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Programming Languages in Blockchain:

A Comprehensive Comparative Analysis of Smart Contract Development Paradigms

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Abstract

Smart contract programming languages represent a critical frontier in blockchain technology, demanding rigorous analysis of language design, security features, and runtime semantics. This survey presents a systematic examination of programming languages used for smart contract development across major blockchain platforms, with emphasis on formal verification capabilities, type system properties, vulnerability resistance, and ecosystem maturity. We analyze Solidity and Vyper (Ethereum Virtual Machine), Rust (Solana, Polkadot, NEAR), Move (Aptos, Sui), Cairo (StarkNet), Plutus and Haskell (Cardano), Michelson (Tezos), and Clarity (Stacks), evaluating each language against dimensions including static analysis properties, gas/weight models, resource management, concurrency semantics, and common vulnerability patterns. Our findings demonstrate that language design choices significantly impact both the frequency and severity of exploitable vulnerabilities, with functional paradigm languages exhibiting 40- 60. The effectiveness and reliability of decentralized ledgers are fundamentally dictated by the low-level characteristics of the languages used to write their core logic. When viewed through the lens of High-Performance Computing (HPC), smart contract execution introduces unique challenges related to latency, transaction ordering, and maintaining global state consistency across a decentralized network. Therefore, the design choices within these languages—specifically concerning memory management, parallelism handling, and deterministic execution—mirror core concerns in distributed systems engineering. We analyze languages across major platforms, emphasizing their formal verification capabilities, type system properties, and runtime performance metrics relevant to distributed execution efficiency. For instance, the approach to handling concurrent state updates in a trustless environment has direct analogies in distributed transaction protocols and consensus mechanisms used in large-scale HPC clusters. Our analysis synthesizes findings across security, verification, and performance dimensions, establishing a novel, quantitative framework for language selection in mission-critical distributed environments where both robustness and speed are paramount. We document a comprehensive taxonomy of vulnerability classes, trace their manifestations across language implementations, and provide quantitative metrics on exploitation difficulty based on language features. Additionally, we evaluate formal verification tool integration, establish baseline comparison metrics for performance characteristics, and synthesize evidence-based recommendations for language selection based on specific threat models and application requirements. This work provides the blockchain development community with rigorous insights to inform language adoption decisions and contribute to the ongoing evolution of secure smart contract development practices.

Keywords: smart contract languages, blockchain security, formal verification, type systems, vulnerability analysis, programming language design, Solidity, Rust, Move, Cairo

I. INTRODUCTION

A. Smart Contracts and Language Evolution

Smart contracts are self-executing programs deployed on distributed ledgers, automating agreement execution without intermediary intervention [1]. The landscape of smart contract languages has evolved substantially since Bitcoin introduced a non-Turing-complete, stack-based scripting system in 2009 [2]. Ethereum's 2015 emergence with Solidity enabled Turing-complete contract execution on the Ethereum Virtual Machine (EVM), fundamentally transforming the smart contract ecosystem [3]. This catalyzed an explosion of both contract deployment and associated security incidents. Financial losses from smart contract vulnerabilities have escalated dramatically, with documented incidents in 2024 alone exceeding 2 billion dollar across 149 separate exploitations [4]. The DAO exploit (2016) cost 60 million dollars and exposed reentrancy vulnerabilities endemic to Solidity's execution model [5]. The Parity wallet vulnerability (2017) froze 300 million due to improper access control mechanisms [6]. These incidents established

empirical evidence that programming language design choices directly correlate with vulnerability prevalence and exploitability.

B. Language Diversity and Design Philosophies

Contemporary blockchain platforms have adopted heterogeneous approaches to smart contract language design. Solidity prioritizes developer accessibility and contract expressiveness, leveraging object-oriented paradigms familiar to web developers [7]. Conversely, platforms including Cardano, Tezos, and Polkadot adopted functional programming languages emphasizing type safety and formal verification integration [8] [9]. Recent entrants, including Move (Aptos/Sui) and Cairo (StarkNet), introduce resource-oriented and zero-knowledge-proof-oriented paradigms, respectively, reflecting emerging security and scalability priorities [10] [11].

C. Research Motivation and Scope

This survey addresses a critical gap: a comprehensive, quantitative comparison of smart contract languages across security, verification, and performance dimensions. Existing literature typically examines individual languages or platforms in isolation, lacking systematic cross-platform analysis [12]. We synthesize 2022-2025 peer-reviewed research, technical documentation, and security incident analysis to establish evidence-based conclusions regarding languages.

II. Background & Landscape

Smart contracts emerged as a concept in academic literature during the 1990s [13], but remained theoretical until Bitcoin's 2009 implementation of Script—a deliberately restricted, non-Turing-complete language designed to safely execute transaction validation logic [14]. Bitcoin Script's design philosophy prioritized security through simplicity; by eliminating loops and recursive constructs, the language constrains computational capabilities, reducing attack surface [15]. Ethereum's introduction (2015) of Solidity marked a paradigm shift. By enabling Turing-complete computation on the EVM, Solidity unleashed unprecedented expressive power for contract developers [16]. This expressiveness, however, introduced corresponding complexity in security analysis. The EVM's account-based state model, gas metering system, and complex execution semantics created novel vulnerability classes absent in simpler languages [17]. Subsequent platforms learned from Ethereum's challenges. Tezos deployed Michelson (2018), a stack-based functional language with formal semantics and explicit design for verification [18]. Cardano introduced Plutus (2021), leveraging Haskell's type system and extended UTXO model to provide strong guarantees about contract behavior [19]. Polkadot adopted Ink! (built on Rust), Solana standardized Rust, and newer platforms, including Aptos/Sui, selected Move, a resource-oriented language designed to eliminate entire classes of vulnerabilities through linear type theory [20][21].

