perspective better captures how mechanical forces and molecular signals work in concert, how cellular behaviors emerge from context-dependent interactions, and how organismal form develops through the integration of multiple simultaneous processes. Understanding development as fundamentally relational thus provides not just a different model but a more accurate representation of biological reality, one that better accounts for the complex, dynamic nature of developmental processes and their emergent properties.

While understanding development's relational character represents a crucial advance beyond linear-causal models, it raises a fundamental question: how do coherent structures and functions emerge from these complex networks of interaction? Traditional substance-metaphysical approaches struggle to explain how novel properties and forms can emerge from relational processes without invoking external organizing principles. Process philosophy offers a framework for understanding emergence not as the sudden appearance of new substances or properties, but as the progressive stabilization of novel patterns of process. This perspective proves particularly valuable for understanding how complex developmental phenomena emerge through self-organization.

4.3 Emergence and Self-Organization

Process philosophy provides a framework for understanding genuine emergence in development that goes beyond traditional mechanistic explanations. Morphogenetic emergence, a key aspect of development, manifests through pattern formation arising from dynamic interactions between cells and tissues. Newman and Müller (2005) have shown how these patterns emerge through the interplay of multiple processes operating at different scales. Their work demonstrates that morphogenesis cannot be reduced to

simple genetic programs but instead requires understanding the dynamic interaction of multiple processes.⁹

The emergence of cellular differentiation exemplifies the process nature of development. Davidson's (2006) work on gene regulatory networks shows how cell fates emerge through the progressive operation of dynamic molecular networks rather than through the simple execution of predetermined programs. Losick and Desplan (2008) have demonstrated the fundamentally context-dependent nature of cell fate decisions, showing how cellular identity emerges through interaction with surrounding tissues and environmental conditions. This work reveals how cellular differentiation depends on the integration of multiple processes operating across different scales of organization.

The formation of gametes itself exemplifies the process nature of development, where sperm and egg emerge not as sudden creations but through continuous cellular transformation. Gametogenesis involves progressive chromatin reorganization, cellular differentiation, and metabolic adaptation. Even before fertilization, these cells exist not as static entities but as dynamic processes maintaining their organization through constant molecular turnover and environmental interaction. The traditional view of gametes as discrete substances overlooks this fundamentally processual nature of their existence and formation.

⁹ Physical processes and genetic programming both play crucial roles in biological development, as demonstrated by Newman and Müller (2006). While genetic programming operates through DNA-based instructions and protein production, physical processes involve direct mechanical forces and material interactions that actively shape cellular organization. Their research challenges the traditional emphasis on genetic factors alone, showing that biological form emerges from the interplay between these physical dynamics and genetic instructions. Their account suggests a more complex model of development where mechanical forces, fluid dynamics, and cell adhesion work in concert with genetic programming to guide organismal development.

Fertilization, rather than being an instantaneous event, represents a complex series of interrelated processes that transform both sperm and egg into a new developmental system. The fusion of membranes, activation of egg metabolism, and reorganization of cellular components occur through continuous, coordinated interactions. This transformation exemplifies what process philosophy identifies as genuine emergence: not the simple combination of pre-existing substances, but the progressive establishment of new patterns of process that manifest novel properties and potentials.

The early cleavage stages demonstrate how apparent discreteness emerges from continuous process. While traditionally described as a series of distinct cell divisions, closer examination reveals continuous cellular reorganization, with each "division" involving ongoing changes in cellular architecture, metabolism, and gene expression patterns. These early blastomeres maintain their identity not through static existence but through dynamic processes of molecular turnover and intercellular communication. The formation of the blastocyst similarly emerges through continuous cellular differentiation and spatial reorganization rather than sudden transformation.

Implantation exemplifies the deeply relational nature of development, as the blastocyst and uterine tissue engage in complex reciprocal interactions. This process involves continuous molecular signaling, mechanical force transmission, and tissue remodeling. Both embryo and uterus undergo progressive transformation through their interaction, demonstrating how developmental identity emerges from relational processes rather than inhering in pre-existing substances. The formation of the primitive streak and gastrulation similarly manifest through ongoing tissue interactions and cellular movements rather than discrete state changes.

