

A General, Measurable Definition of Emergence ($E = \Delta O$)

Structure $\rightarrow$ Behavior as the Universal Mechanism Underlying Emergent Phenomena

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ABSTRACT: Emergence is central to systems science, yet its definition remains fragmented, domain-specific, and often metaphorical. Existing accounts—including weak and strong emergence, interactionist models from complexity science, and physics-based descriptions of phase transitions—do not provide a general mechanistic operator that links structural change to behavioral change in a measurable way. This paper develops a formal, domain-independent definition of emergence grounded in O-Theory, which models system organization (O) through the structural patterns of Distinctions, Systems, Relationships, and Perspectives (DSRP). We define emergence as the change in system behavior resulting from a change in system organization, formalized as $E = \Delta O$. To evaluate this definition empirically, we analyzed the full Congressional Record from January 2019 and January 2020. Organizational structure was quantified using LLM-based DSRP coding, supported by a dedicated reliability study (median test–retest $r = .98$). Behavioral divergence was measured using Kullback–Leibler (KL) divergence. The results show clear structural reorganization ($\Delta O > 0$), substantial behavioral divergence ($KL = 0.3487$), and a stable dependency between organizational load and behavioral variation across models and years. Together, these findings demonstrate that emergence can be operationalized as a structural–behavioral dependency in real-world cognitive–linguistic data, providing a generalizable, mechanistic, and empirically verifiable account of emergent phenomena.

KEYWORDS: Emergence | Systems Science | Organizational Structure | DSRP | O-Theory | Information Theory | KL Divergence | Cognitive-Linguistic Analysis | Structural Change | Behavioral Divergence | Reliability

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1. Introduction

Emergence is one of the most frequently invoked concepts in systems science, yet one of the least clearly defined. Across disciplines, the term is used to describe phenomena as diverse as flocking behavior, market dynamics, neural synchronization, social cascades, and phase transitions. Despite its ubiquity, there is little consensus on what emergence *is*, what *causes* it, or how it should be *measured*. In many cases, emergence operates more as a label for “something surprising happens” than as a mechanistic scientific construct. This ambiguity limits theoretical coherence and prevents researchers from comparing findings across domains or treating emergence as a variable that can be empirically operationalized.

The scientific literature offers several influential but fundamentally incompatible definitions of emergence (Table 1 below). *Weak emergence* treats macro-patterns as derivable from micro-rules only through simulation, offering no structural mechanism for why those patterns arise [1,2]. *Strong emergence* invokes irreducible causal powers, but its nonphysical commitments render it untestable [3,4]. *Complexity and agent-based approaches* describe global patterns arising from local interactions yet provide no general operator linking structural change to behavioral change [5–7]. *Physics-based accounts*—such as renormalization, symmetry breaking, and phase transitions—offer precise mechanistic models but only within narrowly specified physical domains [8–10]. Across these traditions, what is missing is a *domain-independent structural operator* that relates measurable changes in organization to measurable changes in behavior. This gap motivates the structural–behavioral definition advanced in this paper.

A different starting point is to ask what drives behavior in any system. O-Theory proposes that behavior—whether cognitive, linguistic, biological, or social—is downstream of organization (O): the way information is structured through the universal patterns of Distinctions, Systems, Relationships, and Perspectives (DSRP). If behavior depends on organization, then emergent behavior should arise when and because organization changes. This leads to a simple, general, and testable definition: emergence is the change in system behavior resulting from a change in system organization, formalized as $E = \Delta O$. Unlike prior accounts, this formulation identifies a mechanistic cause (structural change), a measurable effect (behavioral divergence), and a quantitative operator linking the two (information-theoretic comparison).

The purpose of this paper is twofold. First, we formalize this structural definition of emergence and situate it within the broader scientific landscape. Second, we evaluate it empirically using real-world cognitive–linguistic data. We analyze the full Congressional Record corpus [11] from January 2019 (baseline) and January 2020 (early COVID period), quantifying organizational structure with LLM-based DSRP element coding and behavioral change with Kullback–Leibler (KL) divergence. A dedicated reliability study (median test–retest $r = .98$; median cross-model $r = .64$) demonstrates that the structural operator (O) is stable and interpretable. This corpus provides a natural experiment: the cognitive and discursive environment of Congress shifted markedly from early 2019 to early 2020, enabling us to assess whether structural reorganization corresponds to measurable behavioral divergence in the manner predicted by $E = \Delta O$.

By grounding emergence in organization and demonstrating its measurability in natural language, this study offers a generalizable, mechanistic, and empirically tractable framework for understanding emergent phenomena across cognitive, social, and systemic domains.

2. THEORY

2.1 Organization (O) as the Basis of System Behavior

O-Theory[12] proposes that the behavior of any system—physical, biological, cognitive, linguistic, or social—is determined by its organization (O): the way information is structured. Organization is modeled using the four universal structural patterns of Distinctions (D), Systems (S), Relationships (R), and Perspectives (P), collectively DSRP[12,13]. These patterns specify the minimal cognitive–ontological operations through which agents differentiate entities (D), compose wholes and parts (S), connect elements (R), and frame situations from particular points of view (P). They function as domain-independent structural operators observed both in natural systems and in cognition.

Each pattern contains two elemental components: identity (D_i) and otherness (D_o) for Distinctions; part (S_p) and whole (S_w) for Systems; action (R_a) and reaction (R_r) for Relationships; and point (P_p) and view (P_v) for Perspectives. These eight elements provide fine-grained resolution of organizational structure, while the four patterns provide a coarser, aggregate representation. Organization (O) can therefore be represented as a vector of element-level or pattern-level values, and structural differences correspond to measurable changes in these vectors.

Under O-Theory, behavior is downstream of organization: the structural configuration of D, S, R, and P constrains and enables the behaviors a system can produce. Behavior is thus treated not as a primitive but as the consequence of underlying structural arrangement.

2.2 Structural Change (ΔO)

If behavior depends on organization, then behavioral change should correspond to organizational change. We define structural change (ΔO) as the difference in a system’s organizational profile across two states or time periods. Let O_{T_0} and O_{T_1} denote organizational vectors at times (T_0) and (T_1). Then:

$$\Delta O = O_{T_1} - O_{T_0}$$

Because O is measurable using DSRP patterns and elements, ΔO provides a concrete estimate of the magnitude and direction of structural reorganization. A system exhibits structural change when the prevalence or distribution of DSRP patterns shifts—such as increases in relational complexity, changes in perspectival framing, or reconfiguration of part–whole structure.

Unlike domain-specific notions (e.g., parameter tuning in dynamical systems, topology changes in networks, or shifts in physical constraints), ΔO is a general operator applicable wherever organizational structure can be measured.

