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Secure, Cost-Optimal, and Integrity-Preserving Data Migration: A Unified Framework for Moving Enterprise Workloads from Proprietary to Open-Source Cloud Databases

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ABSTRACT

This article presents a comprehensive, theoretically grounded framework for secure, cost-optimal, and integrity-preserving migration of enterprise data from proprietary relational database management systems (RDBMS) such as Oracle to open-source cloud-native platforms such as PostgreSQL. We synthesize insights from contemporary research in cloud data security, cost-aware migration strategies, data integrity verification, multi-cloud placement optimization, master data management, and cryptographic key exchange to construct an end-to-end methodology suitable for large-scale enterprise modernization projects. The framework addresses the three core tensions enterprises face during migration: (1) maintaining confidentiality, integrity, and availability while data moves across trust boundaries (security tension); (2) minimizing total cost of ownership and operational expenditure without sacrificing performance or regulatory compliance (cost tension); and (3) assuring semantic correctness—schema, stored-procedure, and business-logic fidelity—when translating proprietary constructs into open-source equivalents (semantic tension). The article provides a rigorous description of preparatory assessment, hybrid migration staging, verification and auditing techniques, workload-aware cost modeling, and long-term operational governance. We further analyze potential failure modes, adversarial threats, and practical limitations, and propose mitigation strategies including cryptographic auditing, incremental migration scheduling, schema refactoring heuristics, and master data harmonization controls. This contribution integrates prior empirical studies and theoretical models into a unified narrative and offers a prescriptive roadmap for researchers, system architects, and enterprise engineers seeking to modernize database infrastructure while preserving security, cost-effectiveness, and trustworthiness.

KEYWORDS

cloud migration, data security, PostgreSQL, Oracle migration, data integrity, cost optimization, master data management

INTRODUCTION

The drive to modernize enterprise information systems has accelerated adoption of cloud platforms and open-source database technologies. Economic pressures, vendor lock-in concerns, and an increasing preference for cloud-native architectures motivate organizations to migrate mission-critical workloads from proprietary systems such as Oracle to open-source alternatives like PostgreSQL, often deployed within cloud infrastructures (Stonebraker & Hong, 2020; Natti, 2023). However, such migrations are not merely technical exercises; they are

complex socio-technical transformations that interact with legal, security, financial, and operational constraints. The literature on cloud data security emphasizes that cloud migration introduces unique threats to confidentiality, integrity, and availability because data traverses new network paths, resides on multi-tenant hardware, and becomes subject to different administrative boundaries (Gupta et al., 2018). Simultaneously, experimental studies of migration cost highlight that naive migration plans often lead to unexpected expenses—ranging from transient transfer charges to ongoing inefficiencies after cutover—unless migration is planned with cost-aware placement and workload optimization (Ramani et al., 2019; Wang et al., 2021).

Existing scholarship tackles important fragments of the migration problem: secure storage and access controls in cloud computing (Gupta et al., 2018), cost-focused migration experiments (Ramani et al., 2019), audit and integrity verification frameworks (Siddiqui et al., 2020; Garg, 2020), and the economics of data placement across multi-cloud systems (Wang et al., 2021). Separately, practitioner-focused literature and tool evaluations discuss the practical steps and conversion tools for Oracle-to-PostgreSQL migrations (Amazon Web Services, 2023; Popescu & Vasilescu, 2022; Chen & Park, 2019). Yet a coherent, scholarly framework that unites security-preserving algorithms, economically rational placement decisions, integrity-auditing protocols, and schema/logic migration strategies into an executable migration methodology remains underdeveloped. This gap creates risk for enterprises: either they adopt low-risk but costly strategies (e.g., prolonged dual-licensing), or they attempt rapid, low-cost migrations that expose them to data integrity incidents, regulatory noncompliance, or persistent performance degradation.

The problem statement motivating this work, therefore, is to develop a unified framework that (a) strictly preserves data security guarantees throughout migration, (b) optimizes the total cost of migration and ongoing operations through workload-aware data placement, and (c) provides provable assurance of data integrity and semantic fidelity when converting proprietary database constructs into open-source forms. We aim to reconcile the tensions between security and economics by integrating cryptographic assurance mechanisms (including secret key exchange and cryptographic auditing), workload-aware cost models, and systematic schema and procedural translation methodologies informed by empirical tool evaluations and conversion best practices (Praveen Kumar, 2017; Dhananjay & Mehta, 2018; Walker & Simmons, 2017).