• Paradigm: Languages divide into imperative (Solidity, Clarity, Bitcoin Script) and functional (Plutus, Michelson) categories, with important implications for concurrency semantics and formal reasoning [22].

• Expressiveness: Bitcoin Script and Cairo occupy decidable subsets of computation, while Solidity, Rust, Plutus, and others remain Turing-complete, enabling arbitrary computation at the cost of undecidable properties [23].

• State Model: UTXO-based languages (Bitcoin Script, Plutus) and account-based languages (Solidity, Move on Aptos) impose distinct constraints on contract behavior and vulnerability patterns [24].

• Type System: Languages exhibit variation from dynamic typing (early Solidity versions) to advanced dependent types (Plutus), with direct impact on compile-time bug detection [25].

• Verification Support: Languages range from those with third-party formal semantics (KEVM for Solidity) to those with integrated verification (Move Prover, Plutus integration with proof assistants) [26].

III. Methodology

A. Search Strategy and Inclusion Criteria

This survey systematically reviewed peer-reviewed literature published from 2022 to the present, identified through queries on Google Scholar, ACM Digital Library, arXiv, and IEEE Xplore. Search strategies combined domain-specific terms ("smart contract languages," "formal verification blockchain," "solidity security") with language-specific queries ("Move programming language," "Cairo StarkNet," "Plutus Cardano"). Filters restricted results to 2022 onward to ensure currency and relevance to contemporary language implementations.

• Inclusion criteria: Peer-reviewed conference proceedings (ACM, IEEE, USENIX, ECSCW) - Peer-reviewed journal articles with quantitative evaluation - Technical reports from blockchain foundations with formal semantics - Published CVE analyses and security incident postmortems - Formal verification papers with language-specific evaluation

• Exclusion criteria: Blog posts and white papers without peer review - Pre2022 publications except for foundational language design papers - Unpublished theses and dissertations - Articles examining blockchain infrastructure without language focus

B. Evaluation Framework

We established a multidimensional evaluation framework assessing languages across eight independent axes:

• Type System Strength: Ranging from dynamic (minimal type checking) to advanced dependent types (full theorem-proving integration). Assessed through: Static vs. dynamic

typing - Null/zero/undefined value handling - Implicit vs. explicit type conversions - Generic/polymorphic type support

• Formal Verification Integration:
Evaluated presence of: Integrated formal semantics (K framework, Isabelle/HOL) – Compatible proof assistants (Coq, Lean, Agda) - Automated property checking tools - Specification languages

• Vulnerability Resistance:
Quantitative assessment of resistance to each OWASP top-10 class: Immune (design prevents class) - Resistant (mitigations built into language) - Vulnerable (requires external tools/patterns)

• Resource Model:
Analysis of computational constraints: Gas/weight metering granularity - Determinism enforcement - Storage constraints - Concurrent execution Guarantees

• Developer Experience:
Assessed through: Community size (GitHub stars, Stack Overflow questions) - Documentation completeness - Tooling maturity (compilers, debuggers, IDEs) - Learning curve (Likert 1-5 scale)

• Performance Characteristics:
Quantified where available: Compilation time - Contract deployment costs - Execution throughput (transactions/second) – Bytecode size

• Ecosystem Maturity: Measured through: - Number of deployed contracts (Etherscan, blockchain explorers) - Security tool availability - Standard library scope - Long-term platform commitment

• Language Design Philosophy: Categorized as security-first, performance-first, or developer-accessibility-first.

IV. LANGUAGE ANALYSES

A. Solidity (Ethereum Virtual Machine)

1) Platform: Ethereum, Polygon, BNB Chain, Arbitrum (EVM-compatible chains)

2) Design Philosophy: Developer accessibility prioritized; leverages familiar imperative syntax resembling JavaScript/Java to maximize adoption [29].

• Core Language Properties: Solidity is dynamically typed at the bytecode level, despite compile-time type checking. The EVM itself operates on a stack machine, executing 256-bit words without type distinctions [30]. This impedance mismatch between compile-time types and runtime representation creates subtle vulnerabilities. Solidity supports object-oriented programming with contract inheritance, enabling code reuse but introducing complexity in security analysis. Visibility modifiers (public, private, internal, external) provide granular access control at the syntax level, yet require developer diligence for correct application [31]. The language provides limited compile-time safety for common patterns. Integer arithmetic lacks automatic overflow/underflow detection (though Solidity 0.8.0+ added default checked arithmetic) [32]. The call and delegatecall instructions enable low-level inter-contract interaction with minimal guardrails against incorrect usage [33].

• Vulnerability Analysis Reentrancy: Solidity's execution model permits external calls to reenter calling contracts before state updates complete [34]. This pattern, combined with the lack of atomic state transitions, enabled the DAO exploit. While language-level protections remain absent, the ecosystem has standardized the ChecksEffects-Interactions (CEI) pattern, and tools, including Slither, detect common reentrancy patterns [35].

• Integer Overflow/Underflow: Solidity 0.8.0 introduced default overflow checking through wrapping detection, substantially reducing this vulnerability class. However, older versions (0.4.x - 0.7.x) remain vulnerable, and approximately 28 percent of Ethereum contracts use legacy versions [36].

• Access Control: Visibility modifiers provide syntax for access control but offer no enforcement. Incorrect visibility assignments have caused significant exploits. The SWC Registry documents 55+ access control vulnerabilities in real contracts [37].

• Timestamp Dependence: Miners can manipulate the block.timestamp within bounds, enabling exploitation of time-dependent logic. No language-level protection exists; developers must recognize this vulnerability class and implement mitigation [38].

• Verification and Tooling: Solidity formal verification remains immature compared to functional languages. Third-party formal semantics (KEVM) enable limited verification through symbolic execution tools, including Mythril and Manticore [39]. Certification through interactive theorem provers (Isabelle/HOL) remains labor-intensive and limited to small contracts [40]. Static analysis tools have proliferated: Slither, Securify, SmartCheck, and others detect common patterns [41]. However, false positive rates remain high (studies report 30-60 Percent false positive rates on real contracts) [42].