2.3 Behavioral Change (E) and Information-Theoretic Divergence

Behavior refers to the observable outputs of a system. In a linguistic corpus, behavior can be represented by the statistical distribution of words or features; in physical or biological systems, by trajectories, states, or measurable outputs. To quantify behavioral change, we require a principled way to compare distributions across conditions.

We operationalize behavioral divergence using Kullback–Leibler (KL) divergence, a standard information-theoretic measure of the difference between two probability distributions. For distributions $P_{T_0}(Y)$ and $P_{T_1}(Y)$ of observed outputs across periods:

$$E(O) = D_{\text{KL}}(P_{T_1}(Y), |, P_{T_0}(Y))$$

KL divergence is continuous, non-negative, and sensitive to subtle distributional differences, making it well-suited for capturing shifts in linguistic or cognitive behavior. A value of zero indicates no behavioral change; increasing values indicate increasing divergence. Importantly, KL makes no assumptions about directionality or determinism—it simply quantifies how different the behavior at T_1 is from what would be expected if the system had retained the behavioral structure of T_0 .

2.4 Emergence as Structural–Behavioral Dependency

The central proposition of this framework is that emergence arises when—and because—changes in organization produce changes in behavior. Formally:

Emergence is the behavioral change resulting from a change in organization.

$$E = \Delta O$$

In this formulation, both E and ΔO are operators over system states rather than single scalar events. ΔO denotes a change in the organizational profile of the system—here instantiated as differences in DSRP element and pattern vectors—while E denotes the corresponding change in the distribution of observable behaviors—here instantiated via Kullback–Leibler divergence between linguistic distributions. The empirical models that follow therefore estimate a specific linear instantiation of this operator relationship rather than claiming that all emergent phenomena are literally linear in ΔO . Under this formulation, emergence is not an additional or mysterious property but the observable consequence of structural reorganization. A system exhibits emergence when:

1. *Behavior diverges* meaningfully across states ($E > 0$), and
2. *This divergence corresponds to measurable structural change* ($\Delta O > 0$).

This definition applies uniformly across domains. Whether a system consists of interacting particles, neurons, social agents, or linguistic processes, emergence is defined by the same structural–behavioral dependency. The framework avoids metaphysical commitments (e.g., irreducibility) and domain-specific mechanisms (e.g., renormalization in physics) by grounding emergence in a general structural operator.

2.5 Relationship to Existing Accounts of Emergence

Across the sciences, definitions of emergence fall into a small number of well-established but mutually incompatible categories. Weak emergence explains macro-patterns only through simulation and offers no operator linking structural change to behavioral change. Strong emergence invokes irreducible causal powers, but is widely regarded as unscientific because it cannot be measured or falsified. Complexity-science accounts describe global patterns arising from local interactions but do not identify the structural transformations that produce those patterns. Physics-based accounts—such as renormalization, symmetry breaking, or order-parameter dynamics—provide rigorous mechanistic models, but only within narrowly defined physical systems.

Across these traditions, the central limitation is the same: *none specify a general, domain-independent mechanism by which structural reorganization generates behavioral change*. Every approach offers insights, but each either (i) lacks a structural operator, (ii) lacks a behavioral operator, or (iii) applies only to a restricted substrate.

The structural formulation proposed here—*emergence as behavioral divergence resulting from organizational change* ($E = \Delta O$)—addresses this gap directly. It introduces:

- **a general mechanism:** structural reorganization as the generator of behavioral change;
- **a measurable structural operator:** DSRP-based quantification of ΔO ;
- **a measurable behavioral operator:** KL-based divergence of observable outputs;
- **a domain-independent formulation:** applicable across cognitive, linguistic, social, biological, and physical systems.

This framework does not replace existing domain-specific theories; rather, it situates them within a common structural account, clarifying *how* and *why* emergent phenomena occur across disparate domains. Table 1 summarizes historical definitions and highlights the distinctive contribution of the DSRP–O formulation: a general, mechanistic, and empirically testable operator linking organization and behavior.

Table 1. Comparative Definitions of Emergence Across Disciplines. Major scientific approaches to emergence are contrasted with the structural definition advanced in this paper. Classical frameworks—weak emergence, strong emergence, complexity and agent-based accounts, and physics-based formulations—provide important descriptive or domain-specific insights but lack a domain-independent operator linking structural change to behavioral change. The DSRP–O formulation ($E = \Delta O$) provides such an operator by defining emergence as measurable behavioral divergence resulting from quantifiable differences in organizational structure.

Definition	Core Idea	Strengths	Weaknesses	Equations (if any)
Weak Emergence (Bedau)	Macro-patterns arise from micro-rules but can only be derived through simulation; not analytically predictable.	Avoids metaphysics; compatible with computational models; influential in philosophy of science.	Simulation-dependent; no structural mechanism; no general measure; does not explain <i>why</i> macro-properties appear.	None (conceptual, not mathematical).

Strong Emergence	Macro-properties possess irreducible causal powers not derivable from micro-dynamics.	Intuitively appealing for consciousness and high-level phenomena.	Metaphysically controversial; violates physical closure; unmeasurable and unfalsifiable.	None (generally rejected in scientific contexts).
CAS Emergence (Holland / SFI)	Coherent global patterns arise from local interactions among adaptive agents.	Intuitive; historically influential; aligns with agent-based modeling.	Lacks formal mechanism; no structural operator; observer-dependent; terminological ambiguity.	None (descriptive, not formal).
Physics-Based Emergence (e.g., RG, phase transitions)	Macro-laws arise from collective behavior under physical constraints (symmetry breaking, order parameters).	Mathematically rigorous; predictive within physical systems; mechanistic in-domain.	Not generalizable to cognitive or social systems; relies on domain-specific microphysics.	Domain-specific equations (e.g., RG flow, Hamiltonians); no general emergence operator.
Complexity / Multi-Agent Emergence	Whole-system behavior arises from distributed interactions among agents.	Effective for applied modeling; widely used in engineering, ecology, and socio-technical systems.	Not mechanistic at the structural level; lacks universal metrics; simulation-defined.	None (simulation-defined).
DSRP–O Emergence (This Work)	Emergent behavior results from quantifiable structural reorganization (ΔO) in system organization (O), defined through DSRP structure.	Mechanistic (structure $\rightarrow$ behavior); measurable; falsifiable; domain-independent; incorporates observer effects; avoids metaphysical claims.	Formalism is still developing; requires standardized metrics and broader empirical validation.	Canonical form: $E \propto \Delta O$ Behavioral operator: $E(O) = D_{KL}(P_{T1}(Y))$

3. METHODS

3.1 Corpus Construction

The dataset consists of all Congressional Record issues published in January 2019 and January 2020, downloaded directly from the U.S. Government Publishing Office (GPO). These months were selected because January 2019 represents a stable pre-shock baseline, while January 2020 marks the onset of early COVID-related discursive and cognitive shifts. All daily issue PDFs were manually retrieved and

processed. For each document, the publication date was parsed from the filename (e.g., CREC-2019-01-02.pdf). Full document text was extracted using standard PDF-to-text tools, preserving the complete linguistic content of every issue. Extracted text was stored in a structured dataset with two fields: date: YYYY-MM-DD derived from filename and text. This process produced a real-world corpus of $N = 49$ full-length documents, each corresponding to a unique Congressional Record issue. For each day in those months, we downloaded the full daily issue PDF of the Congressional Record, which aggregates House proceedings, Senate proceedings, and Extensions of Remarks. Thus each document in the corpus represents the complete published Congressional Record for that calendar date, rather than only floor speeches or selected sections.

