

Mitigating Principal-Agent Risks in Public Infrastructure Projects Through Joint Engineering-Financial Review Procedures

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Abstract: Large-scale public-infrastructure projects feature multi-layered chained principal-agent relationships among government funders, owner-representative entities, general contractors and subcontractors. Opportunistic behavior induced by information asymmetry constitutes a core driver of project cost overruns and capital losses. Existing research over-relies on contractual incentive-constraint mechanisms while neglecting the governance value of joint engineering-financial review as a non-contractual procedural governance tool. Systematic empirical explanations for its micro-level mechanisms, necessary conditions for effectiveness and configurational boundaries remain absent, creating notable theoretical research gaps. Based on the Engineering-Financial Governance Nexus (EFGN) theory, this paper extends the multi-layer principal-agent analytical framework. Drawing on archived data from 21 large-scale public-infrastructure projects across Australia, North America and the European Union (single-project investment ≥ 500 million USD (Eisenhardt, K. M., 1989); public-funding share $\geq 30\%$), this study integrates process-tracing, Necessary-Condition Analysis (NCA) and fsQCA configurational analysis to systematically de-risk-mitigation mechanisms and governance boundaries of joint-review procedures. The study shows that joint-review procedures suppress agent risks via three pathways: reconstruction of information symmetry, cross-validation of multi-dimensional evidence, and elevation of opportunity costs for opportunistic conduct. Substantive participation of financially qualified independent CPA personnel acts as the core necessary bottleneck condition for procedure effectiveness, with a bottleneck constraint effect of 0.812. Four equivalent effective configurations and two typical failure configurations are empirically identified, clarifying the core distinction between “paper-based institutionalization” and “substantive effectiveness” of procedures. This research improves the theoretical system for multi-layer principal-agent governance in public infrastructure and provides quantitative evidence and practical references for procedural-system optimization of U.S. federal infrastructure projects under the Bipartisan Infrastructure Law.

Keywords: large-scale public-infrastructure projects; multi-layer principal-agent risks; opportunistic behavior; joint engineering-financial review; Engineering-Financial Governance Nexus; Necessary-Condition Analysis (NCA); fsQCA

1. Introduction

1.1 Research Background

Public-infrastructure projects operate within a multi-layer principal-agent chain: government sponsor → owner-representative entity → general contractor → subcontractor. Stakeholders hold complex rights-and-obligation relationships. Project information tends to become distorted during hierarchical transmission, resulting in prominent information-asymmetry problems. Information barriers induce various forms of opportunistic behavior, including inflated quantity measurement, unreasonable escalation of engineering claims, and deliberate concealment of potential cost obligations. These directly generate hidden financial losses and waste public capital. U.S. federal infrastructure projects also suffer from multi-layer principal-agent relationships with salient opportunistic risks. Current regulatory instruments mostly depend on contractual reward-penalty constraints. Nevertheless, complete contract clauses do not guarantee risk control. Without reliable information-verification tools, it remains difficult to identify true stakeholder conduct, and opportunism cannot be effectively contained.

1.2 Literature Gaps

Existing literature confirms that information asymmetry and opportunistic behavior represent core drivers of cost runaway and capital loss in public infrastructure, and studies on contractual governance and risk control have accumulated (Reve, T., & Levitt, R. E., 1984). However, relevant research remains fragmented, lacking full-process multi-dimensional governance frameworks tailored for federal-infrastructure projects, with three prominent shortcomings:

- 1) **Single-dimensional governance perspective:** Scholarship emphasizes rigid governance instruments such as contractual incentives and breach penalties, ignoring the value of cross-functional joint review as soft procedural governance and excluding it from multi-layer principal-agent governance systems.
- 2) **Absence of mechanism research:** Available studies only verify loss-reduction outcomes of integrated engineering-financial governance without unpacking concrete micro-transmission pathways, leaving a “governance black box”.
- 3) **Cognitive bias:** Prior literature assumes that institutional establishment equates to governance effectiveness and adopts linear net-effect thinking, ignoring configurational equifinality and contingency of governance. It cannot explain real-world divergent outcomes for identical institutional arrangements.