This introduction continues by situating our contribution within related work. Data security research in cloud computing documents threat surfaces introduced by multi-tenancy, network-level exposures, and inadequate access controls; these must be considered at both architectural and operational levels (Gupta et al., 2018). Cost analyses of migration underline that cloud transfer costs, virtualization overheads, and suboptimal data placement are frequent causes of cost overruns (Ramani et al., 2019; Wang et al., 2021). Data integrity assurance techniques—ranging from provable data possession schemes to third-party audit protocols—offer mechanisms to verify that migrated data remains unaltered and complete (Siddiqui et al., 2020; Garg, 2020). The database migration literature focuses on mechanical and semantic challenges of converting schema, SQL dialects, PL/SQL to PL/pgSQL, stored procedures, triggers, and proprietary optimizer hints (Dhananjay & Mehta, 2018; Tan & Venkatesh, 2020). Research that experimentally evaluates migration tools and conversion strategies gives practical evidence of typical pitfalls and conversion error classes (Popescu & Vasilescu, 2022; Chen & Park, 2019). Combining these perspectives enables constructing a migration methodology that is simultaneously defensible from a security standpoint, economically rational, and operationally feasible.

METHODOLOGY

This section articulates, in rigorous textual form, the methods that compose our unified migration framework. The methodology has five major components: (1) Pre-migration assessment and risk modeling, (2) Secure

staging and cryptographic key management, (3) Incremental conversion and semantic fidelity assurance, (4) Workload-aware cost and placement optimization, and (5) Post-migration verification, auditing, and governance. Each component is detailed, including the rationale, recommended algorithms or procedures, and mapping to literature evidence.

Pre-migration assessment and risk modeling

A robust migration begins with an exhaustive inventory and classification of data assets, workloads, and their security and compliance requirements. This inventory should include schema objects (tables, views, indexes), procedural objects (stored procedures, triggers, functions), data volumes, I/O patterns, latency sensitivity, SLAs, and regulatory obligations such as data residency and retention policies. The literature emphasizes the criticality of such mapping: cost-optimal placement relies on a precise understanding of workload characteristics (Wang et al., 2021), while security decisions depend on data sensitivity classifications (Gupta et al., 2018).

Risk modeling follows inventory. For each asset class, construct threat models enumerating adversarial capabilities (e.g., network eavesdropping, compromised cloud administrator, misconfiguration-induced exposure) and accidental risks (e.g., schema conversion errors, logical corruption). Threat analysis should use established frameworks and produce prioritized risk registers. A conjoined risk and cost model then assigns an expected loss to each migration pathway, enabling cost-benefit trade-offs: for instance, encrypted in-flight transfers incur CPU and key-management costs but reduce breach exposure; storing sensitive data in a dedicated VPC addresses confidentiality concerns at the cost of increased hosting fees (Ramani et al., 2019; Gupta et al., 2018). This quantified risk approach aligns with the principle of economically informed security decisions: organizations should invest in protections up to the point where marginal security benefit equals marginal cost (Wang et al., 2021).

Secure staging and cryptographic key management

Once assets and risks are cataloged, the migration pipeline must ensure that data remains confidential and tamper-evident at all times. The pipeline stages include extraction, transport, transformation, loading, and live cutover. For each stage, the following controls are recommended:

● Encryption-in-transit using mutually authenticated TLS with ephemeral key exchange mechanisms to limit long-term key exposure. Practical cloud guidance recommends TLS 1.2+ with strong ciphers and certificate pinning for critical endpoints (Gupta et al., 2018).

● Encryption-at-rest in both source and target staging environments. To avoid creating weak trust chains, use envelope encryption where a master key protects data encryption keys, and the master key is stored in a hardware-backed key management service (HSM) or cloud KMS (Praveen Kumar, 2017). HSM-backed key storage reduces the risk of key exfiltration by privileged insiders.

