Challenging Gauge/Gravity Duality: A Potential-Centric Perspective

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Abstract

The AdS/CFT correspondence posits a holographic equivalence between a gravitational theory in Anti-de Sitter (AdS) spacetime and a conformal field theory (CFT) on its boundary, linked by gauge-invariant quantities like field strengths $F_{\mu\nu}$ and fluxes Φ. This paper examines that link, drawing on my prior analysis of the Aharonov-Bohm (AB) effect, where such quantities exhibit nonlocality, discontinuity, and incompleteness. I demonstrate that gauge potentials A_μ in the Lorenz gauge—not their invariant derivatives—mediate the AB effect's local, continuous dynamics, a reality extending to gravitational fields $g_{\mu\nu}$ as substantival entities. In AdS/CFT, the CFT's reduction of bulk A_μ and $g_{\mu\nu}$ to gauge-invariant imprints fails to reflect this ontology, a flaw so fundamental that it excludes exact gauge/gravity duality—neither standard mappings nor reformulations suffice. A new mathematical proof formalizes this: the bulk's diffeomorphism freedom cannot correspond to the boundary's gauge freedoms, Abelian or non-Abelian, under this reality. This critique spans the gauge/gravity paradigm broadly, from AdS/CFT to holographic QCD, where symmetry invisibility obscures bulk physics. While duality's successes in black hole thermodynamics and strongly coupled systems highlight its utility, I suggest these reflect approximations within specific regimes, not a full equivalence. I propose a shift toward a framework prioritizing A_μ and $g_{\mu\nu}$'s roles, with gravitational AB effects in AdS as a testing ground. This work seeks to enrich holography's dialogue, advancing a potential-centric view for quantum gravity.

1 Introduction

The AdS/CFT correspondence, introduced by Juan Maldacena in 1998 [3], stands as a profound conjecture in theoretical physics, proposing a duality between a gravitational theory in $d+1$-dimensional Anti-de Sitter (AdS$_{d+1}$) spacetime and a d-dimensional conformal field theory (CFT) on its boundary [1]. This holographic framework equates the dynamics of a bulk theory—typically Type IIB string theory or its supergravity limit—with a boundary CFT, such as $\mathcal{N}=4$ supersymmetric $SU(N)$ Yang-Mills theory

(SYM) in four dimensions. A defining feature of this duality is the transformation of symmetries: gauge symmetries in one theory, such as diffeomorphisms in the AdS bulk or $SU(N)$ gauge invariance in the CFT, become "invisible" in the dual description, encoded instead as global symmetries or geometric structures [1]. The equivalence is anchored in the matching of gauge-invariant observables—correlation functions, Wilson loops, and stress-energy tensors—across the bulk and boundary.

This symmetry mapping has illuminated challenging problems, from black hole thermodynamics to strongly coupled quantum systems, showcasing AdS/CFT's elegance and utility. Yet, I suggest there may be a subtle tension in its reliance on gauge-invariant quantities—such as field strengths $F_{\mu\nu}$, fluxes Φ, or stress-energy tensors $T_{\mu\nu}$—that invites a closer look. My recent work, "The Aharonov-Bohm Effect Explained: Reality of Gauge Potentials and Its Implications" [2], highlights a limitation in these quantities, revealed through the Aharonov-Bohm (AB) effect, where electromagnetic potentials influence particles in field-free regions. I found that Φ or $F_{\mu\nu}$ struggle with nonlocality, discontinuity, and incompleteness, while gauge potentials A_μ, fixed in the Lorenz gauge, provide the local, continuous mediation needed. This insight extends to gravitational fields $g_{\mu\nu}$ as substantive entities (Section 8.4 of [2]), prompting me to explore whether AdS/CFT's boundary perspective fully captures the bulk's reality.

This paper seeks to unravel that question. If A_μ and $g_{\mu\nu}$ with their gauge freedoms are central to the bulk's physics, the CFT's focus on gauge-invariant imprints might miss a deeper layer, raising doubts about the duality's completeness. This exploration extends beyond AdS/CFT to the broader gauge/gravity framework, asking whether the transformation of symmetries reveals all there is to know—or leaves some physics unseen. My aim is not to dismiss this remarkable idea but to consider an alternative: a view where the boundary may not fully reflect the bulk's dynamic essence, supported by a theorem challenging symmetry correspondence, suggesting a shift toward the primacy of potentials.

The journey unfolds as follows. Section 2 outlines my reassessment of gauge-invariant explanations of the AB effect, setting the stage. Section 3 applies this to AdS/CFT, examining the CFT's perspective through electromagnetic and gravitational AB effects, with counterarguments and responses. Section 4 considers the implications—ontological, dynamic, and structural—for AdS/CFT's scope. Section 5 reassesses gauge/gravity duality, proposing through symmetry analysis (5.1), reformulation limits (5.2), broader critique (5.3), a mathematical proof (5.4), and success reinterpretation (5.5) that it may not fully align with the reality of A_μ and $g_{\mu\nu}$, and explores a potential-centric alternative. Section 6 concludes by framing this as an opportunity to deepen our understanding of quantum gravity, with gravitational AB effects as a possible test. Bridging gauge theory insights with holographic ideas, this work invites a conversation—not to upend gauge/gravity duality, but to enrich it with a perspective centered on the vibrant roles of potentials.

2 The AB Effect: Limits of Gauge-Invariant Accounts

The AB effect is a pivotal quantum phenomenon where electromagnetic potentials influence a charged particle's behavior even in regions where the electromagnetic fields vanish. In my recent analysis [2], I argue that traditional gauge-invariant explanations of this effect—relying on quantities like the magnetic flux Φ or field strength $F_{\mu\nu}$—are fundamentally flawed due to issues of nonlocality, discontinuity, and incompleteness. Here, I outline the AB effect, present these critiques in detail, and propose that the gauge potential A_μ, fixed in the Lorenz gauge, is the physically real entity mediating the effect (Section 6 of [2]).

2.1 The AB Effect and Its Generalized Form

Consider a standard AB setup where electrons travel around a long, tightly wound solenoid carrying a magnetic field $\mathbf{B}$, confined entirely within its interior. Outside the solenoid, $\mathbf{B} = 0$, yet the vector potential $\mathbf{A}$ is non-zero, satisfying $\nabla \times \mathbf{A} = \mathbf{B}$. When two electron beams travel along paths C_1 and C_2 encircling the solenoid and recombine, they exhibit an interference pattern shifted by a phase difference:

$$\phi_{AB} = e \oint_C \mathbf{A} \cdot d\mathbf{r} = e\Phi, \tag{1}$$

where $C = C_1 - C_2$ is the closed loop, e is the electron's charge, and $\Phi = \int \mathbf{B} \cdot d\mathbf{S}$ is the magnetic flux through the enclosed area. This shift occurs despite $\mathbf{B} = 0$ along the paths, as confirmed experimentally.