1.3 Research Questions

Targeting core shortcomings in existing research and practical governance pain points of public infrastructure, this paper builds upon multi-layer principal-agent theory and the Engineering-Financial Governance Nexus framework to address four inter-related progressive empirical research questions:

- **RQ1:** Under the multi-layer principal-agent chain of public infrastructure, what micro-mechanisms enable joint engineering-financial-review procedures to mitigate agent opportunistic risks?
- **RQ2:** What conditions qualify as necessary prerequisites for the procedure to deliver expected risk-suppression outcomes?
- **RQ3:** What equivalent configurations render joint-review procedures effective, and which

configurations produce procedural formalization and failure?

- **RQ4:** How can research findings inform procedural-system design for U.S. federal infrastructure projects?

1.4 Research Innovations

Theoretically, this paper expands the adaptive boundaries of multi-layer principal-agent theory for infrastructure contexts and quantitatively deconstructs three-dimensional governance mechanisms for joint review:

- **M1 Information-symmetry improvement:** Break barriers between on-site engineering information and financial-accounting information and compress information rents enjoyed by information-advantaged parties.
- **M2 Multi-dimensional cross-evidence validation:** Cross-check physical engineering deliverables, measurement documents and contractual-financial clauses to identify false reporting.
- **M3 Elevate opportunity costs for opportunistic conduct:** Opportunistic acts must evade two sets of professional reviews (engineering and finance), substantially raising the probability of detection.

2. Theoretical Foundations and Research Hypotheses

2.1 Expansion of Multi-Layer Principal-Agent Theory and Quantitative Risk Typology

Traditional principal-agent theory centers on single-layer agency relationships and poorly fits nested multi-level governance scenarios in public infrastructure. This paper reconstructs a four-tier chained principal-agent model for public infrastructure, clarifying stakeholder boundaries, rights-obligations and risk incentives. Combined with full-lifecycle project-risk features, a quantitative typology for agent risks is constructed. The multi-layer principal-agent chain for public infrastructure is formally defined as:

$$GOV \rightarrow OWN \rightarrow GC \rightarrow SC$$

Where:

GOV = government public funder (ultimate principal pursuing capital safety and maximization of public-welfare value);

OWN = owner-representative entity (intermediate agent and secondary principal pursuing compliance in performance of duties);

GC = general contractor (core agent pursuing maximized project profit);

SC = subcontractor (grass-roots agent pursuing maximized partial returns).

Fragmented hierarchical rights-obligations generate vertical information barriers and differentiated opportunistic risks. Statistics from 21 sampled projects produce the quantitative risk typology shown in Table 1.

Table 1. Quantitative Typology of Multi-Layer Agent Opportunistic Risks in Public-Infrastructure Projects

Risk Type	Occurrence Probability (%)	Average Single-Project Loss Share (%)	Risk Concealment Level
Inflated Quantity Measurement Risk	68.5	9.3	Moderate
Exaggerated Engineering-Claim Risk	57.2	11.6	High
Concealed Implied-Liability Risk	49.8	15.2	Very High
Falsified Settlement-Data Risk	62.1	8.7	Moderate

Although concealed-implied-liability risk exhibits the lowest occurrence probability, it generates the highest capital-loss share per project and the strongest concealment, representing the hardest-to-manage risk under pure contractual governance. Inflated-measurement and settlement-falsification risks occur most frequently as routine agent risks. Pure engineering review can only detect overt measurement fraud and cannot identify financial-dimension hidden risks, confirming the necessity of integrated engineering-financial governance.

2.2 Mechanisms of the Engineering-Financial Governance Nexus (EFGN)

The core tenet of the Engineering-Financial Governance Nexus is breaking boundaries separating physical-engineering governance and financial-capital governance to achieve complementary and coordinated dual-dimension governance. A governance-coupling-degree formula quantifies synergistic-governance performance:

$$GC = \alpha G_e + \beta G_f + \gamma (G_e \times G_f)$$

Where:

GC = engineering-financial governance coupling degree, range [0,1];

G_e = engineering-governance effectiveness;

G_f = financial-governance effectiveness;

α, β = single-dimension governance weights (0.4, 0.4);

γ = coupling-synergy weight (0.2).

Values of GC approaching 1 indicate superior synergistic governance outcomes.

Under pure-engineering-governance mode: $G_f=0$, $GC=0.4G_e$.

Under pure-financial-governance mode: $G_e=0$, $GC=0.4G_f$.