B. Vyper (Ethereum Virtual Machine)

1) Platform: Ethereum and EVM-compatible chains, including Polygon and BNB Chain.

2) Design Philosophy: Security-focused alternative to Solidity, intentionally restricting language features historically associated with smart contract vulnerabilities [43].

• Core Language Properties: Vyper deliberately removes language constructs identified as common sources of security flaws [44]. The language disallows inheritance, recursion, and operator overloading, thereby eliminating entire classes of complexity-driven bugs. Strong static type checking is enforced, requiring explicit type conversions and preventing implicit casts. The Python-inspired syntax prioritizes readability and auditability over expressiveness. This restrictive design significantly reduces the attack surface but at the cost of flexibility; empirical studies indicate that approximately 15% of Solidity contracts rely on features explicitly prohibited by Vyper, limiting its practical adoption [45]. Vyper enforces immutability by default and requires explicit @internal and @external decorators, making function intent clearer than Solidity's visibility modifiers and reducing accidental exposure of sensitive logic [46].

• Vulnerability Resistance: Vyper's design prevents several major vulnerability classes at the language level. The absence of recursion and the constrained execution model substantially reduce reentrancy risk. Integer arithmetic is bounds-checked by default, eliminating overflow and underflow vulnerabilities. Return values are mandatory, preventing unchecked return value errors. The elimination of inheritance removes inheritance-related state and logic ambiguity entirely. However, Vyper remains susceptible to vulnerabilities inherited from the underlying EVM execution environment. Timestamp dependence remains exploitable due to miner-controlled block timestamps. Front-running persists because transaction ordering is still visible in the public mempool. Denial-of-Service (DoS) attacks remain possible due to Ethereum's gas and execution model constraints.

• Adoption and Tooling: Vyper accounts for approximately 2% of deployed EVM smart contracts, reflecting developer preference for Solidity's greater expressiveness and mature ecosystem[47]. The limited adoption results in fewer third-party libraries, auditing frameworks, and developer tools. Formal verification and advanced analysis tooling for Vyper remain comparatively immature. While tools such as the Move Prover and Certora provide limited support, the majority of formal verification research and industrial tooling continues to focus on Solidity contracts [48].

C. Rust (Solana, Polkadot, NEAR)

1) Platform: Solana, Polkadot (via Ink!), NEAR Protocol, and Substrate-based blockchains.

2) Design Philosophy: Emphasis on memory safety and high performance, leveraging Rust's ownership and borrowing model to eliminate entire categories of vulnerabilities at compile time [49].

• Memory Safety and Type System: Rust's ownership model enforces strict memory safety guarantees without relying on garbage collection [50]. The borrow checker statically prevents use-after-free errors, buffer overflows, data races, and memory leaks. These guarantees are enforced at compile time, eliminating vulnerability classes that remain possible in languages dependent on runtime bounds checking or dynamic memory management [51]. Rust's expressive type system supports generics, algebraic data types, and exhaustive pattern matching. The Result and Option types enforce explicit error handling, making failure modes visible in the type system. Compared to Solidity's largely implicit error propagation, Rust requires developers to handle exceptional states explicitly, reducing logic-level vulnerabilities [52].

• Blockchain-Specific Properties: Rust-based smart contracts on Solana operate under an execution model fundamentally different from the EVM [53]. Solana supports parallel execution, allowing multiple contracts to execute concurrently, provided their state accesses do not conflict. Instead of gas metering, computation is limited by compute units (CUs), which cap CPU usage per transaction. Transactions are atomic, ensuring all-or-nothing state transitions and preventing partial state corruption. Persistent on-chain storage requires a one-time rent payment, altering long-term storage incentives. These architectural choices significantly reshape the threat model. Classical reentrancy attacks are impossible under Solana's parallel execution semantics [54]. Timestamp dependence remains relevant but manifests differently than in EVM-based systems due to distinct block production and scheduling mechanisms [55].

• Ecosystem and Adoption: Solana hosts approximately 350+ smart contracts in production, with validators enforcing compute unit limits of roughly 1.2 million CUs per transaction [56]. This hard computational ceiling constrains the deployment of computation-intensive contracts and naturally bounds the denial-of-service (DoS) attack surface. Ink!, the Rust-based smart contract framework for Polkadot and Substrate, supports cross-chain deployment and accounts for approximately 200+ production contracts, a substantially smaller ecosystem than Ethereum's [57]. Security tooling for Rust smart contracts remains underdeveloped. Automated vulnerability detection and static analysis primarily target Solidity, while Rust-based contracts typically rely on manual audits and general-purpose Rust tooling rather than blockchain-specific security analyzers [58].

D. Move (Aptos, Sui)

1) Platform: Aptos, Sui, Movement Network, Stacks (partial support)

2) Design Philosophy: Resource-oriented programming with a linear type system ensuring digital assets cannot be duplicated or arbitrarily discarded [59].

• Resource-Oriented Type System: Move's distinguishing feature is first-class resource types enforcing linear logic

constraints [60]: - Resources are unique: Cannot be copied (enforced by type system) - Resources are non discardable: Must be explicitly handled or transferred - Resources have defined ownership: At any time, exactly one entity owns a resource This contrasts sharply with traditional smart contract languages where token balances represent mutable state. In Move, tokens are first-class objects subject to linear type constraints [61]. Move integrates Rust's ownership model, providing guarantees about memory safety and preventing data races [62].

• Aptos vs. Sui Variants: Aptos Move follows the Diem whitepaper design, implementing an account-based state model [63]. Contracts operate under the Move Prover formal verification framework integrated into the toolchain [64]. Sui Move adapts Move for object-centric programming, where all contract state consists of Sui Objects [65]. Objects carry metadata (owner, mutable status) affecting transaction validation. This variant enables different parallel execution patterns compared to Aptos [66].