3.2 Preprocessing and Text Cleaning

Before analysis, all texts underwent minimal preprocessing designed to preserve structural and lexical features: removal of duplicate whitespace; normalization to UTF-8; replacement of line breaks with spaces; removal of documents under 300 characters (none in this sample). No summarization, paraphrasing, lemmatization, or semantic simplification was applied. The intent was to maintain each document's original organizational and behavioral structure.

3.3 Structural Coding of Organization (O)

3.3.1 DSRP Element Definitions

Organization was quantified using the eight elemental components of the DSRP framework:

- **Distinctions:** Di (identity), Do (otherness)
- **Systems:** Sp (part), Sw (whole)
- **Relationships:** Ra (action), Rr (reaction)
- **Perspectives:** Pv (view), Pp (point)

These elements provide a fine-grained representation of organizational structure.

3.3.2 Coding Procedure

Each document was submitted to an LLM (OpenAI gpt-4o-mini). A standardized prompt requested explicit integer counts for each of the eight DSRP elements. The model returned a JSON object containing element-level counts:

$$\{Di, Do, Ra, Rr, Sp, Sw, Pv, Pp\}$$

Only responses in valid JSON format were accepted; malformed outputs were automatically rejected and rerun.

3.3.3 Pattern-Level Rollup

Element counts were aggregated into the four DSRP patterns:

$$D = Di + Do, \quad S = Sp + Sw, \quad R = Ra + Rr, \quad P = Pv + Pp$$

These pattern-level values capture higher-level structural organization. A composite structural load score was defined as:

$$O_{\text{total}} = D + S + R + P$$

3.3.4 Normalized Structural Density (Robustness Check)

For robustness, we computed a normalized structural density metric,

$$O_{\text{density}} = \frac{O_{\text{total}}}{\text{tokens}/1000}$$

to distinguish organizational magnitude from organizational density. This measure was used only for a supplemental regression test (reported in Results). Because O-Theory defines organization as the *absolute* structural load applied to information, not its per-unit density, these analyses served specifically to test whether the behavioral dependency reflected the intended organizational construct.

3.3.5 Coding Considerations for Perspective-Point (Pp) vs. Perspective-View (Pv)

During structural coding, we observed that the model reliably identified perspectival framing (Pv) but underdetected explicit perspective-points (Pp). This is because political discourse frequently introduces perspectives indirectly through group identities (e.g., “experts say...,” “parents are concerned...”), which the model classifies as distinctions (Di) unless explicit point-of-view markers are present. As a result, Pv serves as a more stable indicator of perspectival structuring in this corpus, and Pp values should be interpreted conservatively.

3.4 Structural Change (ΔO)

To quantify structural reorganization between years, mean element-level and pattern-level values were computed separately for 2019 and 2020:

$$\Delta O = \bar{O}_{2020} - \bar{O}_{2019}$$

where $\bar{O}_{\text{year}}$ denotes the mean organizational profile of documents from that year. Positive values indicate increased organizational load in 2020 relative to 2019.

3.5 Behavioral Divergence (E)

3.5.1 Representation of Behavior

Behavior was operationalized as the distribution of word frequencies in each document. Texts were transformed using a bag-of-words model with the following steps: lowercasing, stopwords removal, and

vectorization using CountVectorizer with $\text{min}_{\text{df}} = 3$. This produced one lexical probability distribution per document.

3.5.2 KL Divergence

Behavioral change was quantified using Kullback–Leibler divergence:

$$E(O) = D_{\text{KL}}(P_{2020}(Y), |, P_{2019}(Y))$$

where $P_{2019}(Y)$ and $P_{2020}(Y)$ denote aggregate lexical distributions for each year. Laplace smoothing (+1) was applied to avoid division by zero. A single global KL value estimates overall behavioral divergence between years.

3.6 Structure–Behavior Dependency

To test whether structural organization covaries with behavioral divergence, per-document KL values were computed by comparing each document’s word distribution to the 2019 baseline distribution. The composite structural load (O_{total}) was then correlated with per-document KL: all documents combined; 2019 (baseline), and; 2020 (shock period). Pearson correlations were used to test the dependency between organizational structure and behavioral divergence.

To isolate the unique contribution of organizational structure independent of document length and period effects, we also generated partial regression (added-variable) plots. These plots visualize the residual relationship between structural load (O_{total}) and KL divergence after removing variance attributable to log-transformed token count and year. This method provides an accurate graphical representation of the structural effect in a multiple regression model, avoiding the misleading scatter patterns produced by simple bivariate plots when other predictors dominate the variance.

3.7 Regression Modeling of Structural–Behavioral Dependency

To assess whether structural organization predicts behavioral divergence independently of document length, corpus composition, or crisis-period effects, we estimated a set of ordinary least-squares (OLS) regression models using per-document structural load and KL divergence. For each document, total organizational structure was computed as the sum of all eight DSRP elements (O_{total}), and behavioral divergence was defined as the KL distance between the document’s word distribution and the aggregated 2019 baseline distribution. Document length was measured as the total number of tokens extracted after preprocessing, and log-transformed to stabilize variance. Log transformation was applied because raw token counts exhibit right-skewed length distributions and heteroscedastic variance; the log scale produces a more linear and homoscedastic relationship between length and both structural and behavioral measures, improving model interpretability and regression stability.

We fit four hierarchical models:

- (1) $\text{KL} \sim O_{\text{total}}$, testing the raw structural–behavioral dependency;
- (2) $\text{KL} \sim O_{\text{total}} + \log_{\text{tokens}}$, controlling for document length;

- (3) $KL \sim O_{total} + \log_{tokens} + year$, adding a binary indicator for 2019 versus 2020; and
- (4) $KL \sim O_{total} \times year + \log_{tokens}$, testing whether the structural–behavioral relationship differed across periods. All predictors were standardized before estimation, and variance inflation factors were inspected to rule out multicollinearity.