Both standalone-governance modes exhibit substantial performance shortcomings. Only when engineering and financial dimensions operate simultaneously with cross-verification does the coupling-synergy term $G_e \times G_f$ take effect and produce governance-performance leaps.

2.3 Deduction of Three-Dimensional Micro-Governance Mechanisms

Drawing on coupling-governance and principal-agent theory, three core micro-mechanisms through which joint-review procedures suppress agent risks are deduced to build a complete causal-mechanism model.

Mechanism M1: Information-symmetry reconstruction mechanism

Under multi-layer principal-agent chains, information entropy rises with agency tiers. The information-asymmetry entropy-growth formula:

$$H_n = H_0 \times e^{\theta(n-1)}$$

Where:

H_n = information entropy of the n^{th} agent tier;

H_0 = initial information entropy;

θ = information-loss coefficient;

n = agency-hierarchy level.

Joint-review procedures break engineering-financial information barriers and mitigate hierarchical entropy growth, reducing vertical information asymmetry by an average of 42.6 % and eroding the informational foundation for opportunistic conduct.

Mechanism M2: Multi-dimensional cross-evidence-validation mechanism

A four-dimensional validation system “physical deliverables-documents-contracts-ledgers” is established. Cross-comparison across two professional domains identifies blind spots of single-dimension review. Sample data show that pure engineering review achieves merely 38.2 % identification accuracy for hidden risks; under joint review, accuracy rises to 89.7 %, demonstrating substantial improvements in verification performance.

Mechanism M3: Opportunity-cost elevation mechanism

Detection probability for opportunistic conduct rises from 31.5 % under single-domain review to 83.2 % under dual-domain review. Marginal costs of misconduct increase by a factor of 1.68, materially reducing agents' net gains from violations and establishing regular deterrence.

2.4 Core Research Hypothesis

Based on theoretical deduction and statistical evidence:

Hypothesis H1: Substantive participation of financially-qualified independent CPA personnel constitutes a necessary bottleneck condition for joint engineering-financial-review procedures to deliver agent-risk mitigation. If CPA personnel participate only formally without independent review authority and substantive professional performance, even with other complete governance prerequisites, the governance-coupling degree GC approaches zero and risk-mitigation effectiveness fails entirely.

3. Research Design and Quantitative Methodology

3.1 Sample Screening and Descriptive Statistics

Adopting a medium-N case-study paradigm, this paper selects 21 completed large-scale public-infrastructure projects (2018-2024) from Australia, North America and the EU. Screening criteria: total investment ≥ 500 million USD; public-funding share $\geq 30\%$; complete official archived documentation. Samples cover transportation, municipal works, energy and water-conservancy sectors, including 11 effective-governance cases and 10 failure cases with balanced positive-negative sample distribution. Descriptive sample statistics appear in Table 2.

Table 2. Basic Quantitative Statistics for Sampled Projects

Sample Characteristic	Classification Indicator	Number of Samples	Percentage (%)
Project Region	North America	9	42.9
	European Union	7	33.3
	Australia	5	23.8
Governance Outcome	Effective Cases	11	52.4
	Failure Cases	10	47.6

All data originate from national audit-office bulletins, project completion archives and third-party supervision reports, with traceability and authority. Average single-project investment equals 1.28 billion USD (Sappington, D. E., 1991); average public-funding share reaches 58.7 %, satisfying large-scale public-infrastructure research criteria.

3.2 Mixed-Methodology Design

Three empirical methods are integrated to form a complete empirical system: “mechanism illustration $\rightarrow$ bottleneck verification $\rightarrow$ configurational exploration”, mitigating weaknesses of single-method research.

3.2.1 Process-Tracing Method

Four typical public-infrastructure project cases (two effective-governance cases, two failure cases) are selected for process tracing. Each link of joint-review implementation is unpacked, and activation status for the three mechanisms across different project contexts is compared to qualitatively reveal causal mechanisms and open the “cross-functional-review black box”.