● Secret key exchange and rotation protocols: Adopt secure ephemeral key exchange for migration sessions (e.g., ephemeral Diffie–Hellman key exchange combined with authenticated key confirmation). The goal is to ensure that compromise of session keys does not expose long-term credentials. Literature in secret key management stresses forward secrecy and periodic rotation to limit exposure windows (Praveen Kumar, 2017).

● Role-based access control (RBAC) and least-privilege principals for migration agents: agent accounts used for extraction and loading should have narrowly scoped privileges; auditing should monitor and log all actions for non-repudiation and forensic analysis (Gupta et al., 2018).

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The operation of cryptographic auditing requires special attention. Integrate authenticated integrity checks (e.g., Merkle tree fingerprints or cryptographic hashes) during extraction. For large datasets, compute chunk-level hashes to facilitate incremental verification post-transfer. The extracted dataset should be accompanied by a manifest of checksums signed by the migration controller to establish provenance and enable third-party attestation during audits (Siddiqui et al., 2020; Garg, 2020).

Incremental conversion and semantic fidelity assurance

Converting an enterprise schema and its procedural artifacts from Oracle to PostgreSQL raises semantic fidelity challenges. Proprietary dialects, optimizer hints, data-type differences, and vendor-specific functions (e.g., Oracle's PL/SQL constructs) necessitate both automated tooling and manual interventions (Dhananjay & Mehta, 2018; Chen & Park, 2019). Our methodology prescribes a staged, conservative translation approach:

1. Syntactic translation pass: Use automated tools to convert basic schema constructs, table definitions, constraints, and straightforward PL/SQL to PL/pgSQL conversions. Tool selection should be informed by empirical tool evaluations: prefer tools with high fidelity ratings on schema conversion and good community support (Popescu & Vasilescu, 2022; Chen & Park, 2019).
2. Semantic equivalence checks: For each automated conversion, generate a set of equivalence tests derived from functional and non-functional requirements. Functional tests include unit tests for stored procedures and integration tests exercising transactions across converted objects. Non-functional tests check performance characteristics such as query latency and throughput against pre-migration baselines (Alvarez & Kumar, 2020).
3. Manual refactoring for idiomatic PostgreSQL design: Where direct conversion yields suboptimal or incorrect behavior, refactor code to exploit PostgreSQL idioms (e.g., set-returning functions, arrays, JSONB types when appropriate) while preserving semantic outcomes. This step often requires domain knowledge and collaboration with application owners (Tan & Venkatesh, 2020; Fernandez & Nguyen, 2021).
4. Staged data transformation: Transformations that alter representation (e.g., migrating proprietary spatial types or proprietary number formats) should be applied incrementally, accompanied by per-record integrity checks and reconciliation processes.
5. Throughout conversion, maintain dual-track verification: (a) record-level checksums ensuring content fidelity, and (b) behavioral tests validating business logic equivalence. A thorough test harness mitigates the risk of silent semantic drift, which often manifests only under production load (Walker & Simmons, 2017; Srivastava & Blake, 2019).

Workload-aware cost and placement optimization

Economic viability is central to migration decisions. Cost models must account for both one-time migration expenses (data transfer fees, tool licensing, engineering labor) and ongoing operational costs (compute, storage, network egress, backups, and support). The literature identifies data placement and workload patterns as primary determinants of long-term cost (Ramani et al., 2019; Wang et al., 2021).

Our framework recommends constructing a workload taxonomy: classify data by access frequency (hot, warm, cold), latency sensitivity (real-time, interactive, batch), and cost-sensitivity (e.g., cost-per-transaction budget). Using this taxonomy, apply multi-cloud or hybrid placements: place latency-sensitive, compliance-critical, or high-I/O workloads in dedicated VMs or instance families that balance cost and performance; place cold, archival

data in low-cost object storage with lifecycle policies; and colocate data and compute when network egress or cross-zone charges would dominate cost (Wang et al., 2021; Ramani et al., 2019).

Mathematically formalizing cost optimization typically involves integer programming or heuristics; however, in practice, a workload-aware greedy placement algorithm informed by empirical cost curves often suffices. The algorithm selects placement that minimizes total expected monthly cost subject to SLA and residency constraints. Incorporate predictive modeling of workload seasonality and scaling behavior to avoid underprovisioning or overprovisioning, which can dramatically alter cost-effectiveness (Ramani et al., 2019).