A generalized version of the AB effect extends this phenomenon to dynamic scenarios, where the flux $\Phi(t)$ varies over time, offering a richer testbed for analyzing gauge-invariant accounts. The phase accumulates over a period T as:

$$\phi_{AB} = \frac{1}{T} \int_0^T e\Phi(t)\, dt, \tag{2}$$

reflecting a continuous buildup driven by the changing electromagnetic environment (Section 2.2 of [2]). This temporal extension highlights the effect's dynamic nature, amplifying the demand for a physical mediator beyond static Φ or $F_{\mu\nu}$.

2.2 Gauge-Invariant Quantities in Quantum Mechanics

To assess the gauge-invariant accounts, we first define the complete set of gauge-invariant quantities for an electron in quantum mechanics, as I detailed previously in [2]. For an electron of mass m and charge e, with wave function $\psi = Re^{iS}$, these include the probability density $\rho = |\psi|^2$ and velocity field $\mathbf{v} = \frac{1}{m}(\nabla S - e\mathbf{A})$ from the Madelung formulation. In electromagnetic fields, the field strength $F_{\mu\nu}$ (yielding $\mathbf{E}$ and $\mathbf{B}$) and integrals like magnetic flux Φ are also gauge-invariant, unchanged under $A_\mu \to A_\mu - \partial_\mu \chi$. This set—$\rho$, $\mathbf{v}$, $F_{\mu\nu}$, and Φ—is deemed sufficient by proponents to describe observable dynamics without A_μ. The AB effect, however, tests this claim's limits, as the following critiques reveal.

2.3 Dynamics for Gauge-Invariant Quantities

Consider the standard AB setup: two electron beams encircle a solenoid with constant magnetic flux Φ, recombining to interfere. Before overlap, each beam travels in a simply connected, field-free region ($\mathbf{B} = 0$), where a gauge choice $\mathbf{A} = 0$ is possible. In this gauge, the Schrödinger equation reduces to the free form, and the solutions ψ_1 and ψ_2 for each beam match those of a free electron, implying ρ and $\mathbf{v}$ are independent of Φ. This holds because, in each path, the gauge transformation adjusts the phase locally, leaving gauge-invariant properties unchanged.

However, after the beams overlap, forming a closed loop C around the solenoid, $\mathbf{A} = 0$ cannot be chosen globally due to the nonzero flux $\Phi = \oint_C \mathbf{A} \cdot d\mathbf{r}$. The interference pattern shifts by:

$$\phi_{AB} = e \oint_C \mathbf{A} \cdot d\mathbf{r} = e\Phi, \tag{3}$$

and the velocity satisfies

$$\oint_C \mathbf{v} \cdot d\mathbf{r} = \oint_C \frac{1}{m}(\nabla S - e\mathbf{A}) \cdot d\mathbf{r} = -e\Phi \tag{4}$$

reflecting Φ's influence. Consequently, $\mathbf{v}$ and ρ (via the continuity equation $\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0$) abruptly depend on Φ at overlap, despite being Φ-independent beforehand.

2.4 Problems with Gauge-Invariant Explanations

The gauge-invariant approach to the AB effect aims to explain the effect without invoking A_μ directly, using quantities like Φ, $F_{\mu\nu}$, or the velocity field $\mathbf{v}$. I identify three critical flaws (Sections 3.4 of [2]), detailed below.

2.4.1 Nonlocality

The gauge-invariant approach's reliance on Φ introduces a nonlocality problem. The phase $\phi_{AB} = e\Phi$ depends on flux inside the solenoid, spatially separated from the electron paths, yet $F_{\mu\nu} = 0$ outside provides no local mediator. Moreover, the approach posits (by its dynamics) that the phase ϕ_{AB} emerges instantaneously at the point of interference, reflecting an action at a distance on the electron despite its confinement to a field-free region—a proposition that strains the causal architecture of special relativity, which insists that physical effects propagate no faster than the speed of light. Such an unmediated action across space suggests a reality where distant entities can affect one another without a local intermediary, a notion that sits uneasily with the principle of locality.

2.4.2 Discontinuity

This nonlocality manifests as discontinuity in the electron's dynamics. Before reaching the interference region, the gauge-invariant properties of the electron, ρ and $\mathbf{v}$, evolve freely, independently of Φ. At interference, ρ and $\mathbf{v}$, and thus ϕ_{AB}, suddenly reflect Φ, with no gradual transition. In the time-varying case, ρ and $\mathbf{v}$ remain unaffected until overlap, despite $\Phi(t)$'s continuous change. This sudden shift stands in stark contrast to the expectation in quantum mechanics that physical states evolve smoothly unless perturbed by local interactions—a principle of continuity that underpins the theory's predictive coherence.

2.4.3 Incompleteness

This discontinuity underscores an incompleteness in the gauge-invariant framework. The set $\{\rho, \mathbf{v}, F_{\mu\nu}, \Phi\}$ cannot explain the phase's continuous accrual. In the generalized AB effect, ϕ_{AB} builds up as $\Phi(t)$ varies, yet Φ or $F_{\mu\nu}$ (zero outside the solenoid) offers no mechanism for this along the paths. The Madelung equations illustrate this (Section 3.5 of [2]):

- Continuity: $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$,
- Momentum: $m\frac{\partial \mathbf{v}}{\partial t} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - m(\mathbf{v} \cdot \nabla)\mathbf{v} - \nabla U$,

where $U = -\frac{1}{m}\frac{\nabla^2 R}{R}$ is the quantum potential. With $\mathbf{B} = 0$ and $\mathbf{E} = 0$ outside, these equations predict no Φ-dependence until interference, resolved only by a nonlocal quantization condition $m \oint_C \mathbf{v} \cdot d\mathbf{r} = 2\pi n - e\Phi$. This leaves the local, temporal process unexplained, rendering the account incomplete.

2.4.4 A Stronger No-Go Result

The above critiques expose the flaws of gauge-invariant explanations—nonlocality, discontinuity, and incompleteness—but a stronger result emerges from the generalized AB effect's dynamic nature (Section 4 of [2]). It is demonstrated that these explanations are not merely inadequate but fundamentally excluded, as their reliance on an instantaneous phase shift at interference clashes with the continuous phase accumulation observed in the time-varying flux scenario. Here, I summarize this no-go result.

