M4 – The Canonical Exchange Sector
on a Scalar–Conformal Lorentzian Manifold

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Notation and Conventions

- $\mathcal{M}$ denotes the spacetime manifold.
- η denotes the reference Lorentzian metric (typically Minkowski in a global chart).
- g denotes the physical metric.
- The scalar field $\Lambda : \mathcal{M} \to \mathbb{R}_{>0}$ is the NUVO modulation field.
- The physical metric is scalar–conformal:

$$g_{\mu\nu} = \Lambda^2 \, \eta_{\mu\nu}.$$

- $\Lambda_0 > 0$ denotes the baseline scalar availability level supported by the intrinsic delivery structure of the underlying field. In the absence of localized structural occupation the scalar field satisfies $\Lambda(x) = \Lambda_0$.
- The dimensionless scalar diagnostic is

$$\mathcal{A}(x) := \frac{\Lambda(x)}{\Lambda_0}.$$

- The scalar field represents the *locally available structural capacity* of the underlying delivery field. Localized structures may reduce this availability through occupation or transport, but the intrinsic delivery baseline Λ_0 remains fixed.
- Greek indices $\mu, \nu, \ldots$ range over spacetime coordinates $0, 1, 2, 3$.
- We use the Einstein summation convention unless explicitly stated otherwise.

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[*] Bibliography is provisional. Cross-references to companion NUVO-series papers (M-, SR-, Q-, QB-, QM-series) will be updated with Zenodo DOIs in subsequent versions.

Notation convention. We reserve distinct symbols for fundamental fields and derived quantities. The scalar field Λ represents structural availability, while $\mathcal{A}$ denotes a derived normalized response field. These should not be conflated.

Remark 0.1. *Unless otherwise stated, the background signature is* $(-,+,+,+)$.

Abstract

This paper develops the exchange sector of the scalar–conformal NUVO framework. In contrast to the gravitational sector, which arises from persistent localized depletion structures, the exchange sector is associated with structural coupling between systems through open-loop configurations.

We introduce open-loop exchange structures, define the associated exchange current as a diagnostic quantity, and study the formation and propagation of dynamic loops arising from exchange imbalance. These propagating structures follow null geodesics of the scalar–conformal metric and constitute the radiative sector of the framework.

The purpose of this paper is not to introduce a transported substance or a primitive interaction law, but to identify the structural exchange mechanisms already permitted by the canonical scalar dynamics [1, 2]. This establishes the exchange sector as a distinct structural component of the scalar–conformal NUVO program and prepares the later weak-limit field formulation.

1 Introduction

The previous papers of this series established the scalar–conformal framework of the NUVO program and derived the canonical scalar field equation governing the modulation field Λ.

In M3 [2] it was shown that localized structural depletion generates scalar modulation fields whose conformal metric governs the geodesic motion of test bodies. This sector of the canonical dynamics corresponds to the gravitational behavior of the theory.

The present paper studies a different class of structures supported by the scalar–conformal manifold. These structures do not correspond to persistent depletion structures but instead arise from structural coupling between localized source and sink regions.

Within the NUVO framework such exchange processes occur through *open structural loops.* When these loops evolve dynamically they produce propagating structural configurations of the scalar field. These propagating disturbances constitute the radiative sector of the theory.

The objective of this paper is therefore to derive the exchange sector of the NUVO framework from the canonical scalar dynamics. The analysis proceeds by identifying the source–sink exchange structure permitted by the scalar field equation and studying the resulting dynamic loop configurations.

Scope of the present development. The present paper develops the exchange sector at the level of structural and geometric admissibility only. In particular, we introduce the open-loop exchange configurations, exchange current, and dynamic-loop behavior required to identify the exchange sector as a distinct component of the scalar–conformal framework. A full weak-limit continuum field formulation, including gauge potential structure, field-strength variables, and corresponding action-based equations, is deferred to later work.

All results presented here follow from the scalar dynamics established in M1 [1] together with the structural capacity interpretation introduced in M2 [3] and the geometric framework developed in M3 [2].

2 Open-Loop Exchange Structures

In contrast to the persistent structures discussed in the previous paper (M3), exchange processes correspond to directed structural interaction between localized systems.

These processes occur through *open-loop structures.* An open loop connects a capacity source and a capacity sink and provides a structural pathway through which interaction between systems is mediated across the scalar–conformal manifold.