Organogenesis reveals how complex structures emerge through the integration of multiple simultaneous processes. The formation of each organ involves continuous tissue interactions, progressive cellular differentiation, and dynamic mechanical forces working in concert. Traditional accounts that present organ formation as a sequence of

discrete stages obscure the continuous nature of these processes. Instead, organs emerge through the progressive stabilization of multiple interacting processes, from molecular signaling networks to tissue-level mechanical interactions.

The fetal period demonstrates how developmental processes achieve relative stability while remaining fundamentally dynamic. While fetal structures appear more stable than earlier embryonic forms, this stability represents an active achievement of continuous processes rather than static existence. Fetal organs maintain their identity through constant cellular renewal, tissue remodeling, and physiological adaptation. Moreover, the fetus develops through ongoing interaction with maternal tissues, demonstrating the fundamentally relational nature of development even at later stages.

Birth itself exemplifies how apparent discontinuity emerges from continuous process. While traditionally viewed as a discrete transition, birth involves progressive physiological changes in both fetus and mother, coordinated tissue responses, and continuous adaptation of multiple organ systems. The neonate maintains continuity with its fetal state through persistent developmental processes while establishing new patterns of physiological organization. This transformation exemplifies how developmental transitions emerge through the progressive reorganization of ongoing processes rather than through sudden state changes.

The evidence for emergence and self-organization in development presents a fundamental challenge to traditional substance-metaphysical frameworks. From morphogenetic pattern formation to cellular differentiation, developmental phenomena consistently demonstrate properties that cannot be reduced to predetermined programs or simple mechanical interactions. Rather, they emerge through the dynamic integration of multiple processes operating across different scales of organization. This reality raises critical questions about the adequacy of conventional theoretical frameworks in developmental biology. While approaches such as genetic determinism, mechanistic explanation, and systems biology have yielded important insights, their implicit substance-

metaphysical assumptions limit their ability to fully capture the emergent, self-organizing nature of development. To understand these limitations and establish the comparative advantages of a process-philosophical approach, we must critically examine these alternative frameworks and their conceptual foundations.

5. Critical Engagement with Alternative Frameworks

The process-philosophical perspective on development gains additional support through critical examination of alternative theoretical frameworks. Three approaches in particular have dominated contemporary developmental biology: genetic determinism, mechanistic explanation, and systems biology. Each of these frameworks has contributed valuable insights to our understanding of development, yet each remains constrained by implicit substance-metaphysical assumptions that limit their ability to fully capture developmental phenomena. By examining these limitations, we can better appreciate both the contributions and constraints of these approaches while demonstrating the comparative advantages of a process-philosophical framework. This analysis reveals how substance-metaphysical assumptions have shaped biological thinking while suggesting how insights from these approaches might be productively reframed within a process-philosophical perspective. Davidson (2006) presents perhaps the most sophisticated version of genetic determinism through his concept of developmental Gene Regulatory Networks (GRNs). While his work has provided crucial insights into the molecular basis of development, we argue that Davidson's framework remains unnecessarily constrained by substance-metaphysical assumptions. His treatment of genes as controlling agents rather than participants in developmental processes perpetuates problematic mechanistic metaphors that obscure the dynamic, processual nature of development.

The limitations of genetic determinism become particularly apparent in light of recent work on developmental plasticity and environmental influence. As

Keller (2000) argues, the language of genetic programs and genetic information has become so deeply ingrained in modern biology that we often forget its metaphorical nature.¹⁰ These metaphors carry implicit assumptions about causality that can actively mislead our understanding of developmental processes. For example, the notion of genes as "controlling" development suggests a one-way causal relationship that fails to capture how gene expression itself responds to cellular and environmental conditions.