The proof centers on two propositions: (1) Gauge-invariant accounts—relying on quantities like Φ, $F_{\mu\nu}$, or $\mathbf{v}$—posit that the phase ϕ_{AB} emerges only at beam overlap, as ρ and $\mathbf{v}$ show no Φ-dependence beforehand; (2) The generalized AB effect, with $\Phi(t)$ varying, yields $\phi_{AB} = \frac{1}{T}\int_0^T e\Phi(t)\, dt$, a phase that accrues continuously along the paths, not instantaneously, depending on $\Phi(t)$'s profile over $0 \leq t \leq T$. These are incompatible: if ϕ_{AB} builds over time as quantum mechanics predicts, an abrupt shift at interference cannot hold. Gauge-invariant quantities, insensitive to this process before overlap, fail to explain the effect, excluding them as viable.

Objections—e.g., that induced fields $\mathbf{E} = -\partial_t \mathbf{A}$ or nonlocal $\mathbf{v}$ suffice—fall short. The induced $\mathbf{E}$ cancels in the phase difference and is negligible for short transitions ($\Delta t \ll T$), while $\mathbf{v}$'s loop integral only captures the outcome, not the dynamic buildup. Experimental proposals bolster this: modulating $\Phi(t)$ or shutting off the solenoid during transit could measure partial phase accrual, confirming its continuous nature against instantaneous models. Thus, the generalized AB effect's evidence—supported by quantum mechanics and testable empirically—rules out gauge-invariant explanations.

2.5 The Reality of Gauge Potentials

These issues of gauge-invariant explanations stem from sidelining A_μ. In the Schrödinger equation, A_μ enters via the minimal coupling $i\partial_\mu \to i\partial_\mu - eA_\mu$, shifting the phase locally along each path:

$$S \to S - e \int_L A_\mu \, dx^\mu, \tag{5}$$

where L is the particle's trajectory. The phase difference $\phi_{AB} = e \int_{C_1} A_\mu \, dx^\mu - e \int_{C_2} A_\mu \, dx^\mu = e \oint_C A_\mu \, dx^\mu$ accrues continuously, respecting locality and spacetime's smoothness. In the generalized case, $A_\mu(x,t)$ tracks $\Phi(t)$'s evolution pointwise, ensuring consistency.

Since A_μ is gauge-dependent, I propose fixing it in the Lorenz gauge ($\partial^\mu A_\mu = 0$), where it satisfies the wave equation $\Box A_\mu = J_\mu$ (coupled to the source current J_μ) (Section 6.1 of [2]). This choice aligns with QED's relativistic covariance and ensures A_μ is a physical field over spacetime, not a mere mathematical artifact. Gauge-invariant quantities like Φ or $F_{\mu\nu}$ derive from A_μ, but only A_μ captures the effect's local, continuous origin. Thus, I reject gauge-invariant ontologies as deficient, asserting A_μ's ontological primacy [2].

3 AdS/CFT Challenges: Gauge Potentials and Boundary Correspondence

3.1 Issues from Gauge-Invariant Imprints

In the AdS/CFT correspondence, bulk gauge fields A_μ and gravitational metrics $g_{\mu\nu}$ map to boundary CFT operators—currents J^μ and stress-energy tensors $T_{\mu\nu}$—with physical effects encoded in gauge-invariant quantities like field strengths $F_{\mu\nu}$, flux Φ, or curvature invariants. My critique of such quantities in the AB effect (Section 2) reveals flaws—nonlocality, discontinuity, and incompleteness—that I argue persist in AdS/CFT's holographic framework. Here, I examine these issues through an electromagnetic AB-like effect and a gravitational AB effect in AdS, demonstrating how the CFT's boundary perspective may fail to capture the bulk's local, continuous dynamics mediated by A_μ and $g_{\mu\nu}$.

3.1.1 Electromagnetic AB Effect in AdS

Consider an AB-like scenario in AdS_5: a charged scalar field (e.g., a string mode) encircles a flux source, such as a D-brane with a magnetic field confined to its interior, in a region where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu = 0$ outside. The bulk phase shift is:

$$\phi_{AB} = e \oint_C A_\mu \, dx^\mu, \tag{6}$$

where C is a closed path around the source, and e is the charge. In the generalized case, a time-varying flux $\Phi(t) = \int \mathbf{B} \cdot d\mathbf{S}$ (e.g., induced by a dynamic D-brane) yields:

$$\phi_{AB} = \frac{1}{T} \int_0^T e\Phi(t)\, dt, \tag{7}$$

accumulating continuously via $A_\mu(x, t)$ along the path. In AdS/CFT, this maps to a Wilson loop in the boundary CFT ($\mathcal{N} = 4$ SYM):

$$W(C) = \mathrm{Tr}\left[P e^{i \oint_C A_\mu^a \, dx^\mu} \right], \tag{8}$$

with expectation value $\langle W(C) \rangle \sim e^{ie\Phi}$, computed via bulk minimal surfaces.

My critique applies as follows:

- **Nonlocality**: The CFT's $\langle W(C) \rangle$ depends on Φ, integrated over the bulk source's distant topology (e.g., deep in the AdS interior). Yet, $\mathcal{N} = 4$ SYM is a local theory on the boundary (e.g., Minkowski $\mathbb{R}^{1,3}$). The phase shift appears without a local boundary mediator, suggesting an action-at-a-distance inconsistent with causality. In contrast, bulk A_μ acts pointwise along C, respecting relativistic locality.
- **Discontinuity**: For a time-varying $\Phi(t)$, $\langle W(C) \rangle$ shifts instantaneously as the bulk flux changes (e.g., via a D-brane current), lacking the smooth temporal evolution $A_\mu(x, t)$ provides. Before interference, boundary operators like J^μ show no Φ-dependence; only at measurement does the phase emerge, echoing the abruptness I critique in the AB effect.
- **Incompleteness**: J^μ or $\langle W(C) \rangle$ captures the final phase but not its continuous, path-dependent accrual. The bulk's A_μ mediates this locally (e.g., via $D_\mu = \partial_\mu + ieA_\mu$), yet the CFT lacks an equivalent field, leaving the dynamic process unexplained. This parallels the Madelung formulation's failure to track phase build-up.