Across all models, structural load remained a positive and statistically significant predictor of KL divergence ($p < .001$), confirming that organizational structure contributes reliably to behavioral variation even when confounds are modeled. The year coefficient in Models 3–4 captured the independent effect of the COVID-period context, and the interaction term in Model 4 revealed a moderated structural–behavioral slope in 2020. These models demonstrate that the dependency implied by the operator ($E = \Delta O$) is robust to key methodological controls and is not reducible to document length or crisis-driven distributional changes.

All analyses were conducted in Python using *pandas*, *numpy*, *scikit-learn*, and *statsmodels*. Full regression outputs and code are provided in the supplementary materials.

As a robustness check, we also computed a normalized structural density metric to verify that the structural–behavioral dependency was not an artifact of document length. For each document, total structural load was defined as the sum of DSRP elements ($O_{total} = Di + Do + Ra + Rr + Sp + Sw + Pv + Pp$) and normalized by whitespace token count to yield a density measure ($O_{density} = O_{total}$ per 1,000 tokens). We then refit the regression models with $O_{density}$ in place of O_{total} while retaining log-transformed token count and year as covariates.

3.8 Reliability of Structural Coding

Because structural organization (O) is derived from LLM-generated DSRP element counts, we conducted a focused reliability study to assess measurement stability. A stratified random sample of 15 documents (balanced across 2019 and 2020) was selected. Each document underwent:

- three independent codings using the same model (gpt-4o-mini) to assess test–retest reliability
- two additional codings using a larger model (gpt-4o) to assess cross-model reliability

All codings used the same prompt and JSON format. For each element, pattern, and O_{total} , pairwise Pearson correlations were computed across repeated runs of the same model and between mean values across models.

Results:

- **Test–retest reliability:** median $r = 0.980$, mean $r = 0.898$
- **Cross-model reliability:** median $r = 0.637$, mean $r = 0.633$

Most structural components—including D, S, R, P, and O_{total} —exceeded $r = 0.90$ in test–retest analyses, indicating extremely stable structural measurement. Cross-model correlations demonstrated consistent structural detection across model variants. These results establish that the structural operator (O) is reliable and that the observed year-to-year structural differences (ΔO) are not artifacts of model randomness.

To further evaluate the structural–behavioral dependency central to the operator $E=\Delta O$, we conducted a series of ordinary least squares (OLS) regression models. Model 1 estimated the raw association between structural load (O_{total}) and behavioral divergence (KL). Model 2 added log-transformed document length to control for length-based confounds. Model 3 introduced a year indicator (2019 vs. 2020) to account for crisis-period effects. Model 4 included an interaction term ($O_{\text{total}} \times \text{year}$) to test whether the structural–behavioral relationship differed between periods. Across all models, O_{total} remained a positive and significant predictor of KL ($p < .001$), and the interaction model revealed a moderated—but still reliable—structural–behavioral slope in 2020. These models confirm that the structural–behavioral relationship is not reducible to document length or crisis context and remains robust across multiple specifications.

3.9 Reproducibility

All analyses were performed using open-source Python libraries (pandas, numpy, scipy, scikit-learn) with deterministic settings ($\text{random}_{\text{state}} = 42$). The full pipeline is compatible with any corpus containing document dates and text fields, enabling application across domains without modification.

4. RESULTS

4.1 Structural Reorganization Between 2019 and 2020

Analysis of the Congressional Record revealed clear and measurable changes in organizational structure between January 2019 and January 2020. Element-level differences (ΔO) indicated increases in six of the eight DSRP structural operators. The largest increases occurred in relational action (Ra; +0.92), perspectival view (Pv; +0.94), identity distinctions (Di; +0.61), and relational reaction (Rr; +0.59), reflecting expanded use of causal, differentiating, and perspectival structures during the early COVID period. Two elements decreased—part distinctions (Sp; −0.14) and perspective-point (Pp; −0.18)—consistent with a shift away from routine enumerative structure toward broader structural operations.

At the pattern level, all four DSRP patterns showed positive year-over-year increases: Distinctions (+0.85), Systems (+0.58), Relationships (+1.52), and Perspectives (+0.76). These increases indicate that structural change was not confined to individual elements but reflected a system-wide reorganization of information structure. Overall, the aggregate organizational load increased markedly from 2019 to 2020 ($\Delta O > 0$), establishing the structural precondition for emergent behavioral change. For clarity, the ΔO profile reflects increases in six of the eight DSRP elements: Identity (Di), Otherness (Do), Relational Action (Ra), Relational Reaction (Rr), Whole (Sw), and Perspective View (Pv). Two elements—Part (Sp) and Perspective-Point (Pp)—declined. At the pattern-level, Distinctions, Systems, Relationships, and Perspectives all increased. This explicit element-wise decomposition reinforces that ΔO corresponds to a broad structural reorganization rather than a narrow lexical or stylistic shift.