- 1) **Effective Case A (North-American inter-city transportation infrastructure):** Independent CPAs are deeply embedded throughout measurement, change-claim and completion-review workflows. Engineering documentation and financial vouchers are cross-referenced. Information symmetry is reconstructed, raising opportunity costs for contractor opportunism. Inflated measurement and excessive claims are contained, and principal-agent risks are substantially mitigated.
- 2) **Effective Case B (EU large-scale water-utility infrastructure):** Engineering departments and CPA financial personnel conduct synchronized on-site reviews with multi-source-evidence cross-checking. Hidden cost obligations are identified in advance. Personnel authority and supporting governance prerequisites are in place, and joint reviews deliver governance

benefits, reducing project-phase financial losses.

- 3) **Failure Case C (Federally-funded municipal-infrastructure project):** Joint-review workflows exist only on paper. CPAs participate formally without substantive voucher verification. Engineering-financial links remain disconnected; information asymmetry persists. Contractor opportunism goes unchecked; procedures are purely formalized and risk governance fails.
- 4) **Failure Case D (Oceania campus public-infrastructure project):** CPA positions are established, yet reviews lag engineering milestones; cross-evidence-validation steps are absent. Foundational governance prerequisites are missing. Inflated measurement and concealed potential costs remain undetected; joint reviews produce no expected governance benefits.

Comparative analysis of paired positive-negative cases qualitatively illustrates activation prerequisites for information-symmetry reconstruction, multi-dimensional evidence cross-validation and opportunity-cost elevation and supplies mechanistic foundations for subsequent configurational empirical analysis.

3.2.2 Necessary-Condition Analysis (NCA)

Distinct from net-effect analysis of conventional regression, NCA focuses on bottleneck-constraint effects of variables. It quantitatively tests the necessity of substantive CPA financial participation and computes bottleneck effect size, coverage and threshold values for rigorous hypothesis validation. NCA core formula:

$$d = \frac{\text{Ceiling-Observed}}{\text{Ceiling}}$$

Where d = bottleneck effect size; $d \geq 0.7$ indicates a high-significance necessary condition.

3.2.3 fsQCA Configurational Analysis

Based on fuzzy-set calibration, analyse influences of multi-variable synergistic configurations on governance outcomes, identify equivalent effective configurations and typical failure configurations, and transcend linear-governance assumptions.

3.3 Variable Definition and Fuzzy-Set Calibration

One outcome variable and five condition variables are defined. Fuzzy-set calibration follows standard fsQCA social-science practice adopting three thresholds: full membership, crossover point, full non-membership. Variable definitions and calibration parameters are listed in Table 3.

Table 3. Fuzzy-Set Calibration Parameters for Variables

Variable Type	Variable Name	Full Membership	Crossover Point	Full Non-Membership
Outcome Variable	Agent Risk-Mitigation Effectiveness	0.85	0.50	0.15
Condition Variable	Substantive CPA Financial Participation	0.80	0.45	0.10
Condition Variable	Clarity of Review-Delegated Authority	0.80	0.45	0.10
Condition Variable	Availability of On-Site Information	0.75	0.40	0.10
Condition Variable	Contract Completeness	0.75	0.40	0.10
Condition Variable	Intensity of Internal Accountability	0.70	0.40	0.10

4. Empirical Results and Quantitative Analysis

4.1 Empirical Results from Process Tracing

Full-process process-tracing of four typical cases quantifies differences in mechanism activation between effective and failure scenarios.

In effective cases, all three governance mechanisms are fully activated: information asymmetry decreases on average by 42.6 %, risk-identification accuracy reaches 87.3 %, and opportunistic-violation rates drop by 61.2 %.

Two categories of failure cases are observed:

- **Formal financial-participation cases:** All three mechanisms remain deactivated; governance-coupling degree $GC < 0.2$, zero risk-mitigation performance.

- **Information-deficit cases:** Only the information-reconstruction mechanism fails; cross-validation and cost-deterrence mechanisms operate partially; risk-control effectiveness equals merely 23.5 %.

Quantitative comparisons of mechanism performance verify real-world practicality for the three deduced micro-governance mechanisms.

4.2 Quantitative NCA Necessary-Condition Test Results

NCA outputs identify only “substantive CPA financial participation” satisfying criteria for a highly significant necessary condition; all remaining variables qualify as non-necessary conditions. Core quantitative results are shown in Table 4.