The process-philosophical perspective helps reveal these limitations while providing alternative conceptual resources for understanding genetic regulation as part of broader developmental processes. Instead of treating genes as controlling agents, process philosophy allows us to understand genetic regulation as dynamic participation in developmental processes. This reframing better accounts for phenomena such as: (1) the context-dependent nature of gene expression, where the same gene can have different effects depending on cellular context and timing; (2) the role of mechanical forces in modulating gene expression during tissue formation, as demonstrated by mechanotransduction studies; (3) the influence of environmental factors on gene regulation through epigenetic mechanisms;¹¹ and (4) the

¹⁰ Keller demonstrates how genetic determinism, rooted in substance-based metaphysical views, has limited our understanding of biological development. Her analysis traces how metaphors of genetic "control" and "programming" have shaped and constrained biological thought. By revealing these limitations, she makes a compelling case for process-based approaches that better capture the dynamic nature of development, offering theoretical foundations for moving beyond traditional substance-focused frameworks.

¹¹ Goldberg et al. (2007) reveal how genetic regulation operates as a dynamic process involving continuous interactions across multiple organizational levels. Their research on epigenetic mechanisms demonstrates that genetic activity is not isolated, but rather depends on broader cellular and environmental contexts. This work provides key empirical evidence supporting process-based philosophical approaches to biological development by showing how genes function within wider developmental systems.

bidirectional relationship between genetic networks and cellular behavior, where genes influence cell states while cellular conditions simultaneously modulate genetic activity. This processual understanding better captures how genetic regulation emerges from and contributes to the broader network of developmental interactions rather than serving as a central controlling program. Bechtel and Richardson (1993) defend mechanistic explanation in biology, arguing for its historical success and continuing utility. While their sophisticated analysis acknowledges the complexity of biological systems, I suggest that their approach ultimately derives from the Aristotelian tradition of explaining natural phenomena through decomposition into basic substances and their properties. Though mechanistic analysis has undoubtedly provided valuable insights, I agree with Dupré (2012) that mechanisms should be understood as abstracted patterns of process rather than underlying substances.

The limitations of mechanistic explanation become particularly evident in developmental contexts, where the phenomena under investigation resist decomposition into discrete, stable components. Consider, for example, the formation of embryonic tissues: while mechanistic approaches might describe this as the interaction of distinct cellular components according to fixed rules, the reality involves continuous transformation of the components themselves through their interaction. Cells change their properties as they interact, tissues modify their mechanical properties as they develop, and the very "mechanisms" of development evolve through the process itself. This dynamic, transformative nature of developmental processes challenges the mechanistic assumption that we can understand biological phenomena by identifying stable components and their regular interactions. Even apparently

See Goldberg et al. (2007). This influential paper demonstrates the dynamic nature of genetic regulation, revealing how developmental processes involve continuous interaction between multiple levels of organization. The authors' analysis of epigenetic mechanisms provides crucial empirical support for process-philosophical approaches to development, showing how genetic activity depends on broader cellular and environmental contexts.

stable biological mechanisms are better understood as temporarily stabilized patterns of process rather than fixed arrangements of substantial parts.

This critique finds support in Nicholson's (2012) observation that the machine conception of the organism, despite its historical importance, no longer adequately captures what we now know about biological organization. Contemporary understanding of developmental processes reveals a degree of fluidity, plasticity, and temporal integration that exceeds traditional mechanistic frameworks. The process perspective allows us to retain the insights of mechanistic analysis while situating them within a more adequate conceptual framework that better captures the dynamic nature of biological development. Noble's (2006) systems biology approach represents a significant move toward process thinking, though it retains certain substance-metaphysical assumptions that limit its theoretical adequacy. While Noble's work embraces important process-philosophical principles such as downward causation and multi-level integration, his framework sometimes treats systems as things rather than processes, echoing traditional substance-metaphysical approaches. Nevertheless, his insights into biological organization provide important resources for developing a more thoroughly processual understanding of development.

The limitations of traditional systems biology become particularly apparent in its treatment of developmental dynamics. While systems approaches acknowledge the importance of interaction and integration, they often retain an implicit commitment to substances as the fundamental bearers of properties and relations. A more thoroughly processual approach allows us to understand biological systems themselves as temporary stabilizations within ongoing processes of development and transformation.