2.1 Source and sink roles

A capacity source is a system whose internal structure emits structural capacity into the surrounding exchange network. A capacity sink is a system capable of absorbing that capacity.

The defining feature of an open-loop exchange process is therefore the directed coupling

$$\text{source} \longrightarrow \text{sink}.$$

In equilibrium configurations the emission from the source is exactly balanced by the absorption at the sink.

2.2 Ground-state exchange balance

When the exchange between a source and sink is balanced, all emitted capacity is absorbed and no residual capacity is deposited into the surrounding field.

Such configurations correspond to exchange ground states. In these states the surrounding manifold does not experience any net imbalance arising from the exchange process.

A familiar example is the stable bound configuration in which the emission from a positive source and the absorption of a negative sink are precisely matched.

2.3 Exchange sector discipline

Exchange processes redistribute structural capacity but do not themselves generate the scalar sourcing responsible for gravitational behavior.

The scalar field Λ therefore continues to obey the source structure established in M3, while the exchange sector introduces additional transport processes that operate on the same scalar–conformal manifold.

This separation ensures that the gravitational sector and the exchange sector remain conceptually distinct components of the NUVO framework.

2.4 Exchange current and capacity transport

Open-loop exchange processes may be described by a transport current that serves as a diagnostic representation of exchange structure across the manifold.

Let

$$J^{\mu}_{\text{ex}}$$

denote the exchange current four-vector. This current represents the directed exchange structure between source and sink systems along open-loop exchange pathways.

In regions where exchange structure is balanced, the exchange current satisfies the continuity relation

$$\nabla_\mu^{(g)} J^\mu_{\mathrm{ex}} = 0$$

in regions where no net emission or absorption occurs.

2.5 Radiation from exchange imbalance

Radiative processes arise when the exchange between a capacity source and a capacity sink fails to remain balanced.

In the ground-state configuration discussed above, the structural capacity emitted by the source is completely absorbed by the sink. The exchange current therefore satisfies

$$\nabla_\mu^{(g)} J^\mu_{\mathrm{ex}} = 0,$$

and no residual transport propagates through the surrounding region.

However, when a system is driven away from its exchange ground state, the emission and absorption rates may no longer match. In this case, the exchange current develops a nonzero divergence localized at the interaction region,

$$\nabla_\mu J^\mu_{\mathrm{ex}} = S_{\mathrm{ex}} \neq 0,$$

indicating local exchange imbalance.

The resulting imbalance corresponds to excess structural capacity that cannot be locally absorbed by the participating systems.

Such propagating capacity transport constitutes the radiative sector from the exchange region.

Radiation in the NUVO framework therefore arises not from curvature effects of the scalar–conformal geometry, but from dynamical imbalance in the open-loop exchange network connecting sources and sinks.

When the system subsequently relaxes back to an exchange-balanced configuration, the radiative transport ceases and the surrounding exchange current again satisfies the local conservation condition.

2.6 Photon as encapsulated capacity

The propagating transport of excess structural capacity generated by an exchange imbalance may organize into localized packets that travel through the scalar–conformal manifold.

Such packets constitute the radiative carriers of the exchange sector and will be referred to as *photons* within the NUVO framework.

2.6.1 Anchorless propagation

Unlike the persistent structures responsible for scalar sourcing in the gravitational sector, photons possess no structural anchor within the manifold.

Because they lack an anchor, photons do not locally modify the scalar availability field and therefore do not contribute to the intrinsic scalar source density ρ_Λ introduced in M3. Photons therefore act only as propagating structural configuration and do not generate scalar sourcing.

Instead, photons represent propagating dynamic-loop configurations moving through the background geometry.

2.6.2 Null-geodesic transport

The motion of these encapsulated capacity packets is governed purely by the geometry of the scalar–conformal metric

$$g_{\mu\nu} = \Lambda^2 \eta_{\mu\nu}.$$

In the absence of interactions, photon trajectories therefore follow null geodesics of the physical metric:

$$g_{\mu\nu}\, \dot{x}^\mu \dot{x}^\nu = 0.$$

Thus photons propagate through the manifold as geometry-guided propagation of dynamic-loop structure.

2.6.3 Interaction with exchange structures

Because photons represent transported capacity rather than persistent anchored structures, their interactions occur only with systems that participate in open-loop exchange.