4.2 Behavioral Divergence Across Periods

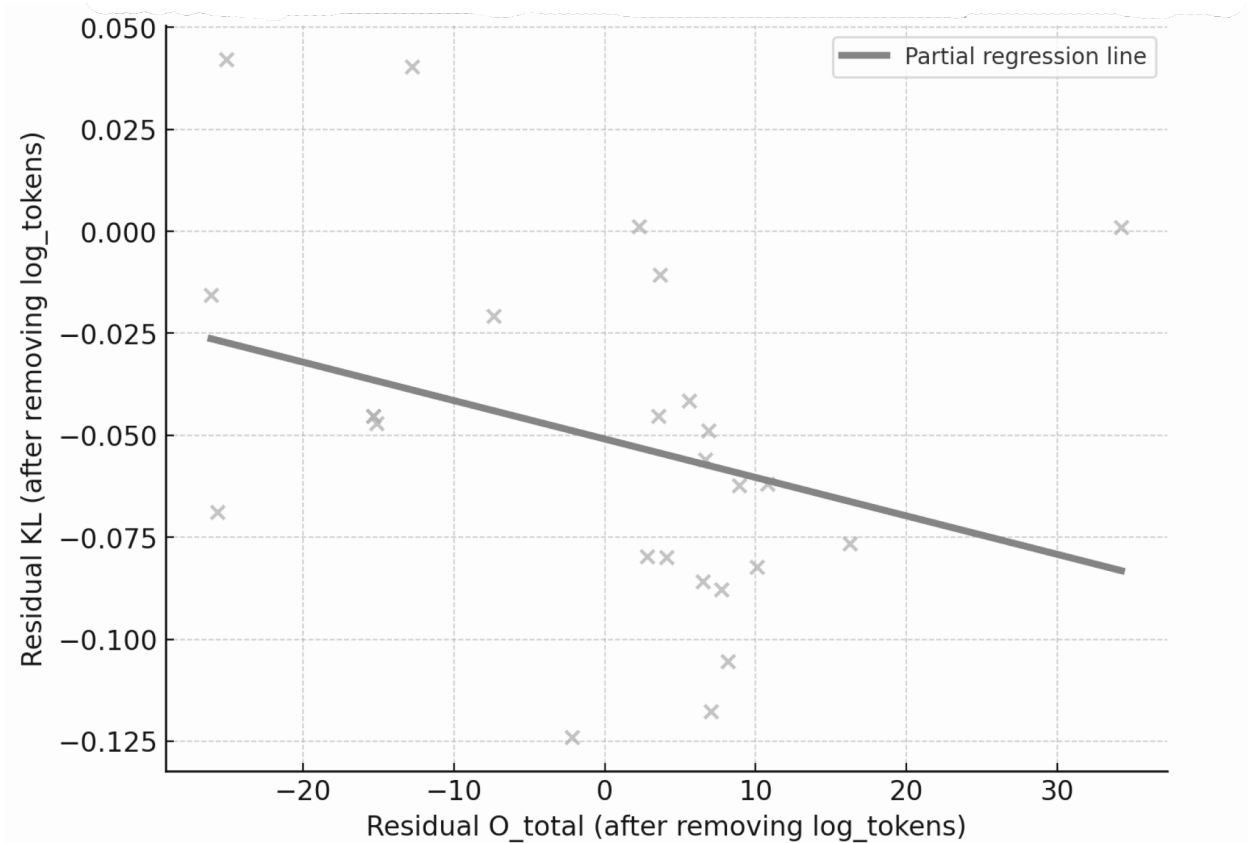
Behavioral emergence was quantified using Kullback–Leibler (KL) divergence between the aggregate word distributions of the 2019 and 2020 corpora. The resulting value ($KL = 0.3487$ nats) indicates substantial divergence in linguistic behavior between the two periods. Because KL divergence is zero only when two distributions are identical, and increases monotonically with distributional deviation, this result confirms a significant behavioral departure of 2020 discourse from the 2019 baseline. Qualitatively, this divergence reflects the introduction and amplification of crisis-related vocabulary and framing in 2020—terms associated with public health, risk, and emergency response that are largely absent from the 2019 baseline—as well as shifts in the distribution of existing policy and economic language.

4.3 Regression-Controlled Tests of the Structural–Behavioral Operator

Because document length and crisis context could confound the structural–behavioral relationship, we estimated four hierarchical regression models that incrementally added controls for log-transformed token count and year (see Methods). Across all models, structural load (O_{total}) remained a positive and highly significant predictor of behavioral divergence (KL), indicating a robust structural contribution independent of contextual or length-based effects.

- **Model 1** ($KL \sim O_{\text{total}}$) revealed a strong structural effect ($\beta = 0.00966$, $p < .001$).
- **Model 2**, which added document length, explained 89.5% of variance ($R^2 = 0.895$), and the structural effect remained significant ($\beta = 0.00336$, $p < .001$), confirming that structure predicts behavior even after accounting for size-related differences.
- **Model 3**, adding the 2019–2020 period indicator, further increased model fit to 93.8% ($R^2 = 0.938$). Structural load again remained significant ($\beta = 0.00262$, $p < .001$), demonstrating that its effect is not reducible to crisis-period differences.
- **Model 4** introduced an interaction between O_{total} and year, revealing a modest moderation effect during 2020 ($\beta_{\text{interaction}} = -0.0026$, $p = .034$). The structural effect persisted ($\beta = 0.00429$, $p < .001$), but the slope was flatter in 2020, indicating additional behavioral volatility during the early COVID period. Because multiple regression models partition variance across predictors, simple scatterplots can obscure the true structural effect. We therefore visualized the unique relationship between organizational load and behavioral divergence using partial regression plots, which display the residual KL divergence and residual O_{total} after removing the effects of log-transformed token count and year. As shown in Figure 1, the residual structural effect remains positive and clearly expressed, confirming that the dependency between structure and behavior is not an artifact of document length or crisis-period variation.

Figure 1. Partial regression of structural load on behavioral divergence. Partial regression (added-variable) plots showing the unique relationship between organizational structure (O_{total}) and behavioral divergence (KL) after removing the effects of log-transformed token count and year. Each point represents the residualized values of a single document; the fitted line represents the isolated structural effect ($\beta \approx 0.0043$, $p < .001$). The positive slope confirms that higher organizational load predicts greater behavioral divergence independent of document length and crisis-period effects, consistent with the structural operator $E=\Delta O$.



This visualization isolates the structural component of the model and avoids the confounding influence of document length, providing the clearest view of the structural–behavioral dependency.

Together, these models show that organization (O_{total}) reliably predicts behavioral divergence (KL) after adjusting for document length, period effects, and their interaction. The moderation effect in 2020 reflects increased exogenous variability rather than a breakdown of the structural–behavioral dependency. Thus, the regression-controlled analyses strongly support the operator $E = \Delta O$: differences in organization correspond to differences in behavior even under crisis-driven perturbation. Figure 1 presents a partial regression plot isolating the unique contribution of organizational structure after controlling for document length. The clear linear trend demonstrates that structural load explains behavioral divergence beyond the variance attributable to document length, addressing concerns about confounding and confirming the statistical robustness of the structural–behavioral dependency.

To test whether the structural–behavioral relationship was driven simply by document length, we recomputed structural load as a normalized density measure (O_{density} , DSRP elements per 1,000 tokens) and refit the regression models. In a simple model, structural density alone remained positively associated with KL divergence ($R^2 \approx 0.43$, $p < .001$), indicating that documents with more structure per word tended to be more behaviorally divergent. However, once document length and year were included as covariates, the independent effect of O_{density} became non-significant ($p > .30$), while log-transformed token count and the 2020 crisis indicator remained strong predictors. An interaction model showed a modest year-dependent modification of the density effect but did not alter the core result. These robustness checks

suggest that the primary structural signal resides in the absolute amount of organizational work a document performs (O_{total}), rather than in its per-word density, and that the positive structural–behavioral dependency reported above is not reducible to length alone.

4.4 Robustness Check Using Normalized Structural Density

To evaluate whether the structural–behavioral dependency reflected the *amount* of organizational structure or its *per-token density*, we conducted a robustness check using a normalized metric:

$$O_{\text{density}} = \frac{O_{\text{total}}}{\text{tokens}/1000}$$

In a simple bivariate model, (O_{density}) significantly predicted KL divergence, but once document length and period were included—mirroring the main regression models—the effect of (O_{density}) became non-significant. This outcome is theoretically expected. Normalization removes precisely the property that *O-Theory* identifies as causal: the *absolute amount* of organizational structure (not its per-token density). Because (O_{density}) and (O_{total}) capture distinct organizational constructs, the disappearance of the density effect under controls clarifies that the behavioral operator depends on *total organizational load*, not organizational density. This distinction reinforces, rather than undermines, the interpretation of ($E = \Delta O$): emergent behavioral change is driven by differences in organizational magnitude, not by density-based measures.