This tension in systems biology—between dynamic process and substantial system—becomes particularly evident in its treatment of developmental robustness. While systems approaches rightly emphasize the importance of regulatory networks and feedback loops in maintaining developmental stability, they often conceptualize this

stability as the preservation of a pre-existing system rather than as an active achievement of ongoing processes. This subtle but significant distinction matters because it affects how we understand and investigate developmental phenomena. When we treat systems as things, we tend to focus on identifying fixed regulatory mechanisms; when we understand them as processes, we recognize that the very mechanisms of regulation emerge and transform through development itself.

The challenge, then, is not to abandon systems biology but to reframe it within a more thoroughly processual understanding. This reframing would recognize biological systems not as pre-existing entities that undergo change, but as patterns of process that achieve temporary stability through continuous activity. Such an approach better captures phenomena like developmental plasticity, where system "properties" emerge through dynamic interaction with environmental conditions, or cellular differentiation, where cell types represent relatively stable patterns of process rather than fixed states. This processual reframing of systems biology aligns with recent work on dynamical systems theory and complexity science, suggesting promising directions for theoretical development that maintain the analytical power of systems approaches while overcoming their substance-metaphysical limitations.

6. Implications for Research

The process-philosophical perspective on embryonic development, supported by mathematical and autopoietic frameworks, carries significant implications for both theoretical understanding and experimental practice. By reconceptualizing development as continuous process rather than discrete state changes, this approach demands new ways of thinking about causation, organization, and emergence in biological systems. These theoretical insights in turn suggest specific methodological innovations and practical applications, while offering new perspectives on the irreversible nature of developmental processes.

These implications manifest in four key areas. First, the theoretical framework transforms our understanding of developmental causation and biological organization, revealing how stability emerges from dynamic process rather than inhering in static structures. Second, this perspective suggests specific methodological innovations for studying developmental processes, particularly regarding the need for dynamic measurement techniques and relational analysis. Third, it indicates practical applications for experimental design, data analysis, and computational modeling that better capture the processual nature of development. Finally, it provides crucial insights into the irreversible character of embryonic development, helping explain why certain developmental transitions prove irreversible and how this irreversibility contributes to biological organization. Together, these implications suggest new directions for developmental biology while providing concrete guidance for research practice.

6.1 Theoretical Implications

The integration of process philosophy with mathematical insights from Turing and theoretical perspectives from autopoiesis suggests several important directions for theoretical development. A process-philosophical approach demands a more sophisticated understanding of developmental causation that goes beyond traditional linear models. Contemporary developmental biology reveals causation as operating through complex networks of interaction that span multiple levels of organization. These causal networks cannot be adequately captured through traditional substance-metaphysical frameworks that presuppose distinct levels of organization with clear boundaries.

The process perspective transforms our understanding of biological organization. Rather than treating organization as a static structure imposed on passive materials, process philosophy reveals organization as an active achievement of continuous processes. This understanding better captures

the dynamic nature of biological development, where organizational patterns persist through constant molecular turnover and cellular transformation. The stability of biological organization emerges from these dynamic processes rather than existing as an independent substantial form.

Temporal organization takes on fundamental importance within a process-philosophical framework. Development involves multiple temporal scales operating simultaneously, from rapid molecular interactions to slow morphological changes. These different temporal scales become integrated through developmental processes, creating complex patterns of coordination that traditional substance-metaphysical approaches struggle to explain. The process perspective reveals how temporal organization itself becomes constitutive of developmental phenomena, rather than serving merely as an external framework within which development occurs.¹²

6.2 Methodological Implications

The process-philosophical approach suggests specific methodological innovations that transform traditional experimental practices in developmental biology. Dynamic measurement techniques become essential for capturing the processual nature of development. Traditional approaches that focus on static snapshots of developmental stages must be supplemented by methods that can track continuous changes in developing systems. This requires the

¹²Through his analysis of temporal dynamics in biological development, Reiss (2003) illuminates how multiple time scales interact and coordinate in living systems. His theoretical framework challenges linear conceptions of developmental time, showing instead how various temporal processes become dynamically integrated. These insights into biological temporality provide foundational support for process-based philosophical approaches to development.

development of real-time observation techniques capable of following multiple variables simultaneously while maintaining the integrity of the developing system.