3.1.2 Gravitational AB Effect in AdS

This critique extends to gravitational potentials $g_{\mu\nu}$ via a gravitational AB effect, as I propose in my prior work (Section 8.4 of [2]). Imagine a test particle (e.g., a massive scalar field) traversing a closed path around a massive source in AdS_5—such as a cosmic string along the AdS radial direction—where the Riemann curvature $R_{\mu\nu\rho\sigma} = 0$ outside the source. The spacetime geometry, described by $g_{\mu\nu}$, induces a phase shift analogous to the electromagnetic case:

$$\phi_g = \int_C p_\mu \, dx^\mu, \tag{9}$$

where $p_\mu = m g_{\mu\nu} dx^\nu / ds$ is the momentum along geodesic path C, and the phase depends on $g_{\mu\nu}$'s holonomy (e.g., a deficit angle from the string). In a gauge-fixed form, $g_{\mu\nu}$ mediates this locally and continuously, akin to A_μ. I argue that $g_{\mu\nu}$ in the true gauge is a dynamical, substantival entity, not merely a mathematical construct (Section 8.4 of [2]).

In AdS/CFT, the CFT accesses only diffeomorphism-invariant observables, and this bulk effect corresponds to the boundary stress-energy tensor $T_{\mu\nu}$, dual to bulk $g_{\mu\nu}$ via the holographic dictionary. If spacetime geometry in the bulk is fundamentally tied to a gauge-fixed $g_{\mu\nu}$—reflecting its physical reality—the CFT's restriction to $T_{\mu\nu}$ or geodesic correlations (e.g., boundary two-point functions) inherits similar issues:

- **Nonlocality**: $T_{\mu\nu}$ encodes bulk geometry globally, integrating over the AdS metric (e.g., via the extrinsic curvature at the boundary). The gravitational phase, tied to a specific $g_{\mu\nu}$ configuration along C, appears in the CFT without a local boundary field, suggesting a nonlocal dependence on the cosmic string's position. Bulk $g_{\mu\nu}$, by contrast, acts locally at each spacetime point.

- **Discontinuity**: A time-varying bulk geometry (e.g., a pulsating string or collapsing mass) alters the phase continuously via $g_{\mu\nu}(x,t)$. Yet, $T_{\mu\nu}$ or its correlations shift abruptly with boundary conformal time, missing the smooth evolution. This mirrors the electromagnetic case's temporal discontinuity.

- **Incompleteness**: The CFT cannot access $g_{\mu\nu}$'s path-dependent role, reducing it to invariant quantities like energy-momentum or curvature scalars. This strips away the dynamic mediation $g_{\mu\nu}$ provides (e.g., via geodesic equations), akin to $F_{\mu\nu}$'s inadequacy for A_μ. The gravitational AB effect's local origin remains unrepresented.

These examples—electromagnetic and gravitational—underscore a broader challenge: if bulk physics relies on A_μ and $g_{\mu\nu}$ as real, local mediators, the CFT's gauge-invariant perspective may obscure their ontological roles. For A_μ, the loss of pathwise influence in $\langle W(C)\rangle$ or J^μ parallels the AB effect's nonlocal and discontinuous flux dependence (Section 3.4 of [2]). For $g_{\mu\nu}$, the reduction to $T_{\mu\nu}$ overlooks spacetime's substantival dynamics, a critique I extend from electromagnetic to gravitational contexts (Section 8.4 of [2]). In both cases, the CFT's boundary view risks being not just a dual description but an incomplete one, failing to mirror the bulk's causal structure. This deepens the tension with AdS/CFT's equivalence, setting the stage for counterarguments and rebuttals.

3.2 Counterarguments

Advocates of the AdS/CFT correspondence might argue that my critique—highlighting nonlocality, discontinuity, and incompleteness in the CFT's gauge-invariant imprints—does not undermine the duality's validity. Here, I outline three detailed counterarguments they could raise, drawing on established holographic principles and the structure of $\mathcal{N}=4$ SYM.

3.2.1 Holographic Locality via Entanglement

The apparent nonlocality of CFT imprints like $\langle W(C)\rangle$ or J^μ, which depend on bulk flux Φ or geometry, could be resolved by holographic locality. The Ryu-Takayanagi prescription [4] posits that the entanglement entropy of a CFT subregion equals the area of a minimal surface in the AdS bulk, suggesting that local boundary operators encode bulk dynamics. For an AB-like effect, correlations in $J^\mu(x)J^\nu(y)$ might implicitly track the bulk A_μ's influence along paths, reconstructing local interactions via entanglement. Similarly, for gravitational effects, $T_{\mu\nu}$'s entanglement structure could reflect $g_{\mu\nu}$'s geometry pointwise, avoiding nonlocal jumps by embedding bulk causality in boundary quantum correlations.

3.2.2 Observable Equivalence and Ontological Flexibility

AdS/CFT requires only the equivalence of physical observables (e.g., partition functions, correlation functions), not identical ontologies across the duality. For the electromagnetic AB effect, $\langle W(C)\rangle = e^{ie\Phi}$ matches the bulk's phase shift, computed via a Wilson line or minimal surface in AdS. Discontinuity in $W(C)$'s response to $\Phi(t)$ might reflect a boundary perspective on bulk dynamics, not a flaw—time evolution in the CFT (via conformal symmetry) could align with bulk continuity indirectly. For gravitational effects, $\langle T_{\mu\nu}(x)T_{\rho\sigma}(y)\rangle$ captures bulk geodesic shifts without needing $g_{\mu\nu}$'s gauge-fixed form explicitly. Thus, the CFT's gauge-invariant view might be a valid, alternative description, not an incomplete one, sidestepping my demand for A_μ or $g_{\mu\nu}$'s local mediation.

3.2.3 Non-Abelian Robustness of $\mathcal{N} = 4$ SYM

The CFT in $\mathrm{AdS}_5/\mathrm{CFT}_4$ is $\mathcal{N} = 4$ SYM with $SU(N)$ gauge symmetry, far richer than the $U(1)$ case of the AB effect. Wilson loops $W(C)$ in $SU(N)$ involve non-Abelian gauge fields A^a_μ, whose path-ordered exponentials capture complex interactions (e.g., gluon exchanges) beyond simple flux Φ. This richness might mitigate incompleteness: $\langle W(C)\rangle$ could encode bulk A_μ's dynamics through $SU(N)$ operator algebra, not just static imprints. For gravitational effects, $T_{\mu\nu}$'s $SU(N)$ contributions (e.g., from scalar and fermion fields) might indirectly reflect $g_{\mu\nu}$'s evolution, leveraging the CFT's supersymmetry and large-N limit to bridge discontinuities. The non-Abelian structure could thus compensate for the loss of gauge potentials' explicit locality.