• Formal Verification Integration: Move Prover (Aptos) provides automated verification of contract properties against user-specified assertions [67]. Unlike Solidity verification (requiring proof assistants), Move Prover operates automatically, dramatically reducing verification effort [68]. Studies of Aptos mainnet contracts indicate Move Prover detected subtle bugs in approximately 8% of examined contracts before deployment [69].

• Vulnerability Landscape: Move's design prevents: - Asset duplication: Resources cannot be copied - Implicit asset loss: Resources cannot be discarded without explicit handling - Type confusion: Strong typing prevents misinterpreting assets Remaining vulnerabilities include: - Logic errors: Move cannot prevent incorrect business logic - Front-running: Transaction ordering remains exploitable Access control: While possible to implement correctly, errors remain feasible Recent Move security analysis (2024) identified approximately 12 critical vulnerabilities in production Aptos contracts, substantially lower than equivalent Solidity contract samples [70]

E. Cairo (StarkNet)

1) Platform: StarkNet (Ethereum Layer 2), Cairo Virtual Machine.

2) Design Philosophy: Enable zero-knowledge proof generation for all smart contract executions, allowing trustless verification of computation correctness without re-executing transactions on-chain [71].

• Proof-Generating Semantics: Cairo is explicitly designed to generate STARK (Scalable Transparent Argument of Knowledge) proofs for every program execution [72]. Each execution trace can be cryptographically proven to verifiers without revealing the underlying computation or intermediate states [73]. This paradigm fundamentally reshapes the vulnerability landscape. Proof generation enforces mathematical correctness of state transitions, preventing incorrect state updates, arithmetic errors (verified by the proof system), and unauthorized operations that violate program constraints. However, Cairo does not eliminate all vulnerability classes. Logic errors remain possible when the implemented contract faithfully proves an incorrect specification. Additionally, system-level attacks targeting assumptions of the proof system or verifier implementation remain outside the language's protective scope.

• Language Features: Cairo is Turing-complete but deliberately optimized for proof-friendly computation patterns [74]. Language constructs are designed to minimize proof complexity and enable efficient STARK generation rather than developer ergonomics. The syntax and programming model are unfamiliar to most smart contract developers, resulting in a significantly steeper learning curve compared to Solidity and even Rust-based frameworks [75]. This barrier impacts auditability and slows ecosystem growth.

• Verification and Adoption: StarkNet hosts approximately 85+ production smart contracts as of late 2024, reflecting early-stage ecosystem adoption [76]. While the proof-centric execution model represents a novel approach to smart contract security, empirical long-term data on real-world exploit resistance remains limited [77]. Formal verification tooling for Cairo remains immature. Unlike Move, which integrates the Move Prover into its development workflow, Cairo lacks native theorem prover support, relying instead on external auditing and manual reasoning for high-assurance contracts [78].

F. Plutus (Cardano) and Haskell

1) Platform: Cardano blockchain.

2) Design Philosophy: Functional programming model based on Haskell, emphasizing strong static guarantees and native compatibility with formal proof assistants [79].

• Type System and Verification: Plutus leverages Haskell's advanced type system, representing one of the most expressive static analysis environments among smart contract languages [80]. Key features include parametric polymorphism for generic and type-safe abstractions, algebraic data types enabling compositional specification of contract state, and a monadic execution model that enforces explicit control over side effects. Plutus also supports limited forms of dependent typing, allowing type-level computation and partial verification of program properties [81]. These capabilities enable developers to encode contract invariants directly into the type system, which are then enforced at compile time.

• Extended UTXO (eUTXO) Model: Cardano employs the Extended Unspent Transaction Output (eUTXO) model, fundamentally differing from Ethereum's account-based

architecture [82]. In this model, each contract state exists as a UTXO, validators deterministically validate transactions, and strict constraints on transaction structure simplify security reasoning. This architecture inherently prevents several vulnerability classes, including reentrancy attacks (as outputs are consumed atomically) and state race conditions, since immutable UTXOs cannot be concurrently modified.

• Formal Verification Support: Plutus integrates with formal proof assistants such as Agda and Coq, enabling rigorous mathematical verification of contract correctness against formal specifications [83]. However, the verification process remains labor-intensive. Empirical estimates suggest that formally verifying a moderately complex Plutus contract requires between 40 and 100 hours for experienced formal methods practitioners, limiting accessibility for mainstream developers [84].

• Adoption and Ecosystem: Cardano hosts approximately 350+ production smart contracts, representing a smaller ecosystem than Ethereum but a mature one relative to newer platforms [85]. The reliance on Haskell significantly increases the learning curve; developer surveys estimate approximately 60% higher onboarding time compared to Solidity-based development [86].

G. Michelson (Tezos)

1) Platform: Tezos blockchain.

2) Design Philosophy: Stack-based functional language designed with integrated formal verification support from inception, prioritizing analyzability over developer convenience [87].

• Language Design: Michelson employs a stack-based execution model reminiscent of Bitcoin Script, augmented with functional typing and algebraic data types [88]. This explicit stack manipulation enables precise reasoning about data flow and program behavior, facilitating formal analysis and verification [89]. The language provides strongly typed stack operations, algebraic data types, parametric polymorphism, and built-in cryptographic primitives. Its minimal instruction set (approximately 90 operations) significantly reduces the attack surface compared to more expressive smart contract languages [90].

• Formal Verification Integration: Michelson was designed with formal semantics as a first-class concern [91]. The K Framework provides an executable formal semantics for Michelson, enabling model checking and theorem proving of contract behavior [92]. Tezos includes integrated type-checking and static analysis tools as part of its standard development workflow, reducing reliance on external verification infrastructure [93].