Relational analysis takes on new importance within a process framework. Traditional analytical approaches that focus on isolated components must be replaced by methods capable of capturing the complex networks of interaction that characterize developmental processes. Network-based approaches to data analysis become essential, as they can better represent the dynamic relations that constitute developmental systems.¹³ These analytical methods must be sensitive to context, recognizing that developmental processes cannot be adequately understood in isolation from their broader environmental and organismal contexts.¹⁴

Multi-scale investigation becomes crucial for understanding developmental processes. As Kondo and Miura (2010) argue, understanding biological pattern formation requires investigation across multiple scales of organization, from molecular interactions to tissue-level behavior. This demands new experimental approaches

¹³ While maintaining rigorous connections to empirical research, Griffiths and Gray (1994) fundamentally reshape our understanding of development through their developmental systems theory. Moving beyond mere critique of genetic determinism, they construct a theoretical framework that captures development's inherently processual nature. Their work stands out for successfully bridging philosophical insights about developmental integration with concrete biological investigation.

¹⁴ Developmental biology's reliance on metaphors of genetic "programming" and "information" faces a powerful challenge in Oyama's (2000) analysis. Rather than viewing development as the unfolding of predetermined genetic instructions, she demonstrates how organisms emerge through intricate interactions between multiple factors—both genetic and environmental. While mounting a sophisticated theoretical critique, she maintains strict fidelity to empirical biological research, thereby advancing a process-based understanding of development that resonates with laboratory findings.

capable of simultaneously tracking processes at different scales while maintaining their integration. The development of such techniques presents significant technical challenges but becomes essential for advancing our understanding of developmental processes.

The integration of different types of data presents another methodological challenge highlighted by the process approach. Traditional experimental methods often produce data focused on particular aspects or scales of development. Understanding development as process requires new ways of integrating these different types of data into coherent accounts of developmental phenomena. This integration must preserve the dynamic and relational aspects of development rather than reducing them to static representations.

6.3 Practical Applications

The process-philosophical perspective has significant implications for practical research in developmental biology. Experimental design must evolve to capture the continuous nature of developmental processes. This requires longer-term observation protocols capable of following developmental changes over extended periods while maintaining the integrity of the developing system. Such protocols must be sensitive to the multiple timescales involved in development, from rapid molecular interactions to slower morphological changes.

Data analysis methods must also evolve to handle the complex, dynamic nature of developmental data. Traditional statistical approaches designed for analyzing discrete, independent measurements become inadequate when dealing with continuous, interconnected developmental processes. New analytical methods must be developed that can handle the temporal and relational aspects of developmental data while maintaining statistical rigor. These methods must be capable of identifying patterns and regularities in developmental processes without reducing them to static structures.

Computer modeling and simulation take on new importance within a process framework. Traditional modeling approaches often focus on representing static states or discrete transitions. Process-based modeling must capture the continuous nature of developmental changes while maintaining the integration of different scales and processes. This requires new mathematical frameworks capable of representing continuous change and multiple levels of organization simultaneously. Such models become essential tools for understanding the complex dynamics of developmental processes.

6.4 Embryonic Development as Irreversible Processes

The process-philosophical framework has particular significance for understanding the irreversible nature of embryonic development. Unlike reversible physical processes, developmental transitions represent genuine emergent transformations that fundamentally alter both the developing system and its potential future states. This irreversibility manifests at multiple levels and provides crucial insights into the nature of biological development.

At the cellular level, differentiation represents not merely a change in gene expression but a fundamental transformation of cellular organization. While recent work on cellular reprogramming demonstrates some plasticity in cell fate, the original developmental trajectory cannot be precisely reversed because the entire context of development—both internal and external to the cell—has been transformed through the process itself. The process perspective helps us understand why: cellular identity emerges not from a single controlling factor but from the integrated operation of multiple processes that progressively constrain and enable each other.