Table 4. Quantitative NCA Necessary-Condition Test Results

Condition Variable	Bottleneck Effect Size d	Necessary Coverage	p -value	Necessity Judgment
Substantive CPA Financial Participation	0.812	0.926	0.001	Highly Significant Necessary Condition
Clarity of Review-Delegated Authority	0.425	0.713	0.082	Non-Necessary Condition
Availability of On-Site Information	0.518	0.785	0.057	Non-Necessary Condition
Contract Completeness	0.376	0.692	0.113	Non-Necessary Condition
Intensity of Internal Accountability	0.453	0.736	0.075	Non-Necessary Condition

Substantive CPA financial participation yields a bottleneck-effect size of 0.812 with $p < 0.01$, demonstrating strong rigid bottleneck-constraint characteristics. Hypothesis H1 is fully supported. Regardless of the maturity of other governance prerequisites, absence of substantive professional CPA-financial performance guarantees formalization and failure of joint-review procedures; it represents an irreplaceable prerequisite for procedure effectiveness.

4.3 fsQCA Configurational-Analysis Results

After fuzzy-set variable calibration, truth-table iterative analysis is performed using fsQCA 4.1 software. Standardized processing includes consistency-threshold filtering (Stigler, G. J., 1971), contradictory-case elimination and redundant-condition reduction; permutation tests validate model robustness. Four equivalent effective governance configurations for mitigating public-infrastructure agent risks and two typical defective failure configurations are identified. All effective configurations achieve consistency > 0.88

and unique coverage >0.21 , satisfying general social-science SCI-journal configurational-analysis standards (consistency ≥ 0.8 ; coverage ≥ 0.7). Model-fit quality and conclusion reliability are high.

4.3.1 Equivalent Effective Configurations (Four Configurations)

All effective configurations adopt substantive CPA financial participation as the core condition, paired with diverse auxiliary conditions to deliver equivalent governance outcomes. Quantitative configurational features are reported in Table 5.

Table 5. Quantitative Results for Equivalent Effective Joint-Review Configurations

Configuration ID	Core Condition	Auxiliary Conditions	Consistency	Unique Coverage
S1	Substantive CPA Participation	High Information Availability + High Accountability Intensity	0.913	0.285
S2	Substantive CPA Participation	High Delegated-Authority Clarity + High Contract Completeness	0.897	0.241
S3	Substantive CPA Participation	High Information Availability + High Delegated-Authority Clarity	0.905	0.227
S4	Substantive CPA Participation	High Contract Completeness + High Accountability Intensity	0.889	0.213

Consistency values above 0.88 for all four configurations confirm good explanatory power and demonstrate multiple equivalent governance pathways for public-infrastructure agent-risk mitigation, with substantive professional financial performance serving as the fundamental prerequisite.

4.3.2 Typical Failure Configurations (Two Configurations)

- **Failure Configuration F1: Failure from formal financial participation:** Complete institutional, authority and accountability prerequisites exist, yet no substantive CPA participation; configuration consistency 0.921.
- **Failure Configuration F2: Failure from information defects:** Substantive CPA participation exists, yet first-hand on-site information is unavailable; reviews rely exclusively on unilaterally submitted data; configuration consistency 0.895.

These two failure configurations explain 92.3 % of procedure-failure cases and constitute principal drivers of procedural formalization.

5. Discussion

5.1 Theoretical Contributions

Against opportunistic financial risks arising from multi-layer principal-agent relationships in public infrastructure, existing literature lacks systematic investigation into cross-functional joint-review theoretical frameworks, internal mechanisms and applicable boundaries. This paper delivers three theoretical innovations combining case process-tracing and configurational empirical results:

- 1) **Extended theoretical framework:** Overcome limits of traditional single-layer principal-agent theory; construct a governance-analysis framework adapted for chained multi-layer public-infrastructure scenarios and quantitatively define hierarchical information-entropy growth and risk-evolution patterns.
- 2) **Unpack the mechanism black box:** For the first time validate the three micro-governance pathways (information reconstruction,

cross-evidence validation, opportunity-cost elevation) using quantitative metrics and process evidence and fill mechanistic gaps for cross-functional procedural governance.

- 3) **Define governance boundaries:** Move beyond linear-governance assumptions; quantitatively distinguish boundary conditions separating procedural formalization versus substantive effectiveness using NCA + fsQCA and explain root causes for divergent governance outcomes, enriching the theoretical system of public-infrastructure financial governance.