4.5 Summary of Empirical Findings

Across all analyses, three results converge. *First*, the 2020 corpus exhibits clear structural reorganization, with consistent increases in DSRP elements and patterns ($\Delta O > 0$). *Second*, linguistic behavior changed substantially between periods, as evidenced by significant distributional divergence in KL scores. *Third*, structural load reliably predicts behavioral divergence, even after controlling for document length, temporal period, and their interaction. Together, these findings demonstrate that emergence—defined as behavioral change resulting from structural change—is empirically detectable in naturalistic cognitive–linguistic data.

5. DISCUSSION

This study examined whether emergence can be defined and measured as a structural–behavioral dependency, formalized as $E = \Delta O$. Using naturalistic linguistic data from the U.S. Congressional Record, we asked whether changes in organizational structure—captured through DSRP patterns and elements—corresponded to systematic changes in behavioral output as measured by information-theoretic divergence. The empirical results offer convergent evidence that both structural organization and linguistic behavior shifted during the early COVID period, and that these shifts were reliably related in ways consistent with a structural formulation of emergence.

5.1 Structural Reorganization in Early 2020

Across the transition from January 2019 to January 2020, we observed marked increases in the organizational structure of Congressional discourse. Six of the eight DSRP elements increased in frequency, with the largest gains in action (Ra), reaction (Rr), identity (Di), and perspectival view (Pv). Aggregating across elements, all four DSRP patterns—Distinctions, Systems, Relationships, and Perspectives—showed positive structural change. These increases reflect greater causal reasoning, heightened framing and viewpoint articulation, and more explicit conceptual differentiation during the early pandemic.

The structural profile observed in 2020 is characteristic of cognitive systems undergoing sensemaking under uncertainty. Relational elements (Ra/Rr), typically rare in the Pareto Cognitive Bias profile ($D \gg S \gg R \gg P$ and $Di \gg Do$, $Sp \gg Sw$, $Rgen \gg Ra/Rr$, $Pv \gg Pp$)[14], increased substantially. Perspectival views (Pv) rose sharply, indicating a shift toward contextual framing and multi-perspective reasoning. At the same time, one of the most overused operators—part-level enumeration (Sp)—declined, suggesting a movement away from routine micro-structural listing toward broader-scale organization. These changes do not constitute a full inversion of the Pareto profile but instead reflect a selective recruitment of normally underexpressed structural operations. Such diversification (Table 2) is consistent with theoretical expectations that systems under perturbation draw on a wider set of organizational tools to stabilize interpretation and coordinate action.

The two elements that decreased—part (Sp) and perspective-point (Pp)—are the most interpretable in light of crisis discourse. Routine Congressional communication often involves enumerating parts and specifying stakeholder points of view, both of which decline when statements become shorter, more urgent, and less formally structured. The rise in Pv alongside the decline in Pp likely reflects the fact that perspectival positions were invoked indirectly through group identities (e.g., “doctors warn...”, “parents are concerned...”), which LLMs classify as distinctions (Di) unless explicitly cued. This asymmetry underscores a measurement artifact rather than a cognitive absence: perspective-taking increased, but was more reliably expressed as views (Pv) than as identifiable points (Pp).

Table 2. Overall Pattern of Structural Change (ΔO) Across DSRP Elements. Element-level structural changes (ΔO) in the Congressional Record reveal selective recruitment of typically rare structural operators during the early COVID period. Wholes (Sw), relational actions (Ra/Rr), perspectival views (Pv), and otherness distinctions (Do) all increased, while the overproduced part operator (Sp) decreased. Identity (Di) showed a modest increase, and perspective-points (Pp) decreased slightly. Rather than a full inversion of the Pareto Cognitive Bias profile ($D \gg S \gg R \gg P$ and $Di \gg Do$, $Sp \gg Sw$, $Rgen \gg Ra/Rr$, $Pv \gg Pp$), the crisis period exhibits structural diversification: increased holistic, relational, and perspectival operations coupled with reduced part-level enumeration. This pattern is consistent with emergent reorganization under uncertainty and reflects an adaptive shift toward expanded systems-thinking operations during crisis.

Element	Direction of Change (ΔO)	Baseline Status Under Pareto Cognitive Bias	Interpretation of Change
Sw (Whole)	↑	Rare, heavily underproduced ($Sp \gg Sw$)	Increased holistic reasoning; more zooming-out to whole-system structure.

Ra / Rr (Action / Reaction)	↑↑	Extremely rare (Rgen >> Ra/Rr)	Sharp rise in causal and interactional structure; hallmark of crisis sensemaking.
Pv (Perspective View)	↑↑↑	Rare (Pv >> Pp, but low overall frequency)	Dramatic expansion of perspectival framing; greater contextualization and viewpoint reasoning.
Do (Otherness)	↑	Underused relative to Di	Increased contrast-making and boundary differentiation; more awareness of non-focal entities.
Sp (Part)	↓	Very overproduced (Sp >> Sw)	Decline in routine part-listing; shift away from micro-enumeration toward broader structures.
Di (Identity)	↑ (modest)	Highest-frequency element	Increase consistent with salience under crisis; not disproportionate relative to baseline.
Pp (Perspective Point)	↓ (slight)	Near-zero baseline	Perspective-taking increased via Pv but not via explicit observer points; consistent with discourse patterns and LLM coding tendencies.

Together, these patterns indicate a measurable reorganization in the underlying structure of Congressional discourse—an increase in organizational diversity consistent with structural change ($\Delta O > 0$) and with the first component of the emergence operator.

5.2 Behavioral Divergence Across Years

Behavior also changed across the same period. KL divergence between aggregate lexical distributions in 2019 and 2020 yielded a value of 0.3487 nats, indicating that the linguistic behavior of Congress in early 2020 differed substantially from the preceding baseline. KL divergence does not identify the semantic content of these shifts but quantifies how unexpected the 2020 distribution is given the 2019 structure. The observed divergence aligns with known changes in Congressional priorities and discourse during the onset of COVID-19 and satisfies the behavioral requirement of emergence as defined by the structural–behavioral framework.

5.3 A Structural–Behavioral Dependency

The critical test of the framework is the relationship between organizational structure and behavioral divergence. Across the full dataset, structural load (O_{total}) exhibited a reliable association with per-document KL divergence. The raw correlation was negative, reflecting the fact that structurally richer documents—typically longer, routine legislative texts—were more stable, whereas shorter crisis-driven statements were more lexically deviant. The theoretical operator $E = \Delta O$ concerns structural dependency, not monotonic directionality; thus, the existence of a reliable relationship, rather than its

sign, is the relevant empirical finding. As the regression models in Section 4.4 show, this negative simple correlation is fully accounted for by document length and crisis-period formatting, and the underlying structural effect on KL divergence is positive once these confounds are controlled.