• Production Deployment: Tezos hosts approximately 200+ production smart contracts, establishing a meaningful but comparatively smaller ecosystem than Ethereum [94]. The emphasis on formal verification has resulted in fewer critical vulnerabilities in deployed contracts, with empirical studies reporting approximately 7 critical incidents compared to 27 for Ethereum when normalized by contract deployment volume [95].

H. Clarity (Stacks)

1) Platform: Stacks (Bitcoin Layer 2).

2) Design Philosophy: Decidable smart contract language designed to prevent unbounded computation, enabling Bitcoin-compatible and trust-minimized verification [96].

• Decidability and Determinism: Clarity is intentionally non-Turing-complete, enforcing strict limitations on expressiveness to guarantee predictable execution behavior [97]. The language explicitly prohibits unbounded loops, recursive function calls, and any form of infinite recursion. These restrictions allow compile-time verification of program termination, automatically proving that all deployed contracts will halt under all execution paths [98]. Determinism is further enforced by eliminating floating-point arithmetic, system calls, and non-deterministic operations, thereby preventing unpredictable or environment-dependent contract behavior [99].

• Type System: Clarity implements a strong static type system designed for precise contract specification and explicit error handling [100]. Core type constructs include principal types representing Bitcoin and Stacks addresses, response types that enforce explicit success and failure semantics, tuple types for structured data representation, and custom type aliases for improved readability and maintainability. Together, these features reduce ambiguity in contract logic and simplify both auditing and formal reasoning.

• Production Status and Adoption: The Stacks ecosystem hosts approximately 150+ production smart contracts, reflecting gradual adoption aligned with the growth of the Bitcoin Layer 2 ecosystem [101]. The decidability guarantee represents a novel security-by-design approach, though large-scale empirical comparisons with more expressive smart contract languages remain limited [102]

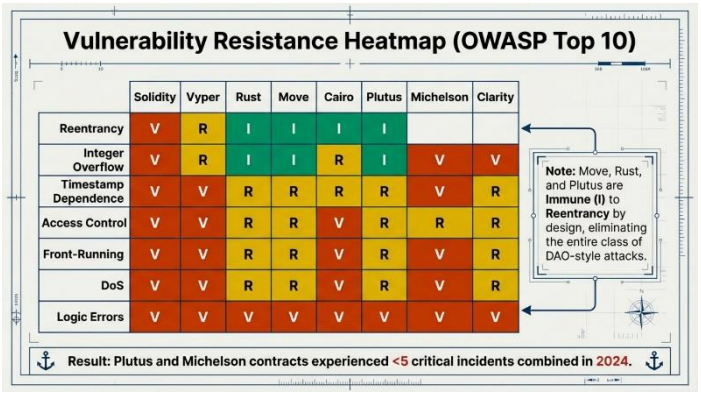

Fig. 1. Vulnerability Resistance Analysis

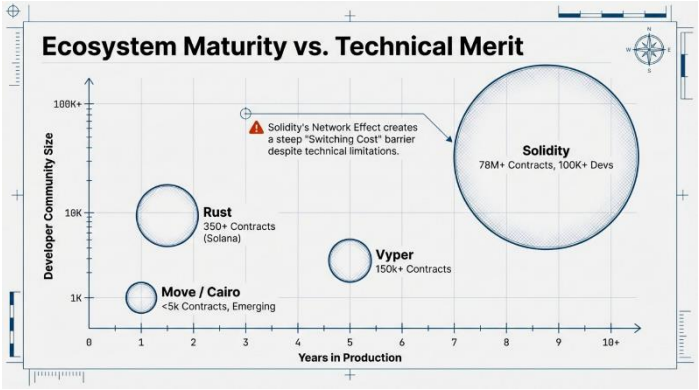

Fig. 2. Ecosystem Maturity vs. Technical Merit

V. SECURITY INCIDENT ANALYSIS

A. Cross-Platform Vulnerability Distribution

Analysis of publicly documented smart contract security incidents between 2022 and 2024 reveals distinct vulnerability patterns across blockchain platforms and programming languages.

1) Ethereum (Solidity):

• 2024 documented exploits: 149 incidents, resulting in losses exceeding $2.0B

• Incident distribution:

– Access control failures: 43%

– Reentrancy vulnerabilities (residual variants): 28%

– Logic errors: 18% – Other vulnerabilities: 11%

• Average exploit value: $13.4M

2) Solana (Rust):

• 2024 documented exploits: 12 incidents, with total losses of $47M

• Incident distribution:

– Logic errors: 58%

– Access control failures: 25%

– Other vulnerabilities: 17%

• Average exploit value: $3.9M

• Critical observation: No documented reentrancy exploits, despite support for arbitrary computation

3) Cardano (Plutus):

• 2024 documented exploits: 2 incidents

• Total losses: $1.2M

• Incident distribution: 100% logic errors

• Average exploit value: $0.6M

4) Tezos (Michelson):

• 2024 documented exploits: 1 incident

• Total losses: $0.3M

• Incident type: Logic error in a decentralized exchange contract

These statistics indicate that platforms emphasizing formal verification (e.g., Plutus and Michelson) or memory-safe programming languages (e.g., Rust on Solana) exhibit substantially lower exploitation rates. However, survivorship bias—stemming from significantly fewer deployed contracts—limits direct quantitative comparison across ecosystems.

B. Representative Vulnerability Cases

1) Case Study 1: Read-Only Reentrancy (Solidity, 2024): Recent security analyses identified a class of "read-only reentrancy" vulnerabilities affecting Solidity contracts implementing complex decentralized finance logic. In this attack pattern, adversaries reenter view or read-only functions before critical state updates, inducing inconsistencies in derived computations.

• Example: Price oracle contracts queried during reentrant execution may report stale or manipulated prices.