A critical nuance is the interaction between security controls and cost—stronger isolation often costs more. For instance, dedicated single-tenant instances or hardware isolation with dedicated HSMs significantly raise monthly costs but reduce insider-exposure risk (Gupta et al., 2018). The framework advocates explicit budget allocations for security controls determined by risk modeling; evidently, certain regulatory contexts (e.g., finance, healthcare) may mandate high-cost isolation irrespective of economic trade-offs.

Post-migration verification, auditing, and governance

After cutover, enterprises require enduring assurance that migration did not introduce silent errors, that data integrity is preserved, and that ongoing operations meet SLAs. Our post-migration program includes the following elements:

● Cryptographic verification: Recompute chunk-level checksums in the target system and reconcile with signed manifests generated during extraction. For mutable systems, maintain append-only integrity logs (e.g., tamper-evident ledger entries) for transactional reconciliation (Siddiqui et al., 2020; Garg, 2020).

● Active auditing and attestation: Schedule periodic, risk-weighted audits, including third-party attestations where regulations or governance require it. Audits should validate access controls, key management processes, and the integrity chain from extraction to live cutover.

● Performance monitoring and anomaly detection: Employ continuous monitoring to detect performance regressions or application-level discrepancies that could indicate migration-induced issues. Baseline metrics gathered during pre-migration phases enable anomaly detection thresholds (Alvarez & Kumar, 2020).

● Master data management (MDM) reconciliation: For enterprises relying on MDM for consistent reference data, the migration must incorporate reconciliation processes to ensure that canonical identifiers, hierarchies, and business rules remain synchronized post-migration (Pansara, 2021). Where data harmonization reveals semantic inconsistencies, the governance function must adjudicate authoritative sources and reconcile differences through controlled transformations.

● Governance and rollback planning: Maintain a documented rollback plan, including retention of source systems until verification is complete, and define explicit criteria for rollback activation. Rollback plans should include data de-synchronization safeguards to avoid "split-brain" inconsistencies and ensure idempotent cutover operations.

RESULTS

Because this work is methodological and synthetic—integrating prior empirical studies, tool evaluations, and theoretical constructs—our "results" are descriptive analyses and reasoned outcomes demonstrating how the framework addresses the core tensions laid out in the introduction. We organize results under five outcome dimensions: security preservation, cost optimization, semantic fidelity, operational feasibility, and auditability.

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Security preservation outcomes

Applying cryptographic staging, ephemeral key exchange, and HSM-backed envelope encryption constrains the primary cloud-induced threat vectors. The layered approach—combining TLS in transit, envelope encryption at rest, and RBAC for migration agents—creates independent failure domains; compromise of one control does not trivially yield full data exposure. Prior work supports these conclusions: data security taxonomies for cloud deployments emphasize that layered cryptography and robust key management are essential to meet confidentiality and integrity requirements (Gupta et al., 2018; Praveen Kumar, 2017).

Moreover, the adoption of signed manifests and chunk-level hashing produces strong, provable evidence of content fidelity between extraction and target loads. The ability to cryptographically assert "bitwise equivalence" (or to enumerate precise diffs) is invaluable during compliance audits and litigation scenarios. Publications on integrity auditing protocols demonstrate that authenticated integrity checks are practical at scale when implemented with chunking and streaming digest computations, thereby enabling verification without requiring full memory-resident datasets (Siddiqui et al., 2020; Garg, 2020).

Cost optimization outcomes

A workload-aware placement policy that classifies datasets by hot/warm/cold tiers and aligns them with appropriate storage and compute classes reduces total ownership costs compared to naive monolithic placements. Ramani et al. (2019) empirically show that cost-sensitive placement choices during migration can deliver measurable reductions in both migration and operational expenditure. Wang et al. (2021) provide a theoretical foundation for multi-cloud placement that balances storage, egress, and compute costs; their models validate the intuition that co-locating compute and frequently accessed data is cost-efficient, while archiving cold data in low-cost object stores is optimal.

Our proposed greedy, workload-aware placement heuristic—although heuristic rather than optimally solved via integer programming—yields near-optimal placements in real-world scenarios because of the modular structure of enterprise workloads (many independent data partitions and locality constraints). In many practical cases, optimization complexity is dominated by a small set of large, latency-sensitive workloads; focusing optimization efforts on these yields disproportionate cost benefits (Ramani et al., 2019; Wang et al., 2021).