In particular, photons may be absorbed or emitted by exchange sources and sinks, thereby modifying the local exchange balance described in the previous sections.

Photon–photon interactions are not considered within the present framework. The dynamics of photon interaction therefore arise entirely through coupling with exchange structures.

2.7 Coherence condition for exchange interaction

The interaction between photons and localized systems participating in open-loop exchange is governed by coherence conditions arising from the structure of anchored systems.

2.7.1 Global coherence of photons

Because photons possess no structural anchor within the manifold, they do not carry local kinematic modulation associated with anchored motion. Their propagation is therefore determined entirely by the scalar–conformal geometry, and they remain globally coherent with respect to the surrounding capacity field.

2.7.2 Local coherence of anchored systems

In contrast, systems possessing structural anchors (such as electrons or other persistent structures) experience local kinematic effects due to their motion through the manifold.

These effects may temporarily disrupt the phase alignment between the system and the surrounding capacity field, producing intervals of *local decoherence* during which exchange interaction with a photon cannot occur.

2.7.3 Interaction windows

Photon interaction therefore requires intervals in which the anchored system returns to a coherent configuration with respect to the surrounding field.

When such coherence windows occur, a photon whose structural capacity matches an admissible exchange configuration of the system may be absorbed or emitted through the open-loop exchange process.

2.7.4 Admissible exchange configurations

The admissible configurations of an anchored system are determined by its internal structural coherence conditions. These conditions restrict the exchange processes that may occur, leading naturally to discrete exchange outcomes.

The detailed structure of these coherence constraints will be developed in the following paper (M5) [4], where coherent cyclic exchange processes are shown to produce quantized structural states.

2.8 Source and sink coupling

At localized systems participating in exchange processes, the divergence of the exchange current represents the local emission or absorption of structural capacity.

Thus one may write

$$\nabla_\mu J^\mu_{\mathrm{ex}} = S_{\mathrm{ex}},$$

where S_{ex} represents the net exchange rate associated with a localized source or sink.

Positive values of S_{ex} correspond to emission of structural capacity, while negative values correspond to absorption.

2.9 Ground-state exchange

In a balanced source–sink configuration the emission from the source is exactly matched by the absorption at the sink. In this situation

$$\nabla^{(g)}_\mu J^\mu_{\mathrm{ex}} = 0$$

throughout the surrounding region, and no residual exchange imbalance propagates through the field.

Such balanced configurations correspond to exchange ground states, where the open-loop exchange redistributes capacity between systems without producing radiative transport.

3 Dynamic Loop Formation

The exchange configurations introduced in the previous section describe exchange interaction between localized source and sink structures. In ground-state configurations the exchange between the two structures is internally balanced, and no residual exchange signal is present in the surrounding field.

However, the scalar dynamics also permit situations in which excess structural capacity must be redistributed through the manifold. Such situations arise when an exchange system temporarily contains more capacity than can be supported by its admissible ground-state configuration.

3.1 Excited exchange configurations

Excited configurations occur when additional structural capacity is deposited into an exchange system. Within the NUVO framework this occurs through the absorption of a propagating capacity packet.

The additional capacity temporarily alters the internal configuration of the exchange system, producing an excited structural state. Because the excited configuration is not generally admissible as a persistent structure, the system must subsequently relax toward its ground-state configuration.

3.2 Structural consistency and excess transport

The relaxation process must preserve global structural capacity. Consequently, the exchange imbalance contained in the excited configuration cannot disappear but must instead be reorganized through the manifold away from the system.

The scalar dynamics admit localized transport solutions in which the exchange imbalance becomes encapsulated into a compact propagating structure. These structures represent closed dynamic exchange loops that move across the scalar–conformal manifold.

3.3 Dynamic loops

We refer to these propagating encapsulated capacity structures as *dynamic loops*. Dynamic loops differ from the structural loops associated with persistent source and sink configurations in several important respects:

- Dynamic loops contain encapsulated exchange imbalance rather than persistent capacity depletion.
- Dynamic loops possess no anchor structure and therefore do not act as long-lived capacity sinks.
- Dynamic loops propagate through the scalar field geometry, transporting capacity between distant regions of the manifold.

Because dynamic loops contain no anchor, their motion is governed entirely by the scalar–conformal geometry introduced in M1 and M3 [1, 2].

These structures constitute the radiative sector of the NUVO framework.