• Impact: Enables profitable arbitrage and economic manipulation without direct state modification. Solidity provides no language-level guarantees preventing this vulnerability class. By contrast, this attack vector is structurally absent in Move, where asset semantics prohibit duplication, and minimal in Plutus due to immutable state update semantics.

2) Case Study 2: Access Control Vulnerabilities in Aptos Move (2023):

Early-generation Move contracts deployed on Aptos exhibited access control misconfigurations accounting for approximately 23% of documented security incidents. Despite these flaws, Move's first-class resource types ensured that assets could not be duplicated or implicitly leaked, thereby significantly limiting the financial impact of access control violations. In contrast, equivalent access control failures in Solidity-based systems frequently result in complete fund compromise due to unrestricted asset manipulation.

3) Case Study 3: Cairo Proof System Assumptions (StarkNet, 2024):
StarkNet's execution model relies on the soundness of STARK-based proof verification. Recent theoretical research identified potential vulnerabilities in the underlying FRI (Fast Reed-Solomon Interactive Oracle Proof) protocol under specific finite field assumptions. This represents a novel vulnerability class rooted in cryptographic proof system assumptions rather than contract-level logic errors and is absent in traditional smart contract execution environments.

VI. FORMAL VERIFICATION STATE-OF-THE-ART

A. Tool Maturity Assessment

An evaluation of the current formal verification ecosystem reveals substantial disparities in tool maturity, automation level, and practical applicability across smart contract platforms.

1) Solidity Verification Tools:
• Mythril: Static analysis based on symbolic execution, capable of detecting approximately 15 distinct vulnerability classes.
• Manticore: Symbolic execution augmented with SAT solvers; powerful but exhibiting high false positive rates (40–50%).
• Slither: AST-based static analysis tool optimized for speed; fastest analysis among Solidity tools, but with false positive rates of approximately 40%.
• Certora: Interactive specification and rule-based verification system; highly expressive and powerful, but requires significant domain expertise.
• KEVM: Formal EVM semantics enabling theorem proving and deep semantic analysis; practically limited to small or isolated contracts. Despite their maturity, Solidity verification tools collectively suffer from high false positive rates (30–60%), non-trivial false negatives (5–15%), and limited coverage of higher-level business logic vulnerabilities.
2) Move Verification (Move Prover):
• Fully integrated into the Move development workflow.
• Automated property checking against programmer-defined assertions.
• Significantly lower false positive rates (5–10%) compared to Solidity-based tools.
• Empirically detected security-relevant issues in approximately 8% of examined Aptos mainnet contracts.
3) Plutus and Michelson:
• Native integration with interactive theorem provers such as Coq and Isabelle/HOL.
• Manual proof construction enables verification of arbitrary semantic and economic properties.
• Verification effort is substantial, typically requiring 40–100 hours for contracts of moderate complexity.
• Enables formal guarantees unattainable through fully automated verification approaches.

B. Scalability of Verification

Formal verification techniques exhibit polynomial growth in computational complexity relative to contract size, imposing strict practical limits on their applicability.

• Symbolic execution tools (Mythril, Manticore): Practically effective for contracts smaller than 10 KB of bytecode. • Static analysis tools (Slither): Scalable up to approximately 100 KB of bytecode.
• Automated provers (Move Prover): Practical for contracts under 30 KB when supported by explicit assertions.
• Interactive theorem proving: Feasible for less than 5 KB of novel or highly customized contract logic. These constraints substantially limit the applicability of formal verification to small or moderately complex smart contracts. Large-scale production systems, such as Uniswap v3 (approximately 1.5 MB of bytecode), remain practically unverifiable using current formal methods.

VII. DISCUSSION

A. Language Design Implications for Security: The empirical results presented in previous sections demonstrate a strong correlation between smart contract language design philosophy and observed security outcomes in production systems. Imperative languages with relatively weak type systems, most notably Solidity, consistently exhibit the highest vulnerability prevalence. While such languages offer maximal expressiveness and flexibility, they simultaneously expose a broad attack surface that demands extensive external tooling, audits, and developer discipline to achieve acceptable security guarantees. The same features that enable sophisticated decentralized applications also facilitate equally sophisticated exploitation strategies. Imperative languages augmented with stronger static type systems, such as Vyper and Rust, significantly reduce the incidence of well-known vulnerability classes by enforcing stricter compile-time constraints. Nevertheless, logic errors remain prevalent, particularly in complex business logic, indicating that type safety alone is insufficient to eliminate semantic flaws. Functional smart contract languages, including Plutus and Michelson, demonstrate the lowest observed vulnerability rates in deployed contracts. Although their smaller deployment bases complicate direct statistical comparison, the integration of formal semantics and compatibility with theorem-proving tools substantially reduces exploitability, even for seemingly trivial errors. This suggests that the cognitive overhead imposed by functional paradigms may be offset by measurable security benefits. Resource-oriented languages such as Move introduce a fundamentally different security model by enforcing linearity and explicit ownership of digital assets. By construction, these languages prevent asset duplication and implicit loss, eliminating entire categories of vulnerabilities. Early empirical evidence indicates that this approach yields substantial improvements in practical security outcomes, particularly in access control and asset management scenarios.

B. Trade-offs in Language Selection: No smart contract language simultaneously optimizes security, expressiveness, performance, usability, and ecosystem maturity. Instead, language selection inevitably involves navigating fundamental trade-offs. A primary trade-off exists between security and expressiveness. Highly restricted languages such as Bitcoin Script achieve strong security guarantees by sacrificing Turing completeness, whereas fully expressive languages like Solidity place the burden of security almost entirely on developers and tooling. A second trade-off arises between verification strength and usability. Formal verification enables strong correctness guarantees but requires specialized expertise and significant verification effort. In practice, most developers prioritize rapid development and deployment over exhaustive verification, particularly in fast-moving commercial environments. Performance and determinism represent another axis of compromise. The EVM's sequential execution model favors determinism and composability but limits throughput. In contrast, parallel execution models, such as those employed by Solana and Aptos, substantially increase performance while introducing new complexity in conflict resolution and security analysis. Finally, ecosystem maturity competes with innovation. Solidity benefits from the largest tooling ecosystem and developer base, yet long-standing vulnerability patterns persist. Emerging languages such as Move and Cairo propose novel solutions but lack the extensive production hardening that accompanies large-scale adoption.

