

Operationalizing the Principle of Dynamical Sensitivity: Response, Coupling, and Cross-Scale Interaction

Author: Martin Kafara
ORCID: 0009-0001-0941-650X

Preprint DOI:
<https://doi.org/10.5281/zenodo.18915677>

Abstract

The first paper introduced the Principle of Dynamical Sensitivity as a conceptual framework suggesting that structures emerging within a shared dynamical physical environment inherit sensitivity to its dynamical properties. The present work aims to operationalize this principle by introducing a simple response-based analytical framework for describing how systems react to the dynamical spectrum of their environment.

In the proposed formulation, the environment is treated as a spectrum of dynamical influences, while the system is characterized by a frequency-dependent response function. Within this framework, dynamical sensitivity is expressed through a spectral sensitivity profile, and the realized response of the system is described as the product of environmental dynamics and system susceptibility.

An integrated criterion is introduced to distinguish weak background influence from dynamically significant interaction. The proposed formalism does not introduce a new physical interaction. Instead, it provides an analytical language intended to compare dynamical sensitivity across physics, chemistry, and biology, and to clarify how resonance, coupling, and synchronization may be understood as particular manifestations of a broader responsiveness to a shared dynamical environment [1-7].

1. Introduction

The Principle of Dynamical Sensitivity, introduced in the preceding paper, proposed that structures emerging within a shared dynamical physical environment inherit sensitivity to its dynamical properties. This principle provided a conceptual framework linking resonance, oscillation, coupling, and synchronization within a broader interpretation of shared environmental responsiveness [1-3, 6, 7].

While the first paper established the conceptual basis of the principle, it did not yet provide an operational language for comparing the dynamical sensitivity of different systems or for distinguishing weak environmental influence from dynamically relevant interaction. The purpose of the present work is to address this gap by introducing a simple response-based analytical framework.

In the proposed formulation, the environment is represented as a spectrum of dynamical influences $e(\omega)$, while the system is characterized by a frequency-dependent response function $\chi(\omega)$. The realized response of the system is described as $R(\omega) = \chi(\omega)e(\omega)$, and the corresponding sensitivity profile is expressed through the magnitude of the response function. This allows the principle introduced previously to be reformulated in a form that is analytically comparable across systems from physics, chemistry, and biology.

A further step is required, however, in order to determine whether a given environmental influence remains merely present in the background or becomes dynamically significant. For this reason, the present work introduces an integrated criterion over a relevant frequency band, allowing the transition from universal sensitivity to effective interaction to be expressed in threshold form.

The aim of this paper is therefore not to propose a new physical force or a complete dynamical theory, but to provide an analytical language for describing environmental response, comparing different classes of systems, and clarifying how resonance, coupling, and synchronization may arise as particular regimes of a more general dynamical sensitivity.

The conceptual structure underlying this operational formulation is illustrated schematically in Fig. 1. The following sections develop the analytical framework, examine its interpretation across physical, chemical, and biological systems, and discuss how cross-scale interaction may be formulated within this response-based perspective.