3.3 Rebuttal

While these counterarguments defend AdS/CFT's operational success, they do not fully address the ontological deficiencies I identify in gauge-invariant frameworks (Section 2). Below, I rebut each point, reinforcing my argument that the CFT's boundary perspective fails to capture the bulk's local, continuous dynamics mediated by A_μ and $g_{\mu\nu}$.

3.3.1 Rebuttal to Holographic Locality

Holographic locality via entanglement (e.g., Ryu-Takayanagi [4]) excels at spatial correlations, mapping CFT subregions to bulk geometry. However, it struggles with temporal continuity, a core issue in my critique. For the generalized AB effect, $\phi_{AB} = \frac{1}{T}\int_0^T e\Phi(t)\,dt$ accrues smoothly via $A_\mu(x,t)$ (Section 2.1), yet J^μ or $\langle W(C)\rangle$ offers static snapshots, missing this dynamic process. Similarly, a gravitational AB effect's phase evolves with $g_{\mu\nu}(x,t)$, but $T_{\mu\nu}$'s entanglement encodes spatial geometry, not its temporal unfolding. The Madelung equations' failure to track phase accrual (Section 2.4.3) parallels this: entanglement may spatially localize effects, but it cannot replace the continuous mediation of gauge-fixed potentials, leaving nonlocality and discontinuity unresolved.

3.3.2 Rebuttal to Observable Equivalence

Observable equivalence ensures AdS/CFT's predictive power (e.g., $\langle W(C)\rangle = e^{ie\Phi}$), but it sidesteps ontology, which I prioritize. If A_μ in the Lorenz gauge is the real state mediating the AB effect locally (Section 2.5), the CFT's reliance on Φ or $F_{\mu\nu}$—nonlocal and discontinuous—renders it ontologically deficient, not merely different. For gravitational effects, $g_{\mu\nu}$ as a substantival entity drives phase shifts continuously, yet $T_{\mu\nu}$ reduces this to invariant energy-momentum, obscuring its dynamical role. My no-go result (Section 2.4.4) excludes gauge-invariant accounts as complete; matching observables does not salvage the CFT's failure to reflect the bulk's physical reality, especially for time-dependent phenomena where continuity is paramount.

3.3.3 Rebuttal to Non-Abelian Robustness

The $SU(N)$ structure of $\mathcal{N} = 4$ SYM enriches CFT operators, but it does not escape my critique. Wilson loops $W(C)$ in $SU(N)$ still integrate over paths, yielding gauge-invariant expectation values (e.g., $\langle W(C)\rangle$) that depend on bulk flux or geometry, not local A^a_μ mediation. Their non-Abelian complexity (e.g., gluon interactions) adds degrees of freedom, but the phase's origin remains nonlocal—tied to distant bulk sources—mirroring $U(1)$'s Φ. For gravitational effects, $T_{\mu\nu}$'s $SU(N)$ contributions enhance correlations, yet they lack $g_{\mu\nu}$'s path-dependent evolution, akin to $\mathbf{v}$'s inadequacy in the Madelung formulation. My analysis applies universally: no gauge-invariant quantity—Abelian or non-Abelian—captures the local, continuous role of gauge-fixed potentials, undermining the CFT's completeness.

4 Implications for AdS/CFT

My critique of gauge-invariant quantities (Section 2) and its extension to the AdS/CFT correspondence (Section 3) reveal significant challenges to the duality's foundational claims. If the CFT's boundary perspective, limited to gauge-invariant imprints like $F_{\mu\nu}$, Φ, or $T_{\mu\nu}$, inherits the nonlocality, discontinuity, and incompleteness I identify in the

AB effect, the equivalence between the AdS bulk and CFT boundary may falter. Here, I explore three key implications—ontological tension, dynamic breakdown, and the need to reassess gauge symmetry's role—followed by potential resolutions and their alignment with my view of gauge potentials as physically real entities (Section 6 of [2]).

4.1 Ontological Tension

The AdS/CFT correspondence assumes that the bulk gravitational theory (e.g., Type IIB string theory in AdS_5) and the boundary CFT (e.g., $\mathcal{N} = 4$ SYM) are ontologically equivalent descriptions of the same physics [3]. My analysis, however, suggests a disconnect. I argue that gauge potentials A_μ in the Lorenz gauge are the real mediators of the AB effect's phase shift, capturing its local, continuous origin. Extending this to the gravitational AB effect, I posit $g_{\mu\nu}$ as a substantival, dynamical entity in the bulk, driving phase shifts in regions where $R_{\mu\nu\rho\sigma} = 0$. In contrast, the CFT relies on gauge-invariant quantities—J^μ or $\langle W(C) \rangle$ for A_μ, and $T_{\mu\nu}$ for $g_{\mu\nu}$—which my no-go result deems ontologically deficient (Section 2.4.4).

This creates a tension: the bulk's physical reality, rooted in A_μ and $g_{\mu\nu}$'s local mediation, is obscured in the CFT's boundary view. For example, a bulk AB phase $\phi_{AB} = e \oint_C A_\mu \, dx^\mu$ depends on A_μ's pathwise influence, yet the CFT's $\langle W(C) \rangle \sim e^{ie\Phi}$ reflects only the integrated flux, missing the causal process (Section 3.1). Similarly, a gravitational phase tied to $g_{\mu\nu}$ (e.g., via a holonomy around a cosmic string in AdS) is reduced to $T_{\mu\nu}$ correlations, stripping away spacetime's dynamic role. If my ontology holds, the CFT's perspective is not merely an alternative but an incomplete representation, challenging the duality's claim to full equivalence beyond observable matching.

4.2 Dynamic Breakdown

The CFT's inability to capture continuous temporal evolution exacerbates this tension, particularly for dynamic processes. In the generalized AB effect, the phase $\phi_{AB} = \frac{1}{T} \int_0^T e\Phi(t) \, dt$ builds smoothly via $A_\mu(x, t)$, requiring a local field to track $\Phi(t)$'s changes pointwise. The CFT's $\langle W(C) \rangle$, however, shifts abruptly with bulk flux, lacking a mechanism to mirror this continuity (Section 3.1). For gravitational effects, a time-varying bulk geometry (e.g., a collapsing mass inducing a gravitational AB phase) demands $g_{\mu\nu}(x, t)$'s smooth evolution, yet $T_{\mu\nu}$ offers static snapshots tied to boundary conformal time, not bulk dynamics (Section 3.3).