Semantic fidelity outcomes

The staged conversion methodology—automated syntactic passes followed by semantic testing and manual refactoring—produces high semantic fidelity with acceptable engineering effort. Empirical tool evaluations show that conversion tools excel at syntax translation but often fail for nuanced semantics embedded in stored procedures and vendor-specific optimizations; thus, our hybrid strategy is consistent with best practices (Popescu & Vasilescu, 2022; Chen & Park, 2019). The combination of automated test harnesses and manual refactoring reduces the risk of business-logic regressions that can be costly when discovered post-cutover (Walker & Simmons, 2017).

A key result is that investing engineering effort in creating comprehensive equivalence test suites before cutover frequently reduces debugging time after migration—front-loading effort yields net time savings. Alvarez & Kumar (2020) empirically demonstrate that post-migration performance regressions are costly; hence preemptive testing is cost-effective.

Operational feasibility outcomes

Our framework is operationally feasible when migration is executed in iterative waves prioritized by risk and business value. The wave-based approach (migrating low-risk, non-critical systems first) builds organizational familiarity with conversion tools and processes while limiting blast radius. This aligns with industry guidance on database modernization and enterprise migration strategies (Walker & Simmons, 2017; Hamilton & Zhao, 2021). Moreover, dual-running strategies that temporarily operate both source and target systems in parallel until verification is complete are practical when supported by robust synchronization mechanisms, albeit with moderate additional cost.

Auditability outcomes

Integrating cryptographic manifests, chunked hashing, and third-party attestation enables rigorous audit trails. Siddiqui et al. (2020) and Garg (2020) show that such integrity protocols are implementable at scale and provide verifiable evidence for compliance auditors. For enterprises subject to regulatory scrutiny, these auditable chains of custody substantially reduce certification and compliance risk.

DISCUSSION

This section provides deep interpretation of the methodology and results, explores counter-arguments, details limitations, and charts future research directions. We analyze trade-offs, discuss contexts where the framework may be impractical or insufficient, and highlight the most pressing open problems for both researchers and practitioners.

Interpreting trade-offs between security and cost

Our framework explicitly acknowledges that security controls and cost-efficiency often conflict. For example, using dedicated single-tenant hardware and separate HSMs yields strong confidentiality guarantees but increases monthly infrastructure cost. Organizations must assess whether regulatory or reputational risks warrant such expense. Here, risk modeling plays a decisive role: by quantifying the expected cost of adverse events, stakeholders can rationally decide which security investments are justified (Gupta et al., 2018; Wang et al., 2021).

There is a normative argument against treating security as purely economic: some regulatory frameworks impose mandatory controls regardless of cost. In such contexts, our framework remains useful because it prescribes efficient ways to implement mandated controls (e.g., envelope encryption using cloud KMS rather than bespoke HSM deployments when permitted), thereby minimizing incremental expense without compromising compliance.

Semantic fidelity complexities and legacy constructs

A persistent challenge in Oracle-to-PostgreSQL migration is dealing with constructs that have no canonical equivalents—especially platform-specific built-ins, optimizer hints, and certain PL/SQL idiosyncrasies. One counter-argument is that full semantic fidelity is unattainable without significant application-level refactoring, effectively changing business processes. Indeed, certain legacy behaviors—relying on implicit type coercions or optimizer-specific behavior—may need redesign. Admitting this reality, our methodology emphasizes conservative timelines and close collaboration with domain experts. The existence of such non-translatable constructs reinforces the value of staged, wave-based migration and the retention of source systems until assurance criteria are satisfied (Dhananjay & Mehta, 2018; Tan & Venkatesh, 2020).

Limitations of cryptographic verification at scale

While cryptographic manifests and chunk-level hashing provide strong guarantees, they are not a panacea.

Hashing large datasets and storing manifests are both resource-intensive. For very large datasets, chunking thresholds must be tuned to balance verification granularity against compute and storage overheads. Additionally, cryptographic verification proves bitwise equivalence at specific timestamps but does not validate semantic correctness—i.e., a dataset could be faithfully transferred but semantically corrupted by a transformation bug. Hence, cryptographic auditing must be coupled with functional equivalence testing to provide holistic assurance (Siddiqui et al., 2020; Garg, 2020).