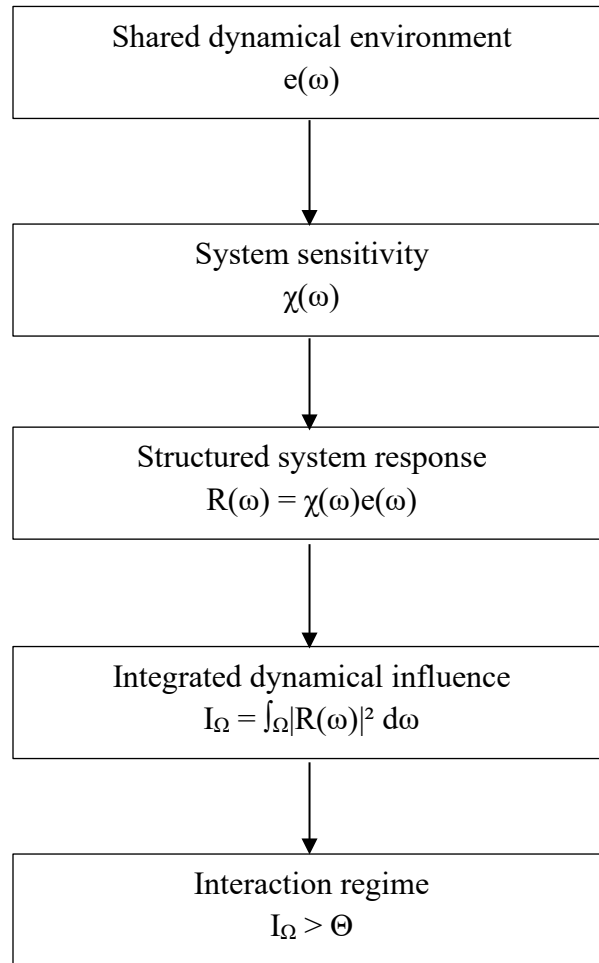


Figure 1. Conceptual framework of dynamical sensitivity.

A system embedded in a shared dynamical environment is exposed to environmental fluctuations described by the spectrum $e(\omega)$. The system's intrinsic response function $\chi(\omega)$ determines how these fluctuations generate a structured response $R(\omega)$. The integrated dynamical influence I_{Ω} measures the overall interaction strength across a frequency band. When this influence exceeds a threshold Θ , dynamically significant coupling may emerge.

2. From Principle to Operational Framework

The Principle of Dynamical Sensitivity proposes that systems emerging within a shared dynamical physical environment inherit sensitivity to its dynamical properties. In order to express this principle in an analytically usable form, it is necessary to introduce a simple representation of both the environment and the system.

2.1. Shared Dynamical Environment as Spectral Input

The shared dynamical environment is represented here as a spectrum of dynamical influences, denoted by $e(\omega)$. This spectrum does not refer to a single physical field only, but more generally to the structured dynamical content of the environment as experienced by a given system. Depending on the context, $e(\omega)$ may correspond to mechanical, electromagnetic, chemical, thermal, or other forms of dynamical excitation [4-7].

In this formulation, the environment is therefore treated not as a static background, but as a frequency-structured source of dynamical input. This representation is intentionally general, allowing the same analytical language to be applied across systems from physics, chemistry, and biology.

2.2. System Sensitivity and Response Function

A system embedded in such an environment is assumed to possess its own frequency-dependent sensitivity, described by a response function $\chi(\omega)$. This function expresses how strongly the system responds to different components of the environmental spectrum. It is not a property of the environment, but an intrinsic dynamical property of the system itself.

The magnitude of this response function may be interpreted as a spectral sensitivity profile $|\chi(\omega)|$.

2.3. Realized Response as Structured Interaction

Once both the environmental spectrum and the response function are defined, the realized response of the system may be expressed in the simple form

$$R(\omega) = \chi(\omega)e(\omega)$$

This expression represents the structured dynamical response of the system to the structured dynamical input of the environment. In this sense, the realized response is not identified with sensitivity itself, but with the actual manifestation of sensitivity under specific environmental conditions.

This distinction is important. The response function $\chi(\omega)$ characterizes the system's potential for responsiveness, whereas $R(\omega)$ describes the actual dynamical interaction realized in the presence of a particular environmental spectrum.

3. Dynamical Sensitivity Spectrum

The response function $\chi(\omega)$ characterizes how a system reacts to different components of the environmental spectrum. In order to distinguish the intrinsic sensitivity of the system from its realized response under specific environmental conditions, we define the dynamical sensitivity spectrum as

$$S(\omega) = |\chi(\omega)|$$

This quantity represents the frequency-dependent sensitivity profile of the system. It identifies those regions of the environmental spectrum to which the system is most responsive, independently of the actual strength of a particular environmental input.

Within this formulation, $S(\omega)$ is treated as an intrinsic property of the system, whereas the realized response $R(\omega)$ depends on the interaction between this intrinsic sensitivity and the actual spectrum of environmental influences.

This distinction is important for the present framework. A system may possess non-zero dynamical sensitivity across a range of frequencies, yet only a subset of these sensitivities may become dynamically relevant under particular environmental conditions.

In order to determine when such sensitivity becomes dynamically significant, it is necessary to introduce an integrated criterion over a relevant frequency band.

4. Integrated Dynamical Influence and Threshold Criterion

The realized response $R(\omega) = \chi(\omega)e(\omega)$ describes how a system reacts to the structured dynamical input of its environment at individual frequencies. However, a non-zero response at isolated frequencies does not by itself imply dynamically significant interaction.