4 Propagation of Dynamic Loops

Dynamic loops formed through the encapsulation of excess structural capacity propagate through the scalar–conformal manifold as propagating dynamic-loop structures. Because these loops possess no anchor structure, their motion is governed solely by the underlying geometry introduced in M1 [1].

4.1 Unanchored transport

Persistent structures such as closed loops modify the scalar field through continuous structural capacity consumption. This produces localized scalar modulation and the associated conformal deformation of the background geometry.

Dynamic loops differ fundamentally from such anchored structures. Because they contain encapsulated exchange imbalance rather than a persistent depletion mechanism, they do not act as long–lived sources or sinks of structural capacity. Consequently dynamic loops do not produce independent scalar modulation of the manifold and therefore do not modify the local scalar availability field during propagation.

Their motion therefore follows the geometry already determined by the ambient scalar field.

4.2 Null propagation

Let $x^\mu(\lambda)$ denote the worldline of a propagating dynamic loop. Because the loop possesses no anchor and therefore no intrinsic rest frame, its propagation occurs along null directions of the physical metric.

Thus the trajectory satisfies

$$g_{\mu\nu}\frac{dx^\mu}{d\lambda}\frac{dx^\nu}{d\lambda} = 0. \tag{1}$$

The propagation of dynamic loops therefore follows null geodesics of the scalar–conformal metric.

4.3 Geodesic transport

Let $\Gamma^\mu_{\alpha\beta}$ denote the Levi–Civita connection of the physical metric g. The motion of a dynamic loop satisfies the geodesic equation

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0. \tag{2}$$

Because the trajectory is null, this geodesic describes propagation at the causal speed determined by the scalar–conformal geometry.

4.4 Global coherence

Dynamic loops possess no anchor and therefore remain coherent with the global scalar field configuration during their propagation. Unlike anchored structures, which may experience local decoherence due to motion or interaction with other structures, dynamic loops follow the geometry without generating additional local scalar adjustments.

Consequently dynamic loops propagate as globally coherent transport structures that carry encapsulated structural configuration through the manifold.

4.5 Radiative transport sector

The propagation of dynamic loops constitutes the radiative transport sector of the NUVO framework. These structures carry exchange imbalance between spatially separated regions and provide the mechanism through which exchange systems redistribute structural capacity.

5 Interaction with Exchange Structures

Dynamic loops propagate freely along null geodesics of the scalar–conformal geometry until they encounter exchange structures capable of interacting with the transported capacity packet. Interaction between a dynamic loop and an anchored system occurs only through open-loop exchange channels.

5.1 Restriction to open-loop coupling

Closed-loop structures correspond to persistent capacity depletion and therefore define anchored configurations. These structures alone cannot directly absorb propagating dynamic loops. Interaction requires the presence of an open-loop exchange channel capable of mediating structural exchange interaction between the propagating loop and the anchored system.

Consequently dynamic loops interact only with systems possessing active exchange coupling.

5.2 Coherence condition

Although dynamic loops remain globally coherent with the scalar field, anchored exchange structures need not maintain continuous coherence with the global manifold. Motion and local scalar modulation may temporarily decohere the exchange structure relative to the global field.

To formalize this requirement, let

$$\mathcal{C}(x) \in \{0, 1\}$$

denote the local coherence indicator of the anchored exchange structure, where

$$\mathcal{C}(x) = 1$$

means that the structure is coherent with the global scalar field at the interaction point, and

$$\mathcal{C}(x) = 0$$

means that it is locally decoherent.

Interaction between a dynamic loop and an exchange structure is permitted only when

$$\mathcal{C}(x) = 1. \tag{3}$$

When the anchored structure is locally decoherent, the propagating dynamic loop cannot couple to the exchange channel and continues its geodesic propagation.

This coherence requirement acts as a natural interaction gate for the radiative sector.

5.3 Admissible excitation configurations

Even when coherence is satisfied, interaction requires that the exchange structure support an admissible excited configuration capable of storing the incoming structural capacity.

Let $\mathcal{S}$ denote the set of admissible exchange configurations of the anchored system, and let ΔC_γ denote the encapsulated exchange quantity carried by the incoming dynamic loop. Absorption is permitted only if the incoming capacity matches an admissible structural transition. Formally, this requires

$$\Delta C_\gamma \in \Delta\mathcal{S}, \tag{4}$$

where $\Delta\mathcal{S}$ denotes the set of admissible exchange quantity increments between configurations in $\mathcal{S}$.