This dynamic breakdown threatens AdS/CFT's applicability to time-dependent phenomena. In string theory, bulk processes like black hole formation or cosmological evolution involve A_μ and $g_{\mu\nu}$ evolving causally, influencing fields locally (e.g., via $D_\mu = \partial_\mu + ieA_\mu$ or geodesic equations). The CFT's gauge-invariant operators, while predictive for equilibrium states (e.g., via AdS black hole thermodynamics), struggle to reflect out-of-equilibrium dynamics without invoking bulk-like potentials explicitly. My critique suggests that the duality's success in static or near-equilibrium contexts may not extend to regimes where continuity and locality are critical, limiting its scope as a complete physical framework.

4.3 Gauge Symmetry Reassessment

The "invisibility" of gauge symmetry across AdS/CFT—bulk diffeomorphisms becoming CFT conformal symmetries, and CFT $SU(N)$ gauge symmetry encoding bulk geometry—has been a celebrated feature [3]. My analysis, however, casts this as a limitation. If A_μ and $g_{\mu\nu}$ in the true gauge (Lorenz and massive gauges, respectively) are the physical states (Sections 6 and 8.4 of [2]), their gauge freedom is not a mere redundancy but a structural necessity for local mediation. The CFT's stripping of this freedom—reducing A_μ to $F_{\mu\nu}$ or Φ, and $g_{\mu\nu}$ to $T_{\mu\nu}$—introduces the flaws I critique (Section 3.1), suggesting that gauge symmetry's absence in the dual is not a reframing but a loss of critical physics.

This prompts a reassessment: does AdS/CFT's gauge-invariant boundary obscure rather than encode the bulk's reality? For instance, bulk diffeomorphisms ($g_{\mu\nu} \to g_{\mu\nu} + \nabla_\mu \xi_\nu + \nabla_\nu \xi_\mu$) allow $g_{\mu\nu}$ to mediate gravitational effects locally, yet the CFT's conformal invariance lacks this flexibility, fixing the boundary metric (e.g., Minkowski). Similarly, bulk A_μ's gauge freedom ($A_\mu \to A_\mu - \partial_\mu \chi$) ensures relativistic consistency, absent in the CFT's global currents. My view challenges the duality to justify this loss beyond observable equivalence, potentially requiring a reformulation that retains gauge potentials' roles.

4.4 Potential Resolutions

Two resolutions might reconcile AdS/CFT with my critique:

1. **Bulk-Centric Ontology**: Accept that the bulk's A_μ and $g_{\mu\nu}$ are ontologically primary, with the CFT as a derived, approximate description. This aligns with my Lorenz gauge ontology (Section 7.1 of [2]), treating the CFT as a coarse-grained view suited for gauge-invariant observables but not the full physics. For example, bulk AB effects would dictate the CFT's interpretation, with $\langle W(C) \rangle$ as a projection of A_μ's reality.

2. **Extended CFT Framework**: Modify the CFT to incorporate bulk-like gauge potentials explicitly, blurring the gauge-invariant boundary paradigm. This could involve auxiliary fields mimicking A_μ or $g_{\mu\nu}$, restoring locality and continuity. Such an extension would echo my substantivalist turn (Section 8.4 of [2]), integrating spacetime and matter fields dynamically.

Both options shift AdS/CFT toward my framework, where gauge-fixed potentials are central. The first preserves the duality's structure but prioritizes the bulk, while the second redefines the CFT, potentially weakening its holographic purity but enhancing its physical fidelity.

5 Revisiting Gauge/Gravity Duality

The critique of the AdS/CFT correspondence articulated throughout this paper—anchored in the ontological primacy of gauge potentials A_μ and gravitational fields $g_{\mu\nu}$ over their gauge-invariant reductions (Sections 2–4)—culminates in a deeper implication: the very concept of gauge/gravity duality may be untenable. Gauge/gravity duality, as exemplified by AdS/CFT, hinges on a transformative equivalence where a gauge theory on a lower-dimensional boundary (e.g., $\mathcal{N} = 4$ SYM with $SU(N)$ symmetry) fully captures a gravitational theory in a higher-dimensional bulk (e.g., Type IIB supergravity in $\mathrm{AdS}_5 \times S^5$) [1]. Central to this framework is the "invisibility" of gauge symmetries: bulk diffeomorphisms manifest as boundary conformal symmetries, and boundary gauge freedoms encode bulk geometry (Section 1). My analysis, however, reveals that this symmetry mapping falters when A_μ and $g_{\mu\nu}$ are recognized as physically real entities with meaningful gauge freedoms, leading to the conclusion that no such duality can persist, neither in its standard form nor in any reformulated guise. This section develops this argument through a symmetry mismatch (Section 5.1), the collapse of reformulated duality (Section 5.2), its broader implications (Section 5.3), a mathematical proof of exclusion (Section 5.4), and a reconciliation of duality's successes as approximations (Section 5.5).

5.1 Gauge Freedom Mismatch in Standard Duality

Consider the symmetry structures of the dual theories. In the boundary CFT, the gauge field A_μ^a possesses gauge freedom:

$$A_\mu^a \to A_\mu^a + D_\mu \chi^a = A_\mu^a + \partial_\mu \chi^a + f^{abc} A_\mu^b \chi^c, \tag{10}$$

which I argue is not a mere redundancy but a physical attribute mediating local, continuous dynamics, as demonstrated in the AB effect (Section 2.5). In the bulk gravitational theory, $g_{\mu\nu}$ exhibits diffeomorphism freedom:

$$g_{\mu\nu} \to g_{\mu\nu} + \nabla_\mu \xi_\nu + \nabla_\nu \xi_\mu, \tag{11}$$

equally substantive in driving gravitational effects (e.g., gravitational AB phase, Section 3.1.2). In standard AdS/CFT, these freedoms are rendered "invisible" in the dual description: bulk diffeomorphisms correspond to CFT conformal symmetries (e.g., $SO(2,4)$), while CFT gauge transformations influence bulk geometry nonlocally (e.g., via Wilson loops $\langle W(C) \rangle$). My no-go result (Section 2.4.4) excludes gauge-invariant accounts as complete, asserting that A_μ and $g_{\mu\nu}$'s gauge freedoms are essential to their physical roles.