In order to evaluate the overall influence of the environment on the system, we introduce the integrated dynamical influence over a relevant frequency band Ω :

$$I_{\Omega} = \int_{\Omega} |R(\omega)|^2 d\omega$$

This quantity expresses the total effective dynamical influence of the environment on the system within the considered spectral domain. It therefore allows the distinction between weak background responsiveness and dynamically relevant interaction.

A threshold condition may then be introduced in the form

$$I_{\Omega} > \Theta$$

where Θ denotes the minimum level of integrated influence required for the interaction to become dynamically significant. In this way, universal sensitivity is distinguished from effective interaction: systems may remain in principle responsive to environmental dynamics, while only some conditions produce observable or structurally relevant dynamical effects.

The choice of the relevant frequency band Ω and the threshold Θ is not universal, but depends on the class of system under consideration and on the practical level at which interaction is regarded as dynamically relevant. In this sense, Θ should be understood as a functional or empirical threshold of detectability, effectiveness, or structural relevance rather than as a fundamental boundary of sensitivity itself. Likewise, Ω denotes the spectral domain judged to be relevant for the interaction being analyzed.

5. Physics, Chemistry, Biology as Instantiations

The response-based framework proposed in the preceding sections is intended to remain general enough to apply across multiple scientific domains. Although the specific physical realization of environmental dynamics and system response differs from one field to another, the basic structure of the framework remains unchanged: a system is exposed to a spectrum of environmental influences, possesses its own sensitivity profile, and produces a realized response whose integrated effect may or may not become dynamically significant.

5.1 Physics

In physics, the proposed framework is naturally compatible with oscillatory and resonant systems. Mechanical oscillators, electromagnetic resonators, coupled wave systems, and other frequency-selective structures may all be described as systems whose response depends on the relation between environmental excitation and intrinsic dynamical modes. In such systems, the response function may often be interpreted directly in the language of susceptibility, resonance, and spectral selectivity [1, 4, 5].

Within this domain, the distinction between intrinsic sensitivity and realized response is especially transparent: a system may possess a resonance structure even when the surrounding environment does not excite it strongly enough to produce a significant dynamical effect.

5.2 Chemistry

In chemistry, the same logic can be applied to oscillatory reactions and reaction–diffusion systems. Chemical oscillators exhibit intrinsic dynamical modes that may respond selectively to fluctuations in concentration, energy input, or other environmental parameters. Here again, a distinction may be made between the latent sensitivity of a chemical system and the realized response that emerges only under sufficiently structured or sufficiently intense environmental conditions [2, 6].

The response-based framework therefore allows chemical systems to be interpreted not merely in terms of local kinetics, but also in terms of their broader dynamical receptivity to structured environmental influence [2, 6, 7].

5.3 Biology

In biology, dynamical sensitivity appears in a wide variety of systems, including neural oscillations, circadian rhythms, physiological regulation, and collective biological behavior. Biological systems are often strongly environment-dependent, yet their responses remain selective rather than uniform. The present framework provides a way to

describe this selectivity in terms of sensitivity profiles and realized response to structured environmental dynamics [1-3].

This perspective is particularly relevant in cases where biological systems display coordinated behavior only when environmental forcing, internal sensitivity, and coupling conditions jointly exceed a relevant threshold. In such cases, the proposed framework may help distinguish general environmental influence from effective dynamical organization [2, 3].

6. Resonance, Coupling, Synchronization as Special Cases

Resonance, dynamical coupling, and synchronization may be interpreted as specific regimes within a unified response-based formulation. Each of these phenomena arises from the structure of the response function and from its interaction with the spectrum of the environment [1].

Within the present framework, these phenomena are not treated as fundamentally separate classes of behavior, but as distinct manifestations of the same general principle: a system with non-zero dynamical sensitivity may exhibit qualitatively different responses depending on the relation between its intrinsic sensitivity profile and the structured dynamical input of the environment.

6.1 Resonance

Resonance corresponds to the regime in which the realized response of the system reaches a maximum in the vicinity of one of its characteristic frequencies. In the present framework, this may be expressed as

$$|R(\omega_0)| = \max_{\omega \in \Omega} |R(\omega)|$$

where ω_0 denotes a characteristic frequency at which the overlap between environmental excitation and system sensitivity is strongest. Resonance therefore represents a frequency-selective amplification of the realized response.