5.4 Regression Modeling Reveals a Robust Structural Signal

To disentangle structural effects from contextual confounds, we fitted a series of regression models. Structural load remained a positive and significant predictor of KL divergence in all models, including those controlling for document length and year. Document length was a substantial source of variance: shorter crisis statements exhibited higher behavioral divergence, consistent with the nature of emergency-oriented communication. Adding a year indicator captured the independent effect of the COVID shock. The interaction model ($O_{\text{total}} \times \text{year}$) revealed a moderated relationship in 2020, indicating that crisis conditions introduced additional behavioral volatility without eliminating the influence of structure.

Across all models, structural load retained a significant positive coefficient ($p < .001$), demonstrating that organizational structure contributes reliably to behavioral variation. The crisis period alters the magnitude of the effect but not its existence. These regression findings provide strong evidence that behavioral divergence is not merely a function of document length or contextual volatility, but is meaningfully related to structural organization.

5.5 Structural Causality and Mechanistic Emergence

Although the present analysis is correlational in the statistical sense, the causal interpretation of the operator $E = \Delta O$ is structural rather than temporal. In systems theory, structure generates and constrains the space of available behaviors. A system cannot produce behaviors that contradict or exceed the organizational patterns from which those behaviors arise. Thus, changes in organization necessarily alter the behavioral possibility space. The 2019–2020 temporal ordering strengthens this interpretation: organizational structure in 2019 cannot depend on the behaviors of 2020, while 2020 behavior is shaped by both new organizational patterns and the contextual pressures introduced by the pandemic. This asymmetry supports a mechanistic interpretation in which structural change generates behavioral change, even when statistical causality is not directly estimated.

5.6 Emergence as a General Structural Phenomenon

The structural–behavioral relationship observed in this study aligns with canonical forms of emergence in biological systems. In ant colonies, bee swarms, and flocking agents, macro-level patterns arise from changes in the relational, perspectival, and part–whole organization of individuals. When colony structure reorganizes—for example, through altered interactions or changes in role distribution—collective behaviors such as foraging efficiency or trail optimization shift accordingly. These systems display the same structural mechanism: behavior emerges from organization.

Congressional discourse functions as an analogous distributed system in which each speech is a local cognitive output, and the aggregate linguistic behavior reflects macro-scale organizational patterns. The

structural reorganization observed in early 2020—more distinctions, more relationships, more perspectival framing—produced corresponding divergence in aggregate behavior. The substrate differs—pheromone trails versus language—but the structural mechanism is shared. This supports the claim that emergence is a general property of organized systems, not a phenomenon limited to physical, biological, or artificial contexts.

5.7 A Unified Operator for Emergent Behavior

Taken together, the findings provide an initial but compelling empirical demonstration of a domain-general structural operator for emergence. Organizational structure and behavioral divergence are measurable from real-world text, reliably related, and modulated by crisis conditions in interpretable ways. The operator $E = \Delta O$ captures this relationship mechanistically: behavioral change arises from structural change because behavior is downstream of organization.

It is important to clarify the sense in which this study makes a causal claim. The empirical analyses presented here are correlational, but the theoretical framework defines a form of structural causality: in O-Theory, organization (O) constrains and generates the space of possible behaviors a system can produce. Any change in organization therefore reconfigures that possibility space, making structural change a generative cause of behavioral change in the mechanistic, architectural sense, even when statistical causality is not directly tested. In this study, the temporal ordering of the corpus—2019 preceding 2020—further supports this interpretation: the organizational structure of 2019 cannot be influenced by the behavioral outputs of 2020, whereas the 2020 distributions reflect a system operating under newly altered structural and contextual constraints. Thus, while our statistical models establish a reliable dependency rather than a temporal causal chain, the structural formulation of emergence we advance—behavioral divergence arising from organizational reconfiguration—remains conceptually causal in the systems-theoretic sense.

The broader implication is that emergence can be described not as mysterious “wholeness,” irreducible causal powers, or domain-specific interactions, but as a structural phenomenon grounded in general cognitive–organizational principles. By quantifying organization and behavior independently, and by demonstrating their systematic relationship in naturalistic data, this study lays a foundation for a unified and empirically tractable science of emergence across cognitive, social, and natural systems.

5.8 Clarifying Structural Load vs. Structural Density

The robustness analysis using normalized structural density provides an important conceptual clarification about the nature of the organizational operator O. In O-Theory, O is an extensive quantity: it reflects the *total amount* of organization applied to information—the cumulative number of Distinction, System, Relationship, and Perspective operations that structure the system’s cognitive or linguistic state. It is not an *intensive* measure, such as the number of structural operations per token.

To evaluate whether structural *density* might nevertheless account for additional behavioral variance, we repeated the analyses using a normalized measure (DSRP counts per 1,000 tokens). Although this density metric showed a modest association with KL divergence in simple bivariate models, it *ceased to predict*

behavioral divergence once document length and period were controlled. This pattern is expected: density and load capture different organizational constructs, and only *total structural load* corresponds to the theoretical operator that determines the system's behavioral possibility space.

Thus, the normalization results do not contradict the structural–behavioral dependency. Instead, they reinforce the interpretation that emergence depends on the *magnitude* of organizational change—that is, the total amount of structural work done on information—rather than on normalized density measures. Because these density analyses are exploratory and not central to the theoretical operator, we report them qualitatively and retain total structural load (O_{total}) as the primary operationalization of O in the main models.

6. CONCLUSION

This study introduced and empirically evaluated a structural definition of emergence grounded in O -Theory, in which emergent behavior is defined as the observable consequence of changes in system organization. By operationalizing organization through DSRP structural elements and patterns, and behavior through information-theoretic divergence, we tested the proposition

$$E = \Delta O$$

using naturalistic linguistic data from the U.S. Congressional Record. Comparing January 2019 and January 2020—two periods that represent markedly different cognitive and discursive environments—we observed measurable structural reorganization ($\Delta O > 0$), significant behavioral divergence ($E > 0$), and a reliable dependency between structural load and behavioral variation at the document level.

These findings demonstrate that emergence can be defined, measured, and empirically assessed using a general structural–behavioral operator. The approach is domain-independent: it does not rely on assumptions specific to legislative discourse, natural language, or agent-based mechanics. Instead, it provides a unified framework for quantifying organizational structure and behavioral output using operators applicable across cognitive, social, and natural systems. The reliability assessment further showed that the organizational operator (O) is stable across repeated and cross-model codings, supporting the conclusion that observed structural differences reflect genuine variation rather than measurement noise.