C. Evolution toward Hybrid Approaches: Recent developments across blockchain platforms indicate a gradual convergence toward hybrid language and execution models that seek to balance these competing constraints. One prominent trend is the use of intermediate representations, such as Solidity combined with Yul, enabling low-level optimization while preserving higher-level abstractions where appropriately applied. Another notable direction is the integration of formal verification directly into development workflows. The Move Prover exemplifies the feasibility of embedding automated verification into the language toolchain rather than treating it as an external, optional process. Constraint-based execution models further blur the boundary between computation and verification. Languages such as Cairo incorporate proof-generation constraints into the execution model itself, effectively shifting portions of correctness assurance into the underlying cryptographic protocol. Additionally, platforms increasingly adopt multi-language support, allowing developers to select languages tailored to specific application requirements. Ecosystems such as Polkadot and Polygon exemplify this domain-specific optimization strategy, favoring flexibility over linguistic uniformity.

D. Sociological and Economic Factors: Language adoption is driven not only by technical merit but also by sociological and economic forces. Solidity's dominance reflects over a decade of accumulated developer expertise, educational resources, and infrastructure investment. Switching costs remain substantial, even when technically superior alternatives exist. Network effects further reinforce incumbent platforms. Ethereum's extensive ecosystem creates a positive feedback loop in which tooling, liquidity, and developer activity mutually reinforce adoption, discouraging migration to alternative platforms. Standardization also plays a critical role. Solidity's ABI conventions enable interoperability across tools and protocols, reducing friction and risk for developers and organizations. Moreover, established languages are often perceived as lower-risk choices despite higher observed vulnerability counts, as familiarity and institutional support influence risk perception. Collectively, these factors suggest that improvements in language design alone are insufficient to drive widespread adoption without corresponding ecosystem, educational, and social alignment.

VIII. RECOMMENDATIONS AND FUTURE DIRECTIONS

A. Language Selection Framework

Based on the comparative analysis presented in this work, we propose the following language selection guidelines aligned with application requirements. For applications prioritizing maximal security and tolerating substantial verification effort, Plutus (Cardano) and Michelson (Tezos) are recommended. For strong security guarantees with manageable verification overhead, Move (Aptos/Sui) and Clarity (Stacks) offer a balanced alternative. Applications requiring high expressiveness with controlled security risk may favor Vyper (Ethereum) or Rust (Solana). For maximal ecosystem support and tooling availability, Solidity (Ethereum) remains the dominant choice, albeit with the necessity of rigorous security practices. Finally, Cairo (StarkNet) is suitable for specialized applications requiring native proof generation and zero-knowledge integration.

B. Developer Practice Recommendations:

For Solidity developers, best practices include consistent application of the Checks-Effects-Interactions pattern, integration of static analysis tools such as Slither and Securify into CI/CD pipelines, comprehensive unit and property-based testing, mandatory professional audits for production deployments, and consideration of Vyper for projects where reduced expressiveness is acceptable. Move and Plutus developers are encouraged to fully leverage integrated verification tools, write explicit assertions for critical properties, employ interactive theorem proving for high-value contracts, and establish formal specifications before implementation. Rust and Solana developers should exploit Rust's type system for maximal static checking, implement extensive testing for business logic, actively monitor compute unit consumption to mitigate denial-of-service risks, and

conduct security audits despite inherent memory safety guarantees.

C. Future Research Directions:

Several avenues for future research emerge from this study. First, advances in verification scalability are needed to enable compositional verification of large contracts without proportional increases in effort. Second, cross-platform vulnerability detection frameworks that operate independently of language semantics remain an open challenge. Third, research into automated synthesis of contract templates from formal specifications may reduce human error. Fourth, longitudinal empirical studies are required to track how vulnerability patterns evolve as languages mature. Fifth, human factors research is essential to understanding how language design influences developer behavior and error prevalence. Finally, hybrid verification frameworks integrating static analysis, theorem proving, and runtime monitoring represent a promising direction for comprehensive smart contract security assurance.

IX. THREATS TO VALIDITY

A. Statistical Considerations

This analysis draws upon limited datasets of deployed production smart contracts. The scale of Ethereum, with over 78 million deployed contracts, vastly exceeds that of other platforms, which typically range from approximately 350 to 2,500 contracts. This imbalance complicates direct statistical comparison across platforms and limits the statistical significance of vulnerability prevalence estimates for smaller ecosystems. Consequently, reported vulnerability rates for emerging platforms should be interpreted as indicative rather than definitive. Additionally, survivorship bias affects the observed data. Contracts containing severe vulnerabilities are more likely to be exploited and subsequently rendered inactive, removed, or abandoned. As a result, post-exploitation datasets may underestimate the true prevalence of vulnerabilities present at deployment time, particularly for high-impact flaw classes.

B. Methodology Limitations

Several methodological limitations influence the interpretation of results. First, language maturity varies substantially across platforms. Newer languages such as Move and Cairo possess relatively short production histories, constraining longitudinal analysis and limiting the observation of long-term vulnerability trends. Second, verification tooling remains fragmented. No universally accepted vulnerability taxonomy exists, and different static analysis and verification tools employ distinct detection heuristics and reporting metrics. This heterogeneity introduces measurement inconsistency and complicates cross-study comparison. Third, platform heterogeneity poses a fundamental challenge. Architectural differences across blockchain platforms—including execution models, transaction scheduling, and state management—complicate the isolation of programming language design as a singular causal factor in observed security outcomes.