In this sense, resonance is not introduced as an independent mechanism, but appears naturally whenever the environmental spectrum contains components that coincide with highly sensitive regions of the system's response profile [1, 7].

6.2 Dynamical Coupling

Dynamical coupling may be understood as the regime in which the response of a system is no longer determined solely by its intrinsic dynamics, but is significantly modulated by environmental or inter-system influences. In this case, the environment does not merely provide background fluctuations; it participates in shaping the realized dynamical behavior of the system [2, 6, 7].

Within the proposed framework, coupling becomes dynamically relevant when the integrated influence of environmental excitation exceeds the threshold required for effective interaction. In this way, coupling is interpreted not as an all-or-nothing relation, but as a regime emerging from sufficiently strong and sufficiently structured response.

6.3 Synchronization

Synchronization represents the regime in which two or more systems exhibit coordinated dynamical behavior as a result of compatible sensitivity profiles, sufficient coupling, and sustained environmental or mutual forcing. In the present framework, synchronization is not regarded as a separate principle, but as a higher-order manifestation of response compatibility between interacting systems [2, 3].

This interpretation is especially important because it places synchronization within the same analytical language as resonance and coupling. Rather than standing apart as a special phenomenon, synchronization appears here as a particular coordinated regime of realized response within a shared dynamical environment [2, 3, 7].

6.4 Transition to Cross-Scale Interpretation

The interpretation of resonance, coupling, and synchronization as special regimes of a unified response framework prepares the ground for a broader question: whether systems operating at different physical scales may also be described within the same response-based language. This question motivates the following discussion of cross-scale interaction.

7. Toward Cross-Scale Interaction

The preceding sections introduced a response-based framework in which environmental dynamics, system sensitivity, realized response, and threshold-dependent interaction can be expressed in a unified analytical language. Within this framework, resonance, dynamical coupling, and synchronization were interpreted as particular regimes of realized response. The next question is whether the same language may be extended to interactions between systems operating at different physical scales.

Within the present formulation, cross-scale interaction does not imply a direct or universal coupling between all systems. Rather, it denotes the possibility that systems belonging to different characteristic scales may nevertheless exhibit dynamically relevant response to overlapping or mutually compatible regions of environmental dynamics [4-7].

To express this possibility, we introduce an integrated cross-scale influence over a frequency band relevant for inter-scale compatibility:

$$I_{\Omega_{\text{cross}}} = \int_{\Omega_{\text{cross}}} |R(\omega)|^2 d\omega$$

Here, Ω_{cross} denotes the spectral region in which environmental forcing and system response remain sufficiently compatible for interaction across scales to become plausible. Cross-scale interaction is then treated as dynamically relevant when

$$I_{\Omega_{\text{cross}}} > \Theta_{\text{cross}}$$

This formulation preserves the main logic of the present work. Universal dynamical sensitivity does not imply that all systems interact equally or continuously. Instead, it suggests that systems embedded within the same dynamical environment may under certain conditions become effectively responsive to structures of environmental dynamics that bridge different physical scales.

In this sense, cross-scale interaction is not introduced as a new category of force, but as a special extension of the same response-based framework already used to describe resonance, coupling, and synchronization. It therefore remains consistent with the general

aim of the paper: to provide an analytical language for interpreting dynamical sensitivity without introducing new physical interactions.

Although the present treatment remains deliberately general, it establishes a formal bridge between local dynamical responsiveness and the broader possibility of interaction across physical scales. This bridge will be important for the final discussion of the scope and limitations of the proposed framework.

It should be emphasized that sub-threshold influence does not imply the absence of dynamical sensitivity. A system may remain responsive in principle to environmental dynamics even when the resulting response does not exceed the threshold required for observable resonance, effective coupling, or synchronization.

In this sense, the threshold distinguishes not between sensitivity and non-sensitivity, but between latent responsiveness and dynamically effective response.

8. Limitations

The response-based framework proposed in this work is intended as an analytical language for describing dynamical sensitivity and its possible manifestations across different systems and scales. It should therefore be understood as a conceptual and formal framework, rather than as a complete predictive theory of interaction.

Several limitations follow directly from this status. First, the framework does not specify a unique physical mechanism for every possible form of interaction. Instead, it describes how environmental dynamics, system sensitivity, and realized response may be related within a unified formulation.