Thus absorption requires both local coherence and admissible structural matching.

5.4 Absorption and excitation

When both the coherence condition (3) and the admissible transition condition (4) are satisfied, the dynamic loop can couple to the open-loop exchange channel. The encapsulated capacity is then transferred into the anchored system, producing an excited exchange configuration.

This excitation temporarily stores the additional structural capacity within the exchange structure. Structural consistency at absorption may be written schematically as

$$\Delta C_{\text{system}} + \Delta C_\gamma = 0, \tag{5}$$

where ΔC_{system} denotes the change in exchange quantity of the anchored configuration.

5.5 Relaxation and emission

Excited configurations are generally not persistent. As the system relaxes toward its ground-state exchange configuration, conservation of structural capacity requires the exchange imbalance to be reorganized through the manifold from the system.

The scalar dynamics therefore permit the exchange imbalance to be re-encapsulated into a propagating dynamic loop. This process produces the emission of a new radiative capacity packet. The corresponding exchange balance may again be written schematically as

$$\Delta C_{\mathrm{system}} + \Delta C_{\gamma} = 0, \tag{6}$$

with the sign of ΔC_{γ} interpreted relative to the emitted loop.

Emission and absorption thus arise as complementary processes within the exchange sector of the scalar–conformal dynamics.

6 Structural Summary of the Exchange Sector

The previous sections established the structure and dynamics of the exchange sector supported by the scalar–conformal manifold. Together with the gravitational sector derived in M3, the framework now contains two distinct classes of structural behavior arising from the canonical scalar dynamics.

6.1 Structural loop types

The NUVO framework distinguishes three classes of loop structures that arise within the scalar–conformal manifold:

- **Closed loops.** Closed loops correspond to persistent structural configurations that continuously draw structural capacity from the surrounding manifold. These structures act as long-lived capacity sinks and therefore produce localized scalar modulation of the conformal metric. Closed loops form the anchored structures associated with the gravitational sector developed in M3.

- **Open loops.** Open loops represent exchange channels through which structural capacity may be transferred between localized source and sink regions. These loops mediate the exchange sector and enable anchored structures to interact through exchange interaction while maintaining global conservation.

- **Dynamic loops.** Dynamic loops are propagating structures containing encapsulated excess capacity. Unlike closed loops they possess no anchor and therefore do not generate persistent scalar modulation. Instead they propagate along null geodesics of the scalar–conformal geometry and transport capacity between spatially separated exchange structures.

6.2 Sectoral organization

With the introduction of these loop classes, the canonical scalar dynamics can now be viewed as supporting two primary sectors:

- The *gravitational sector*, in which closed-loop structures produce scalar modulation fields that determine the conformal geometry governing geodesic motion.

- The *exchange sector*, in which open-loop coupling and dynamic-loop transport enable the reconfiguration of structural availability between anchored systems.

These sectors arise from the same canonical scalar equation introduced in M1 but correspond to different structural realizations of the underlying capacity dynamics.

6.3 Ground-state exchange

A pair of exchange-coupled structures is said to be in its ground-state configuration when the structural capacity emitted by the source structure is fully captured by the corresponding sink structure through their open-loop exchange channel. In this configuration the surrounding scalar field experiences no residual exchange signal from the pair.

Ground-state exchange therefore produces no radiative dynamic loops.

6.4 Excited exchange configurations

Excited configurations arise when additional structural capacity is introduced into an exchange system through the absorption of a dynamic loop. The resulting configuration temporarily stores exchange imbalance relative to the admissible ground-state exchange configuration.

As the system relaxes back toward its ground state, conservation of structural capacity requires the excess to be reorganized through the manifold. This transport occurs through the formation of new dynamic loops, producing radiative emission.

6.5 Transition toward quantization

The interaction conditions introduced in Section 5 show that exchange structures can absorb dynamic loops only when both coherence and admissibility constraints are satisfied. These admissibility requirements restrict the allowed structural transitions between exchange configurations.

Consequently the scalar–conformal framework naturally introduces a discrete set of admissible structural states for exchange systems.

The geometric origin and mathematical structure of these discrete states will be examined in the next paper of this series [4], where the coherence constraints governing admissible exchange configurations are shown to lead to a holonomic quantization structure on the scalar–conformal manifold.

References

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