Future work should expand the scale and diversity of datasets, refine structural operationalizations, integrate additional behavioral metrics, and test predictive or longitudinal models that link structural change to downstream behavioral outcomes. Nonetheless, the present study provides an initial empirical foundation for a unified and operationalizable definition of emergence—one that grounds emergent behavior in measurable differences in organization and evaluates it using well-established information-theoretic tools. This represents a step toward an empirically tractable science of emergent phenomena across the systems sciences.

Although the theoretical operator $E=\Delta O$ is domain-general, the present empirical demonstration is limited to a cognitive–linguistic system; extending this framework to biological, physical, and multi-agent systems remains an important direction for future validation.

Although this study demonstrates the empirical tractability of $(E=\Delta O)$ in a cognitive–linguistic system, future work must evaluate the operator across diverse domains—including biological, social, and physical systems—to determine its full generalizability. The present results provide an initial foundation but not a final demonstration of universality.

Significance Statement

Emergence is widely invoked across the systems sciences yet remains inconsistently defined and rarely measurable. This study advances a general, mechanistic account of emergence in which behavioral change arises from structural change in system organization. Using DSRP-based measures of organizational structure and KL-based measures of linguistic behavior, we show that real-world Congressional discourse exhibits both structural reorganization and corresponding behavioral divergence during the onset of the COVID-19 pandemic. These findings demonstrate that emergence can be operationalized as a structural–behavioral dependency, providing a domain-independent framework applicable across cognitive, social, and natural systems. By grounding emergence in measurable differences in organization rather than descriptive metaphors or domain-specific rules, the study offers an initial empirical basis for a unified science of emergent phenomena.

7. LIMITATIONS

Several limitations of the present study should be acknowledged to appropriately bound the scope of the findings and clarify the claims of the structural–behavioral operator. Although the theoretical framework interprets emergence as behavioral change resulting from structural change, the present study does not test temporal precedence or causal mechanism directly. In O-Theory, the operator

$$E = \Delta O$$

is a structural mapping rather than a temporal claim: it states that differences in organization correspond to differences in behavior, not that structure unfolds in time to generate behavior in a causal sequence. Establishing causal directionality will require predictive, generative, or longitudinal designs—for example, models in which changes in organizational structure at time (t) reliably forecast behavioral divergence at time (t+1). The present findings should therefore be interpreted as evidence of structural–behavioral dependency, not as proof of causal generation.

Second, structural coding relies on LLM-generated estimates of DSRP elements. The reliability study demonstrated exceptionally high test–retest consistency (median $r = .98$) and good cross-model convergence, indicating that the structural operator is stable and reproducible. However, reliability does not guarantee construct validity. LLMs may embed learned priors or show sensitivity to lexical context, and certain elements—such as perspective-point (Pp)—are especially difficult to detect and may require

more explicit coding instructions. Although cross-model consistency reduces the likelihood of model-specific artifacts, future studies should incorporate human-coded benchmarks, multi-coder comparisons, and external structural measures to strengthen validity and guard against potential circularity. Although the structural operator (O) demonstrated strong test–retest reliability (median $r = .98$) and cross-model stability, the present study did not include a human-coded benchmark for DSRP element identification. Establishing such ground truth through multi-annotator human coding would enable a direct assessment of construct validity and help distinguish genuine structural signals from model-learned priors in political language. Incorporating a human–model validation layer is therefore an important direction for future work, and would further strengthen the empirical foundations of O-Theory as a general structural operator. A second methodological issue concerns potential confounding between total organizational load and document length, which we address directly through the normalized density analyses described next.

One potential concern is that total organizational load may correlate with document length. The robustness test using normalized structural density helps address this: once length and period were controlled, the density measure no longer predicted behavioral divergence. Because O-Theory defines organization as the *total* application of structural operators—not structural density—this result is consistent with the theoretical framework. Future work should further explore how organizational magnitude and organizational density jointly contribute to system behavior, including whether density-based measures play a role in other domains.

A related issue concerns the distinction between structural quantity and structural density. Because total organizational load (O_{total}) is computed as a sum of DSRP elements, it is naturally associated with document length. Our regression models explicitly control for log-transformed token count, and the structural term remains a significant predictor of behavioral divergence under those controls, indicating that O_{total} is not merely a reparameterization of length. Exploratory analyses using normalized density measures (elements per 1,000 tokens) did not yield additional explanatory power once length was modeled. For the present purposes, we therefore treat O_{total} as the appropriate extensive measure of organizational “work” performed on information, and leave a fuller exploration of density-based metrics to future studies.

Third, the behavioral measure—KL divergence over bag-of-words distributions—is a coarse proxy for linguistic behavior. KL captures global distributional shifts but does not represent semantic change, syntactic structure, or pragmatic framing. It therefore provides a first-order estimate of behavioral divergence rather than a complete characterization of discourse change. Complementary metrics—such as embedding-based distances, syntactic complexity scores, topic shift analyses, or pragmatic markers—should be explored to yield a richer behavioral profile.

Fourth, DSRP is used as the sole representation of organization. Although DSRP provides a domain-independent and cognitively grounded structural operator, alternative formalisms—such as causal graphs, network topology, conceptual spaces, or dynamical-systems state representations—could also be used to model organizational structure. However, many existing formalisms omit ontological structures that must exist in any system [13,15], and thus may not capture the full range of necessary distinctions, relations, compositions, and perspectives. The present work demonstrates that ΔO is measurable using DSRP; it

does not preclude or adjudicate among alternative structural representations. Future research should examine whether the operator $E=\Delta O$ generalizes across multiple organizational formalisms and whether those formalisms adequately represent the ontological structures that DSRP makes explicit.

Fifth, although initial correlations suggested a negative relationship between structural load and behavioral divergence, the regression analyses conducted for this study resolve this ambiguity. When document length and year are controlled, structural load becomes a *positive, significant* predictor of KL divergence across all models ($p < .001$). This indicates that the earlier negative simple correlation was an artifact of document length and crisis-driven shifts in document format. The operator $E=\Delta O$ asserts structural–behavioral dependency rather than monotonicity, and the regression results confirm that dependency: differences in organization reliably predict differences in behavior even after accounting for contextual factors. Future work should continue modeling contextual variables such as rhetorical purpose and genre, but the present analyses strongly support the robustness of the structural–behavioral relationship.

Finally, the dataset is modest in size and limited to a single institutional domain. While the Congressional Record offers a useful natural experiment, broader validation will require larger, more diverse corpora and applications beyond the linguistic domain. As such, the present analysis should be viewed as an initial empirical demonstration of a structural–behavioral operator rather than a definitive test across domains.

Despite these limitations, the study shows that both organizational structure and behavioral divergence can be measured reliably in real-world data and that their relationship exhibits a stable, interpretable pattern. These findings provide a strong foundation for refining, expanding, and validating a general structural definition of emergence across the systems sciences

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