Second, the introduction of threshold criteria such as $I_{\Omega} > \Theta$ or $I_{\Omega_{\text{cross}}} > \Theta_{\text{cross}}$ should not be interpreted as implying a threshold for dynamical sensitivity itself. These criteria refer only to the conditions under which sensitivity becomes dynamically effective, observable, or structurally relevant.

A system may therefore remain dynamically sensitive in principle even when its realized response remains below the threshold required for resonance, effective coupling, synchronization, or cross-scale interaction. In this sense, the threshold distinguishes latent responsiveness from effective interaction, not sensitivity from non-sensitivity.

Third, the proposed formulation remains intentionally general. It does not yet provide a full model for every specific physical, chemical, or biological system, nor does it claim that all systems are equally capable of entering regimes of resonance or synchronization. The framework instead identifies a common analytical structure within which such differences may be described.

Finally, the present work does not address information transfer, signaling, or communication as explicit components of the framework. These questions may arise naturally from the present formulation, but they require a further conceptual and formal step beyond the scope of this paper.

These limitations do not weaken the Principle of Dynamical Sensitivity. Rather, they clarify the level at which the present paper operates: it establishes an operational framework for describing dynamical responsiveness, while leaving more specific mechanisms and higher-order interpretations for subsequent work.

9. Discussion

The present work extends the conceptual proposal formulated in the preceding paper by introducing an operational framework for describing dynamical sensitivity in analytically comparable terms. The main contribution of this paper is not the introduction of a new interaction, but the formulation of a common response-based language through which environmental dynamics, system sensitivity, realized response, and threshold-dependent interaction may be related within a single structure.

Within this perspective, resonance, dynamical coupling, and synchronization no longer appear as isolated phenomena belonging to separate explanatory domains. Instead, they may be interpreted as distinct regimes of realized response emerging from the relation between the spectrum of environmental excitation and the intrinsic sensitivity profile of the system [1-3, 7].

This point is especially important for the interdisciplinary scope of the framework. Although the physical realization of the variables differs across physics, chemistry, and biology, the analytical structure remains comparable. Such comparability is the principal advantage of the proposed formulation: it does not erase disciplinary differences, but provides a shared language for describing them.

At the same time, the framework preserves an essential distinction already implied by the original principle: dynamical sensitivity is treated as more general than observable interaction. A system may remain sensitive in principle to the dynamical structure of its environment even when its realized response remains below the threshold required for resonance, effective coupling, synchronization, or cross-scale interaction.

This distinction strengthens rather than weakens the framework. It allows the proposed theory to remain compatible with the claim of universal sensitivity while avoiding the trivial conclusion that all systems must always interact in an effective or observable manner.

The framework remains intentionally limited in scope. It does not yet provide a full predictive model for all classes of systems, nor does it address information transfer or communication as explicit categories. However, by distinguishing sensitivity, realized response, integrated influence, and threshold-dependent interaction, it establishes a formal basis upon which such questions may later be approached more rigorously.

In this sense, the present paper should be understood as an intermediate step between the conceptual formulation of the principle and its possible future extensions. It does not close the hypothesis, but gives it a more precise analytical form.

A further question naturally follows from the present framework: whether sufficiently structured realized response may, under some conditions, support not only dynamical coordination but also the propagation of informationally relevant patterns. The present work does not address this question explicitly. However, the distinction introduced here between sensitivity, realized response, and effective interaction may provide a suitable formal basis for such an extension in future work.

10. Conclusion

This work operationalized the Principle of Dynamical Sensitivity by introducing a simple response-based analytical framework for describing how systems embedded within a shared dynamical physical environment react to structured environmental influences. Within this framework, the environment is represented as a spectrum of dynamical excitation, the system by a frequency-dependent response function, and the realized response as the interaction between both.

The proposed formulation made it possible to distinguish intrinsic dynamical sensitivity from realized response and to separate latent responsiveness from dynamically effective interaction through threshold-based criteria. In this way, resonance, dynamical coupling, synchronization, and cross-scale interaction could be interpreted as particular regimes within a unified response-based language rather than as isolated phenomena requiring separate explanatory principles.