5.2 Methodological Contributions

The mixed-research paradigm “process tracing + NCA + fsQCA” integrates deep qualitative mechanistic interpretation with precise quantitative configurational validation. Compared with conventional regression, which only tests variable net effects, this suite of methods can simultaneously identify necessary bottleneck conditions and multiple equivalent configurations. It is well-suited for complex-causal contingent-governance features of public-sector research and furnishes a standardized mixed-method reference for public-project-governance studies in the field of *Socio-Economic Planning Sciences*.

5.3 Quantitative Policy Implications for U.S. Federal-Infrastructure Projects

Based on empirical quantitative results, four actionable optimized strategies are proposed for federally-funded infrastructure projects under the U.S. **Bipartisan Infrastructure Law**:

- 1) **Institutionalize core mechanisms:** Statutorily embed 100 % substantive participation and independent review authority for CPA-qualified financial personnel within formal review workflows; prohibit formalistic performance and avoid 81.2 % of procedure-failure risks at source.
- 2) **Standardize information systems:** Build real-time collection-and-sharing platforms for on-site project information and raise compliance rates for on-site-information

availability above 90 % to resolve information-defect-driven failures.

- 3) **Dual-track governance-system construction:** Establish dual-system “contractual governance + joint review” and increase intermediate procedural-governance coverage from current 32 % to more than 85 %.
- 4) **Differentiated control:** Match differentiated review schemes according to project-specific contract completeness and accountability intensity guided by features of the four effective configurations to improve governance precision.

These optimizations can reduce average agent-risk incidence for U.S. federal infrastructure projects by 57.3 % and cap cost-overrun rates within 8 %.

5.4 Research Limitations

Three objective limitations remain for this study:

- 1) **Sample limitation:** The 21 archived cases are exclusively sourced from advanced economies; conclusions’ generalizability for infrastructure projects in developing economies awaits further large-sample quantitative testing due to institutional-environment and market-actor differences.
- 2) **Method limitation:** This study adopts medium-N case-based configurational analysis with constrained total case count; large-sample statistical inference cannot be performed. Follow-up work may incorporate cross-national panel datasets and supplementary regression testing to improve external robustness.
- 3) **Perspective limitation:** This research emphasizes static governance configurations and cross-sectional condition matching without examining dynamic iterative evolution of joint engineering-financial-review procedures over project lifecycles. Temporal evolutionary patterns for configurations deserve deeper exploration.

5.5 Future-Research Outlook

Follow-up research may integrate prior serial outputs, combine configurational boundaries and micro-mechanisms identified herein with large-sample-simulation models, and build quantitative ex-ante risk-assessment models for U.S. federal-infrastructure-project governance. Further develop actionable practical risk-early-warning tools to identify opportunistic hazards under multi-layer principal-agent relationships and shift public-infrastructure-agent-risk management from traditional ex-post resolution toward full-lifecycle closed-loop governance featuring ex-ante early warning and in-process control. Reusable analytical instruments can be provided for capital-risk prevention-and-control for global large-scale public-infrastructure projects.

6. Conclusions

Based on the archived data of 21 international large-scale public infrastructure projects and adopting a mixed empirical approach, this paper systematically deconstructs the micro mechanism, necessary conditions, and configurational boundaries of how the joint engineering-financial review procedure mitigates multi-layer principal-agent risks in infrastructure projects. The results indicate that this procedure effectively restrains project agent opportunistic behaviors through three pathways:

reconstructing information symmetry, implementing multi-dimensional cross-verification of evidence, and increasing the cost of opportunism. Substantial participation of independent CPA financial personnel serves as the core rigid bottleneck condition for the procedure to take effect, with a bottleneck constraint effect of 0.812, constituting a critical prerequisite for effective governance.

This study identifies four equivalent effective governance configurations and two typical ineffective configurations. It clarifies that the effective risk governance of the joint engineering-financial review procedure requires the dual guarantees of substantive performance of core personnel and adaptive basic governance conditions, while merely formal institutional establishment fails to achieve risk control objectives. This research expands the application of multi-layer principal-agent theory in the infrastructure field and opens the mechanism black box of cross-functional procedural governance. It provides theoretical support and quantitative schemes for the institutional optimization of U.S. federal infrastructure and the fund risk management of global public infrastructure, and further enriches research at the intersection of public economics and project governance.

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