Organizational challenges and human factors

Technical designs often founder on human and organizational obstacles: resistance to change, lack of in-house PostgreSQL expertise, and governance conflicts between database administrators and application owners. Empirical studies of migration projects highlight that non-technical issues—departmental politics, contractual obligations, and skill gaps—are frequently the largest contributors to schedule slips and cost overruns (Walker & Simmons, 2017; Rouse & McKendrick, 2021). Our methodology therefore recommends dedicated change management processes, targeted staff training, and, where necessary, engagement with external migration specialists who have a track record in complex conversions (Popescu & Vasilescu, 2022).

Potential adversarial threats in migration pipelines

Adversaries may target migration pipelines because they present predictable windows of elevated data movement and occasionally relaxed telemetry. Threats include interception of unencrypted data, manipulation of staging manifests, and exploitation of least-privilege misconfigurations. To counter these, the framework prescribes defense-in-depth: encrypt data at every hop, sign manifests with keys stored in HSMs, and instrument migration agents with tamper-evident behavior including code signing and runtime integrity checks. Furthermore, monitoring and anomaly detection must focus on migration-specific indicators such as unusual spike patterns, anomalous access to staging artifacts, and atypical agent behavior (Gupta et al., 2018; Praveen Kumar, 2017).

Future research directions

Several open research questions emerge from this synthesis:

1. Automated semantic translation frameworks: There is room for research into automated translation systems that use program analysis and formal methods to guarantee behavioral equivalence for a wider class of procedural constructs. Advances in program synthesis and semantic lifting may yield tools that reduce manual refactoring effort (Dhananjay & Mehta, 2018).

2. Scalable cryptographic auditing: Research into scalable, low-overhead integrity verification—possibly leveraging probabilistic checks, authenticated data structures, and secure hardware—could make cryptographic assurance more practical for exabyte-scale datasets (Siddiqui et al., 2020).

3. Cost-aware, security-constrained placement algorithms: While heuristic approaches work in practice, formal optimization methods that integrate stochastic workload forecasts, security constraints, and regulatory boundaries could yield better provable guarantees for placement decisions (Wang et al., 2021).

4. Human-centered migration tooling: Tools that better integrate human feedback, provide explainability for conversion decisions, and support collaborative refactoring could materially reduce project friction. Research on developer ergonomics and migration workflows would provide evidence-based design guidance.

5. Longitudinal empirical studies: There is a need for systematic, replicable studies documenting long-term outcomes of migrations—cost trajectories, incident rates, and performance evolution—to better inform future

migrations and refine best practices (Ramani et al., 2019; Walker & Simmons, 2017).

CONCLUSION

Enterprises face a confluence of pressures—economic, technical, and regulatory—that motivate migration from proprietary RDBMS platforms to open-source, cloud-native database systems. However, migration is fraught with technical complexity, security risk, and economic uncertainty. This article synthesizes research across cloud security, cost-optimized placement, integrity auditing, and database migration practice to propose a unified, operationally actionable framework for secure, cost-optimal, and integrity-preserving migration from Oracle to PostgreSQL in cloud environments.

Key recommendations emphasize a staged migration pipeline with rigorous pre-migration risk modeling, cryptographically secure staging and manifesting, hybrid automated/manual conversion with comprehensive equivalence testing, workload-aware placement to control long-term costs, and robust post-migration auditing and governance. We underscore that while technical mechanisms can provide strong assurances, human and organizational factors frequently determine migration success. Therefore, the framework includes governance, training, and collaboration practices to mitigate socio-technical risks.

While the framework synthesizes best-known practices and empirical insights, important research challenges remain—particularly in scalable cryptographic auditing, automated semantic translation, and integrated cost-security optimization. We encourage both researchers and practitioners to apply, evaluate, and refine this framework in real-world migration projects and to document longitudinal outcomes to build an evidence base for future work. By aligning security, cost, and fidelity objectives in a single migration methodology, organizations can realize the economic and architectural benefits of open-source cloud databases while preserving trust and compliance.

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