The framework does not introduce a new physical interaction and does not yet constitute a complete predictive theory. Its contribution lies in providing an analytically comparable structure through which dynamical sensitivity may be described across physics, chemistry, and biology while preserving the original claim that sensitivity is more general than observable interaction.

The present paper should therefore be understood as a formal extension of the conceptual principle introduced previously. It does not close the hypothesis, but gives it a more precise operational form and establishes a basis for future work on higher-order consequences of structured dynamical response.

11. References

- [1] Strogatz, S. H. (1994). *Nonlinear Dynamics and Chaos*. Westview Press.
- [2] Kuramoto, Y. (1984). *Chemical Oscillations, Waves and Turbulence*. Springer.
- [3] Strogatz, S. H. (2003). *Sync: The Emerging Science of Spontaneous Order*. Hyperion.
- [4] Weinberg, S. (2008). *Cosmology*. Oxford University Press.
- [5] Carroll, S. (2004). *Spacetime and Geometry*. Addison-Wesley.
- [6] Prigogine, I., & Stengers, I. (1984). *Order out of Chaos*. Bantam.
- [7] Haken, H. (1977). *Synergetics*. Springer.

Appendix A.

Technical Note on Normalization and Threshold Choice

The response-based formulation introduced in the main text is intended primarily as an analytical framework rather than as a fully system-specific spectral theory. Accordingly, the quantities $e(\omega)$, $\chi(\omega)$, and $R(\omega)$ are treated in a generic spectral sense.

The precise dimensional interpretation of the integrated quantities I_Ω and $I_{\Omega_{\text{cross}}}$ depends on the adopted Fourier convention, the physical units of the environmental excitation and response function, and, where appropriate, on additional weighting factors such as state density or spectral weighting.

In the present paper, these quantities are therefore interpreted primarily as integrated measures of effective dynamical influence rather than as universally defined energetic observables. Their role is to express the extent to which structured environmental excitation overlaps with the response profile of a system in a dynamically relevant way.

The choice of the relevant frequency band Ω and the threshold Θ is not universal, but depends on the class of system under consideration and on the practical level at which interaction is regarded as dynamically relevant. In this sense, Θ should be understood as a functional or empirical threshold of detectability, effectiveness, or structural relevance rather than as a fundamental boundary of sensitivity itself.

The same consideration applies to Ω_{cross} and Θ_{cross} , which are introduced for the special case of cross-scale interaction. These quantities indicate the domain and threshold under which cross-scale response becomes dynamically effective, not the existence or non-existence of sensitivity itself.

Appendix B.

Illustrative Example of Spectral Overlap and Integrated Influence

To illustrate the logic of the proposed framework, consider a simple model response function of Lorentzian type:

$$\chi(\omega) = \frac{1}{m(\omega_0^2 - \omega^2) + i\gamma\omega}$$

where m is an effective scaling parameter, ω_0 is the characteristic frequency of the system, and γ determines the width of the response peak.

The corresponding dynamical sensitivity spectrum is

$$S(\omega) = |\chi(\omega)|$$

which exhibits the familiar Lorentzian peak around $\omega \approx \omega_0$. This means that the system is most sensitive to environmental excitation in the vicinity of its characteristic frequency.

Let the environmental excitation $e(\omega)$ be represented by a structured spectrum concentrated either near or far from ω_0 . The realized response is then given by

$$R(\omega) = \chi(\omega)e(\omega)$$

If the dominant components of $e(\omega)$ overlap strongly with the Lorentzian sensitivity peak, the magnitude of $R(\omega)$ increases in the corresponding region and the integrated influence

$$I_\Omega = \int_\Omega |R(\omega)|^2 d\omega$$

also increases. By contrast, if the environmental spectrum is concentrated outside the sensitive region of the system, the overlap is weak and the resulting integrated influence remains small.

This simple example illustrates the central logic of the framework: the magnitude of effective interaction is governed not by the presence of environmental excitation alone, nor by intrinsic sensitivity alone, but by their structured spectral overlap.

In this sense, the model does not aim to provide a full physical description of all systems, but to demonstrate in a transparent way how the formal quantities introduced in the main text may be interpreted “on the fingers” without leaving the conceptual scope of the paper.

For sufficiently strong overlap, the integrated influence may exceed the threshold Θ , leading to dynamically effective interaction. For weak overlap, the system may remain sensitive in principle while the realized response remains below the level required for observable effect.