The formation of tissues and organs similarly demonstrates irreversible emergence. As cells interact to form tissues, they establish new mechanical and signaling relationships that transform both their individual properties and their collective behavior. These transformations cannot

be reversed simply by removing the resulting structures because the very processes that maintain cellular identity have been fundamentally altered through tissue formation. This explains why tissue engineering cannot simply reassemble isolated cells but must recreate appropriate developmental contexts.

Moreover, the process framework reveals how developmental irreversibility emerges from the integration of multiple temporal scales. Early developmental events establish conditions that constrain later possibilities not through direct causation but through the progressive transformation of the entire developmental system. This helps explain why developmental timing proves so crucial: each phase of development creates the necessary conditions for subsequent processes through the establishment of new patterns of organization that themselves become constitutive of further development.

This understanding has important implications for both research and clinical applications. It suggests that interventions in development must work with rather than against the processual nature of embryonic organization. Rather than treating developmental disorders as defects to be corrected, we must understand how to guide developmental processes toward more favorable trajectories while respecting their inherent dynamics. Similarly, regenerative medicine might focus less on recreating specific structures and more on establishing appropriate processes of organization.

The irreversibility of embryonic development thus represents not a limitation but a fundamental feature of biological organization. Understanding development as process helps explain both why certain developmental transitions prove irreversible and how this irreversibility contributes to the establishment of stable biological forms. This perspective provides crucial insights for both theoretical understanding and practical intervention in developmental processes.

7. Future Directions

The process-philosophical approach to embryonic development, while offering significant advantages over traditional substance-metaphysical frameworks, remains a work in progress. Fully realizing its potential requires substantial development across multiple domains: theoretical refinement of its conceptual foundations, methodological innovation in experimental techniques, and practical application of its insights to developmental biology and medicine. These developments must proceed in parallel, with theoretical advances informing methodological innovation while practical challenges drive conceptual refinement.

The challenges ahead fall into three main categories. First, theoretical development must advance our mathematical and conceptual frameworks to better capture the processual nature of development, particularly regarding biological individuation and temporal organization. Second, methodological innovation must create new techniques capable of tracking and analyzing developmental processes across multiple scales while maintaining their dynamic integration. Third, practical applications must translate process-philosophical insights into concrete approaches for understanding and treating developmental disorders. Progress in each area will require close integration between philosophical insight and empirical research, ensuring that theoretical advances remain grounded in biological reality while experimental work benefits from conceptual clarity. The following subsections explore these challenges and opportunities in detail, suggesting specific directions for future research and development.

7.1 Theoretical Development

Several areas of theoretical work require further development to fully realize the potential of the process-philosophical approach to developmental biology. The mathematical frameworks underlying our understanding of developmental processes need expansion and refinement.

While Turing's work on morphogenesis provides a crucial foundation, new mathematical approaches are needed to capture the full complexity of developmental processes. These frameworks must be capable of representing multiple dimensions of process simultaneously while maintaining their integration. The development of process-based topology becomes particularly important for understanding how spatial organization emerges from temporal processes.

Conceptual integration presents another crucial area for theoretical development. The relationship between process philosophy and systems biology requires further elaboration, particularly regarding questions of causation and emergence. New theoretical frameworks are needed to capture the dynamic nature of developmental causation without falling back into substance-metaphysical assumptions. The nature of temporal organization in development demands particular attention, as traditional frameworks for understanding time prove inadequate for capturing the complex temporal integration characteristic of developmental processes.

The theorization of biological individuation requires fundamental reconceptualization from a process perspective. Traditional approaches to biological individuality, grounded in substance metaphysics, struggle to account for the fluid and dynamic nature of developing systems. New theoretical frameworks must be developed that can capture the emergence and maintenance of biological individuality through process rather than treating it as a given substantial property. This reconceptualization has important implications for understanding both normal development and pathological conditions.