This creates an irreconcilable mismatch. The bulk gravity theory lacks a direct analogue to the CFT's $SU(N)$ gauge freedom—bulk A_μ fields (e.g., from D-branes) do not mirror the boundary's non-Abelian structure. Conversely, the CFT, with its fixed Minkowski metric, lacks diffeomorphism freedom akin to the bulk's $g_{\mu\nu}$. If these gauge freedoms are physically real, as my ontology demands (Sections 4.1, 4.3), their absence in the dual theory implies a loss of critical physics. The CFT cannot replicate the bulk's spacetime dynamics without $g_{\mu\nu}$-like freedom, nor can the bulk encode the CFT's gauge dynamics without an $SU(N)$-like field. This asymmetry undermines the duality's claim of full equivalence, suggesting that the theories describe distinct physical realities rather than dual perspectives of the same system.

5.2 Reformulation and the Collapse of Duality

One might propose reformulating AdS/CFT to preserve these gauge freedoms, as explored in my potential resolutions (Section 4.4). The second option—extending the CFT to incorporate bulk-like potentials explicitly—aims to restore the locality and continuity of A_μ and $g_{\mu\nu}$. However, this approach reveals a fatal flaw: it dismantles the gauge/gravity distinction itself. If the boundary CFT includes a gauge field A_μ with freedom $A_\mu \to A_\mu - \partial_\mu \chi$ and a gravitational field $g_{\mu\nu}$ with diffeomorphism freedom, it ceases to be a pure gauge theory dual to a gravitational bulk. Instead:

- Gauge on the boundary (e.g., A_μ) corresponds to gauge in the bulk (e.g., bulk A_μ), not gravity.
- Gravity on the boundary (e.g., $g_{\mu\nu}$) corresponds to gravity in the bulk, not gauge symmetry.

The bulk, already possessing $g_{\mu\nu}$ and A_μ (e.g., in string theory), mirrors this structure. Far from a duality, this becomes a theory-theory equivalence where both sides feature gauge and gravitational sectors without transformative mapping.

This collapse is profound. Gauge/gravity duality's essence lies in its asymmetry: boundary gauge symmetry (e.g., $SU(N)$) encoding bulk geometry, and bulk diffeomorphisms manifesting as boundary conformal symmetry. Preserving A_μ and $g_{\mu\nu}$'s freedoms on both sides eliminates this asymmetry, rendering the boundary a bulk-like spacetime with its own gravitational dynamics. The holographic principle—bulk physics encoded on a lower-dimensional boundary—loses meaning, as the boundary itself becomes a higher-dimensional theory akin to the bulk. Thus, even a reformulated framework fails to sustain gauge/gravity duality, as the gauge-to-gravity and gravity-to-gauge correspondence dissolves.

5.3 Implications for Gauge/Gravity Duality Broadly

This exclusion extends beyond AdS/CFT to the broader paradigm of gauge/gravity duality (Section 5). In other contexts—e.g., Klebanov-Strassler throats or holographic QCD—the same symmetry mismatch persists: boundary gauge freedoms lack bulk gravitational duals, and bulk diffeomorphisms lack boundary gauge equivalents. My critique of gauge-invariant reductions (Section 2.4) applies universally: if A_μ and $g_{\mu\nu}$ are the real mediators, their gauge freedoms must be present in any dual theory. Yet, the hallmark of gauge/gravity duality—transforming these freedoms into "invisible" structures—contradicts this requirement. Attempts to reformulate (e.g., adding bulk-like fields to the boundary) consistently erase the duality's defining feature across all instances, from conformal to non-conformal settings.

The implication is stark: if gauge freedoms are physically substantive, as my analysis of the AB effect and its gravitational analogue suggests (Sections 2.5, 3.1), gauge/gravity duality cannot hold. The standard form fails due to the absence of dual gauge freedoms, and reformulation fails by negating the gauge/gravity distinction. This leaves no room for a duality where one theory's gauge symmetry maps to another's gravity, or vice versa. Instead, it points to a paradigm where gauge and gravitational potentials coexist as fundamental entities, their freedoms intact, without reliance on holographic duality—a framework I propose as a potential successor (Section 4.4.1).

5.4 A Mathematical Exclusion of Gauge/Gravity Duality

My critique has argued that gauge/gravity duality falters when A_μ and $g_{\mu\nu}$ are recognized as physically real with substantive gauge freedoms (Sections 2.5, 4.1). Here, I formalize this as a rigorous mathematical proof, demonstrating that the bulk's diffeomorphism freedom cannot correspond to the boundary's gauge freedoms—Abelian ($U(1)$) or non-Abelian ($SU(N)$)—under my ontology, thus excluding duality entirely.

Consider the symmetry groups: in the bulk (e.g., AdS_{d+1}), $g_{\mu\nu}$ transforms under $\mathrm{Diff}(M)$, with $g_{\mu\nu} \to g_{\mu\nu} + \nabla_\mu \xi_\nu + \nabla_\nu \xi_\mu$, an infinite-dimensional group. On the boundary, A_μ transforms under $\mathcal{G} = C^\infty(\partial M, G)$, where $G = U(1)$ ($A_\mu \to A_\mu + \partial_\mu \chi$) or $SU(N)$ ($A_\mu^a \to A_\mu^a + D_\mu \chi^a$), finite-dimensional per point. AdS/CFT maps $\mathrm{Diff}(M)$ to the conformal group $SO(2,d)$, and $\mathcal{G}$ to bulk geometry via $T_{\mu\nu}$ or J^μ. My premise—$g_{\mu\nu}$ and A_μ are real, their freedoms essential (Section 2.5)—clashes with this.

Theorem 5.4: There exists no gauge/gravity duality where the bulk diffeomorphism freedom of $g_{\mu\nu}$ corresponds to the boundary gauge freedom of A_μ (Abelian $U(1)$ or non-Abelian $SU(N)$) when $g_{\mu\nu}$ and A_μ are physically real with substantive gauge freedoms.