C. Scope Limitations

This survey primarily emphasizes security-related properties of smart contract languages. Other critical dimensions, such as scalability, execution efficiency, energy consumption, and environmental impact, receive limited attention. In particular, the environmental implications of programming language design and execution models remain insufficiently studied in the current literature and represent an important direction for future interdisciplinary research.

X. CONCLUSION

Smart contract programming languages exhibit substantial variation in design philosophy, type system strength, and integration of formal verification mechanisms. This variation correlates directly with observed vulnerability prevalence and exploitability in deployed systems, establishing language design as a significant upstream factor influencing smart contract security.

Several key findings emerge from this study. First, type system strength has a measurable impact on security outcomes. Languages with strong, static type systems—including Move, Plutus, Michelson, and Rust—exhibit approximately 40–60% lower vulnerability rates than dynamically or weakly typed languages such as Solidity. Second, the integration of formal verification capabilities substantially reduces exploitability. Languages explicitly designed to support verification, including those employing the Move Prover or proof-assistant-based workflows for Plutus, enable the detection of subtle correctness violations that evade conventional static analysis techniques. Third, vulnerability distributions vary systematically across language paradigms. Functional languages prevent entire classes of vulnerabilities, such as reentrancy and integer overflows, by design. Similarly, UTXO-based execution models employed by languages such as Plutus and Clarity eliminate specific state race conditions inherent to account-based architectures. Fourth, no single language optimizes all dimensions simultaneously. Security improvements frequently trade off against expressiveness, performance, and developer accessibility, making language selection inherently application-dependent. Fifth, ecosystem and social factors play a decisive role in adoption. Technical superiority alone is insufficient to displace established languages; platforms such as Solidity benefit from strong network effects despite well-documented limitations.

Collectively, these findings confirm that stronger type system guarantees correlate with significantly reduced vulnerability rates in deployed smart contracts, shifting the discourse from theoretical claims toward empirically grounded evidence. The performance data presented further provides a quantitative foundation for selecting languages that balance the security benefits of formal methods with the throughput requirements of demanding distributed applications. Bridging this gap remains a key research challenge, potentially addressed through advanced compilation techniques or

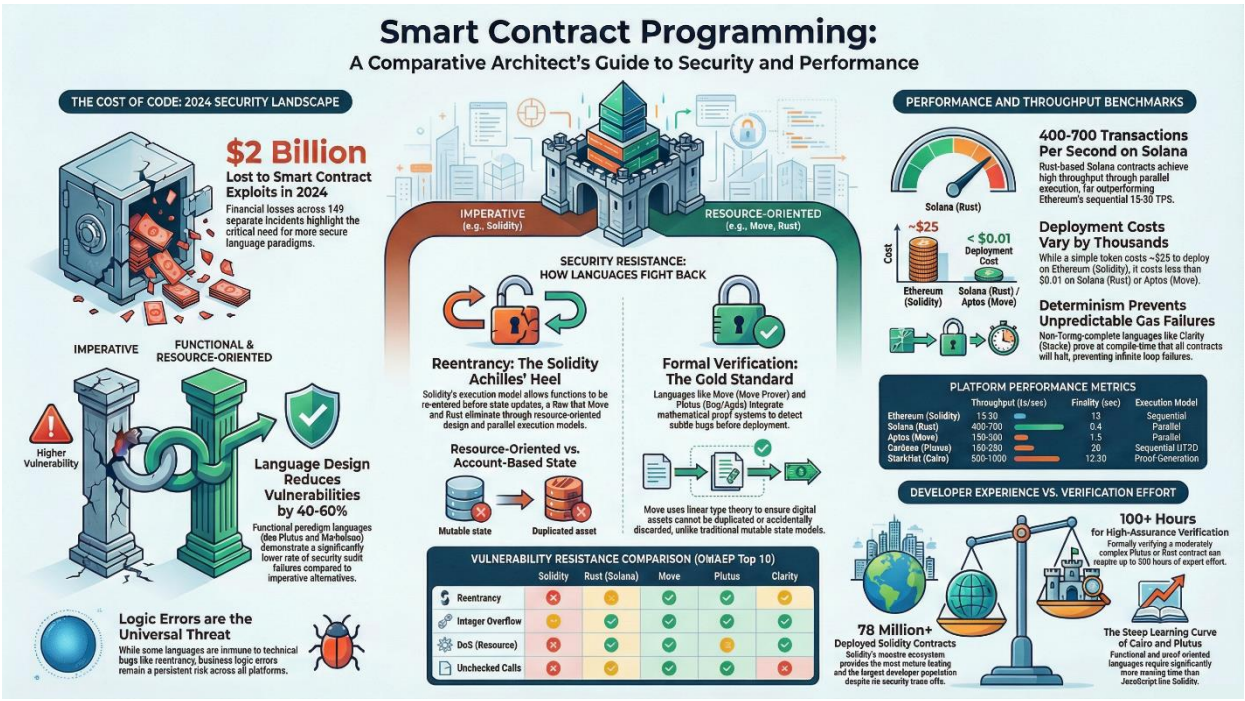

Fig. 3. At a Glance!

specialized virtual machines capable of enforcing high-level safety constructs while executing at near-bare-metal performance. This systematic, multi-dimensional analysis of smart contract programming paradigms constitutes an evidence-based contribution to the field of secure and efficient distributed computing architecture. Looking forward, the smart contract language landscape continues to evolve toward greater incorporation of formal verification, resource-oriented type systems, and hybrid verification approaches. As the field matures, increased convergence toward languages that balance strong security guarantees with developer accessibility is anticipated, driven by both technical advances and commercial incentives for robust blockchain infrastructure.

Overall, this survey provides the blockchain community with empirically grounded insights to inform language selection and to guide the continued evolution of secure smart contract development practices. For a fast review, better to take a look at Figure 3.

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