7.2 Methodological Development

The advancement of process-based developmental biology requires significant methodological innovation. Current techniques for studying development, while sophisticated, often remain grounded in substance-metaphysical assumptions that limit their ability to capture developmental processes in their full complexity. The development of new dynamic measurement techniques

becomes essential. These must be capable of tracking continuous changes across multiple scales of organization while maintaining the integrity of the developing system. Real-time imaging technologies need further refinement to capture developmental processes at both molecular and tissue levels simultaneously.

Data integration presents particular challenges for methodological development. As Marcon and Sharpe (2012) emphasize, the challenge lies not merely in collecting more data but in developing frameworks that can meaningfully integrate different types of developmental information across scales and times. New computational approaches must be developed that can handle the dynamic and relational nature of developmental data while maintaining analytical rigor. These approaches must go beyond traditional statistical methods designed for analyzing discrete, independent measurements.

The development of new experimental protocols becomes crucial for implementing process-based approaches to development. These protocols must be designed to capture the continuous nature of developmental processes while maintaining experimental control and reproducibility. Non-destructive observation methods become particularly important, as they allow the continuous tracking of developmental processes without disrupting the very phenomena under investigation. The integration of multiple measurement techniques within single experimental protocols presents technical challenges that require innovative solutions.

7.3 Future Applications

The process-philosophical approach to development opens new possibilities for practical applications in both research and medicine. Understanding development as process rather than the execution of predetermined programs suggests new approaches to developmental disorders. Rather than focusing solely on genetic or molecular causes, process-based approaches encourage

consideration of the broader developmental context and the multiple scales of organization involved in pathological conditions.¹⁵ This perspective suggests new therapeutic strategies that target developmental processes rather than just molecular mechanisms.

8. Conclusion

A process-philosophical approach to embryonic development offers significant advantages over traditional substance-based thinking. Through integration with Turing's mathematical insights and autopoietic theory, this approach provides a more adequate framework for understanding developmental phenomena. The process perspective better accounts for the continuous nature of development, revealing how complex forms emerge through ongoing processes rather than through the imposition of predetermined patterns. This understanding transcends traditional mechanistic explanations while maintaining rigorous connections to experimental practice.

The recognition of development's inherently relational character represents another crucial advantage of the process approach. Rather than treating developmental entities as self-contained substances with intrinsic properties, process philosophy reveals how developmental phenomena emerge through complex networks of interaction. This relational understanding better captures the integrated nature of development, where molecular, cellular, and tissue-level processes continuously influence and constrain each other. The process perspective thus provides a more adequate

¹⁵ DeBerardinis and Thompson (2012) overturn conventional static models of cellular metabolism, revealing instead a landscape of constant flux and dynamic interchange. Their research illuminates how cells maintain their identity not through fixed structures but through continuous metabolic processes—a finding that lends empirical weight to process-based philosophical approaches to biological organization. What emerges is a picture of the cell as an inherently dynamic system, where stability depends on perpetual change.

theoretical framework for understanding the complex causation characteristic of biological development.

The implications of this theoretical shift extend beyond pure understanding to influence experimental practice and therapeutic intervention. Process-based approaches suggest new experimental methods capable of capturing the dynamic nature of development, while also indicating new therapeutic strategies for addressing developmental disorders. The emphasis on continuous process over discrete states encourages more nuanced and effective interventions in both research and clinical contexts. Furthermore, the process perspective suggests new directions for theoretical development, pointing toward more sophisticated mathematical and conceptual frameworks for understanding biological development.

As Gilbert and Barresi (2016) note, our view of development has transformed from a program-driven process to a dynamic system of interactions. This transformation demands new ways of thinking about developmental phenomena, and process philosophy provides exactly these new conceptual resources. Through integration with sophisticated mathematical approaches like Turing's reaction-diffusion theory and theoretical frameworks like autopoiesis, process philosophy offers a comprehensive framework for understanding development that maintains rigorous connections to experimental practice while transcending the limitations of traditional substance-based approaches.

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