Proof:

1. *Symmetry Groups*: Bulk $\mathrm{Diff}(M)$'s Lie algebra $\mathrm{Vect}(M)$ has commutators $[\xi_1, \xi_2]^\mu = \xi_1^\nu \partial_\nu \xi_2^\mu - \xi_2^\nu \partial_\nu \xi_1^\mu$, infinite-dimensional and non-compact. Boundary $\mathcal{G}$'s algebra $\mathfrak{g}$ has $[t^a, t^b] = i f^{abc} t^c$, finite-dimensional and compact (for $SU(N)$) or trivial (for $U(1)$).
2. *Reality Constraint*: $g_{\mu\nu}$ and A_μ are real, gauge-fixed, with local, continuous dynamics per the AB effect. Gauge-invariant reductions ($F_{\mu\nu}$, $T_{\mu\nu}$) are incomplete (Section 2.4.4).
3. *Standard Mapping*: $\mathrm{Diff}(M) \to SO(2,d)$ loses $g_{\mu\nu}$'s full freedom; $\mathcal{G} \to T_{\mu\nu}$ reduces A_μ to $F_{\mu\nu}$, violating locality and continuity.
4. *Structural Mismatch*: No homomorphism exists from $\mathrm{Vect}(M)$ to $\mathfrak{g}$ due to dimensionality and algebraic differences. $\mathrm{Diff}(M) \not\simeq \mathcal{G}$.
5. *Reformulation*: Extending the boundary to $\mathcal{G}' = \mathrm{Diff}(\partial M) \times C^\infty(\partial M, G)$ mirrors the bulk, collapsing the gauge/gravity distinction (Section 5.2).
6. *Conclusion*: Standard duality fails due to symmetry mismatch; reformulation eliminates holography. No consistent duality holds under this ontology.

Q.E.D.

This theorem reinforces Section 5.1's mismatch: $\mathrm{Diff}(M)$ and $\mathcal{G}$'s structural incompatibility precludes correspondence when $g_{\mu\nu}$ and A_μ are real. It extends Section 5.2's collapse: reformulation aligns gauge with gauge and gravity with gravity, negating duality. Applied broadly (Section 5.3), it excludes all gauge/gravity frameworks mathematically, urging a shift to a potential-centric paradigm (Section 6).

5.5 Successes as Approximations

The gauge/gravity duality framework, particularly AdS/CFT, has yielded remarkable—and often surprising—insights, from black hole thermodynamics to strongly coupled quantum systems, raising the question of how my critique reconciles its exclusion of duality with these achievements. I suggest that these successes arise as approximations within specific regimes, reflecting a deeper interplay of symmetry and emergence rather than a full equivalence, while aligning with my emphasis on the local, continuous roles of A_μ and $g_{\mu\nu}$ (Sections 2.5 and 3.1). Here, I explore this reconciliation, recognizing the duality's practical utility while underscoring its limitations.

In black hole thermodynamics, AdS/CFT maps the CFT partition function to an AdS black hole's thermodynamics, reproducing the Bekenstein-Hawking entropy and Hawking-Page transition [3]. This success, striking in its precision, hinges on equilibrium states where the CFT's gauge-invariant $T_{\mu\nu}$ captures bulk geometry's coarse-grained features (e.g., horizon area). My analysis (Section 4.2) shows this falters in dynamic scenarios, where $g_{\mu\nu}$'s evolution drives effects like gravitational phase shifts unrepresented in $T_{\mu\nu}$ (Section 3.1.2). The surprise lies in the conformal symmetry match—AdS isometries aligning with CFT symmetries—enabling such accuracy without $g_{\mu\nu}$'s full freedom.

Similarly, in strongly coupled systems—e.g., the quark-gluon plasma's viscosity-to-entropy ratio via holographic QCD—AdS/CFT leverages the large-N limit and near-equilibrium conditions to match experimental data. This effectiveness stems from emergent bulk fields approximated by boundary operators (e.g., correlation functions), despite my no-go result deeming these incomplete for local dynamics (Section 2.4.4). The deeper reason is the CFT's ability to coarse-grain over microstates, mimicking A_μ and $g_{\mu\nu}$'s macroscopic effects where fine details are less critical. In regimes requiring such precision—e.g., rapid flux variations (Section 3.1.1)—the duality's boundary perspective struggles, suggesting its utility is context-specific.

This reinterpretation respects AdS/CFT's contributions while framing its successes as emergent approximations, driven by symmetry alignments and coarse-graining, not a direct reflection of A_μ and $g_{\mu\nu}$'s reality. My critique questions the claim to deeper equivalence (Section 5.1), suggesting these results are projections of a physics fundamentally governed by potentials. A potential-centric framework could encompass these as special cases, with tests like gravitational AB effects probing where approximations hold and where the primacy of local mediators prevails.

6 Conclusion

The AdS/CFT correspondence presents an elegant vision: a gravitational bulk in Anti-de Sitter spacetime mirrored by a conformal field theory on its boundary, connected through gauge-invariant observables like $F_{\mu\nu}$, Φ, and $T_{\mu\nu}$. My analysis, inspired by the Aharonov-Bohm (AB) effect's revelation of flaws in such quantities—nonlocality, discontinuity, and incompleteness (Section 2)—suggests a different perspective. I have argued that gauge potentials A_μ in the Lorenz gauge and gravitational fields $g_{\mu\nu}$ as substantival entities govern the bulk's local, continuous dynamics (Sections 3 and 4), a reality the CFT's boundary view struggles to fully reflect. This leads me to propose that gauge/gravity duality, as traditionally conceived, may not hold (Section 5).

This perspective is not a dismissal but a reconsideration. If A_μ and $g_{\mu\nu}$ carry physically meaningful gauge freedoms, as the AB effect and its gravitational analogue suggest, their transformation or absence in the CFT reveals a gap in the symmetry mapping. Even reformulating the duality to include these potentials risks blurring its core distinction, aligning gauge with gauge and gravity with gravity rather than bridging them holographically. This challenge extends beyond AdS/CFT to other gauge/gravity frameworks, where my no-go result (Section 2.4.4) questions the completeness of invariant-based descriptions. Yet, I recognize duality's stunning successes—such as in black hole thermodynamics—which emerge as approximations within specific contexts, hinting at a deeper interplay of symmetry and emergence.

What emerges is an invitation to explore a new path. I suggest a framework where A_μ and $g_{\mu\nu}$ stand as central, their gauge freedoms preserved, offering a unified view of spacetime and matter fields without reliance on holographic duality. This potential-centric approach does not seek to erase AdS/CFT's insights but to build upon them, reframing its achievements as projections of a physics rooted in local mediators. It encourages a shift from the boundary's gauge-invariant lens to the bulk's dynamic reality, fostering a broader understanding of quantum gravity.

Looking ahead, this shift calls for both theoretical and empirical steps. Gravitational AB effects in AdS—phase shifts around massive sources—offer a promising test to probe this ontology, grounding my critique in observable phenomena. Theoretically, we might develop a narrative where gauge and gravitational potentials take precedence, illuminating their interplay without the constraints of duality. This paper, weaving AB insights with a careful reassessment of holography, does not aim to close a chapter but to open one—inviting a dialogue to refine our theories with the steady guidance of potentials as our foundation.

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