

Appendix C

Operational Status, Effective Fields, and the Non-Necessity of Microscopic Constituents

Questions are sometimes raised about the possible “microscopic constitution” of the propagation medium underlying the response fields χ and ψ , informally phrased as: “what are the atoms of the medium?”.

Within the present framework this question is not physically well posed. The reason is operational and follows directly from the structure of measurement and from standard effective field theory practice.

C.1 Measurement as Local Interaction

All experimental observations reduce to localized interaction events between the system and the apparatus, involving exchange of energy and momentum. Detectors register ionizations, tunneling currents, scattering products, or energy deposits. No experiment accesses “constituents” directly.

Formally, observables are encoded in response functions and correlation functions, such as cross sections, spectra, or expectation values of the form

$$\langle \mathcal{O}(x_1)\mathcal{O}(x_2)\dots \rangle, \quad (1)$$

which depend exclusively on the dynamical response of the theory.

Thus experimental access is mediated entirely by interaction events and their correlations. What is measured is the response of the system, not a microscopic substrate.

C.2 Reconstruction as an Inverse Problem

Inferring a dynamical structure from local probes constitutes an inverse problem: one reconstructs an effective description from measured response data. It is well known that inverse problems are generically underdetermined: distinct microscopic realizations may lead to identical response functions at a fixed range of scales.

This situation is standard throughout physics:

- scattering theory reconstructs potentials or couplings from cross sections,
- tomography reconstructs densities from line integrals,
- condensed matter reconstructs continuum variables from long-wavelength probes,
- effective field theories reconstruct infrared dynamics independently of ultraviolet details.

Consequently, microscopic constitution is not itself an observable property, but an interpretative choice compatible with the same measurable data.

C.3 Effective Field Variables

Within effective field theory, the appropriate degrees of freedom are those that parametrize observable response at the scale of interest. Such variables are introduced directly as local dynamical fields.

Importantly, these fields are not required to be coarse-grained averages of hidden particles. They are simply the minimal variables needed to encode the measured correlation structure.

Standard examples include:

- gauge fields A_μ in electromagnetism,
- continuum elastic or phonon fields at long wavelengths,
- effective order parameters in condensed matter systems.

These quantities are routinely treated as primary degrees of freedom without specifying an atomic microstructure, because the latter is neither required for internal consistency nor experimentally accessible at the scales considered.

The response fields χ and ψ are introduced in precisely this sense. They represent local propagation structure and enter the theory at the same level of description as any other effective field.

C.4 Decoupling and Scale Separation

Effective field theory further clarifies that long-distance observables depend only on the light degrees of freedom and on a finite set of relevant operators. Heavy or short-distance physics decouples, contributing only suppressed corrections.

Schematically,

$$S_{\text{eff}} = \int d^4x [\mathcal{L}_{\text{IR}}(\chi, \psi, \text{matter}) + \sum_{n \geq 2} \frac{c_n}{\Lambda^{2n-2}} \mathcal{O}_n], \quad (2)$$

where Λ denotes the ultraviolet scale. At energies $E \ll \Lambda$, all ultraviolet details are irrelevant for prediction.

Thus specifying a microscopic completion is not necessary for predictive control in the infrared regime addressed here.

C.5 On the Notion of “Microscopic Atoms of the Medium”

The request for “atoms of the medium” implicitly assumes a particulate ontology appropriate to material fluids or gases. Such a request is meaningful only when the variables of interest are thermodynamic averages (density, temperature, pressure) that explicitly presuppose hidden constituents.

The present variables do not belong to this class. They are field-theoretic degrees of freedom defined directly at the operational level of measurement. Since observables depend only on response functions and correlators, no experiment can distinguish between different microscopic realizations that produce the same effective dynamics.

C.6 Interpretation

The propagation-response description should accordingly be understood as a field-level representation of dynamical structure rather than as a material medium endowed with constituent particles.

The fields χ and ψ are best interpreted as primary effective degrees of freedom encoding propagation properties, in the same technical sense in which gauge fields function in standard formulations of electromagnetism. The question “what are the atoms?” is not answerable because it is not operationally meaningful at the level of description employed.

Note on sources. The considerations above follow standard effective field theory and operational practice. For decoupling, infrared autonomy, and the primacy of effective degrees of freedom, see Weinberg [1], Burgess [2], and Donoghue [3]. For the scattering/observable framework in quantum field theory, see Peskin and Schroeder [4]. For the generic non-uniqueness of inverse reconstructions, see Kirsch [5]. The thermodynamic derivation of gravitational field equations without specified microstructure is developed in Jacobson [6].

References

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