

# Tridirectional Discriminating-Power Formal Verification of Smart Contract Reentrancy Defense Against Production-Deployed Solidity Source

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**Abstract**—We present the first machine-checked correctness proof of the OpenZeppelin reentrancy-guard pattern against a Lean 4 state-machine model of production-deployed Solidity source with a composition meta-theorem spanning multiple production protocols. All thirteen theorems are machine-checked in Lean 4 with zero sorry, zero user-introduced axioms, and an axiom footprint bounded by [propext] across the entire corpus — propositional extensionality, a standard classical axiom in Lean 4’s mathlib4; per-function inner lemmas are kernel-only, master/wrapper theorems carry [propext]-only records, and the Layer 6-D capstone composes exactly the union of the prior-layer records by direct conjunction. The corpus is gated under continuous integration across four parallel verification blocks that re-check each theorem and its axiom record on every push.

Smart contract reentrancy has caused over US\$500M in cumulative documented losses since 2016, with the DAO 2016 attack alone draining  $\approx 3.6$ M ETH and forcing a contentious hard fork that split Ethereum into two persistent chains. The OpenZeppelin ReentrancyGuard mutex pattern has emerged as the de facto defense across most production DeFi protocols, yet no prior formal verification effort has established its discriminating power — the property that the guard pattern blocks attacks against vulnerable instances, preserves correct execution for non-attacking transactions, and distinguishes structurally-adjacent safe and vulnerable variants. Prior work has formalized either guard correctness on toy contracts or attack feasibility on isolated vulnerable instances, but not both directions plus boundary cases against production-deployed source.

The verification covers three production protocol instantiations — DAO 2016, Compound v2 cToken family, and Aave V3 flashLoan — together with one constructed minimal-diff mutant of Aave V3’s production flashLoan (flashLoanVulnerable) authored to isolate a single security-critical structural difference for discriminating-power isolation. We apply mutation-testing methodology to formal verification by constructing this minimal-diff mutant, enabling a controlled experiment that naturally-occurring near-misses rarely provide. The resulting tridirectional structure pairs (a) a negative-instance attack reproduction of the DAO 2016 vulnerable pattern, (b) a positive-instance correctness proof against the Compound v2 cToken family, and (c) a boundary-case proof distinguishing Aave V3’s safe-by-design flashLoan (CEI-correct) from the flashLoanVulnerable mutant. A single capstone meta-theorem composes the three protocol instantiations under a no-retrofit composition discipline (each protocol-instantiation proof was sealed prior to capstone authoring, with no underlying-proof modifications during composition), establishing a machine-checked composition meta-theorem demonstrated at the first cross-protocol stress test (Compound v2  $\rightarrow$  Aave V3, within

the lending-family domain; broader-family portability is future work, §9.4).

We release the full Lean 4 source, CI gating configuration, and reproduction commands at <https://github.com/rayiskander2406/qanary-contracts> with reproducibility verified at tagged commit v1.6-phase7-closure (the post-audit content seal; the substantive proof substrate is independently reproducible at v1.3-layer6-closure per Appendix A.3).

## 1 Introduction

Smart contract reentrancy has been a foundational vulnerability class on Ethereum-style chains since the DAO 2016 attack, yet the gap between widely-adopted defensive coding patterns and machine-checked correctness guarantees remains uneven. This paper closes part of that gap with the first machine-checked correctness proof of the OpenZeppelin reentrancy-guard pattern against a Lean 4 state-machine model of production-deployed Solidity source, organized along three machine-checked discriminating directions (negative, positive, boundary) and composed under a no-retrofit composition discipline that establishes guard-pattern correctness as a portable cross-protocol claim against multiple production protocols.

### 1.1 Problem statement

Smart contract reentrancy is one of the oldest and most consequential vulnerability classes on Ethereum-style chains. The DAO 2016 attack drained  $\approx 3.6$ M ETH ( $\approx$ US\$60M at attack-time price) and forced a contentious hard fork splitting Ethereum into two persistent chains; the attack class has not subsided despite years of awareness — Lendf.Me April 2020 ( $\approx$ US\$25M; ERC-777 callback reentrancy), Fei/Rari Capital Fuse pools 2022 ( $\approx$ US\$80M; classical reentrancy), and dozens of smaller incidents cumulatively cross US\$500M in documented losses. In response, the OpenZeppelin ReentrancyGuard modifier — a single-storage-slot mutex enforcing the predicate “not currently executing inside this contract” before re-entry — has emerged as the de facto defense across most production DeFi protocols (Compound, Aave, Uniswap-style AMMs, and the majority of TVL-significant deployments). Despite the pattern’s ubiquity, no prior formal verification effort has produced a machine-checked correctness

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proof of it against production-deployed contract source. Auditors rely on pattern recognition combined with informal reasoning; academic work has formalized either toy-scale instances, attack-feasibility on isolated vulnerable contracts, or guard correctness on simplified models — never the combination that would establish discriminating power: the guard pattern’s ability to distinguish defended-correctly from defended-incorrectly from undefended cases, machine-checked in all three directions, against production source. This paper supplies that combination.

## 1.2 Limitations of prior approaches

We characterize four limitations of the prior verification landscape that this paper addresses.

**Auditor-pattern-recognition layer.** Manual auditing relying on pattern recognition is fast but informal. Recurring reentrancy incidents at audited protocols demonstrate that the pattern-recognition layer alone is insufficient: auditors with strong track records have approved contracts that subsequently lost user funds to reentrancy variants. Pattern recognition catches the common cases but degrades at structural-adjacency boundaries, where syntactically-similar code paths differ in security-critical semantics.

**Toy-example formal verification.** A substantial body of academic work has formalized reentrancy reasoning against simplified contract models — abstract state machines, idealized storage layouts, decoupled modifier semantics. These models capture the intuition of the guard pattern but do not transfer to production contract code, which involves real Solidity storage layout, modifier interaction with inheritance hierarchies, cross-function state mutation under reentrant invocation, and gas-cost interactions with control-flow choices. Closing the gap between toy-model correctness and production-source correctness is non-trivial; ignoring it produces verification claims that reviewers reasonably discount.

**Single-direction formalization.** Prior verification work on production-leaning contracts typically formalizes one of the two basic directions: either attack feasibility on a known-vulnerable contract (negative instance) or guard correctness on a defended contract (positive instance). Rarely both. Almost never both together with boundary cases that exercise the guard pattern’s ability to distinguish defended-correctly from structurally-adjacent vulnerable variants. The composite claim — that the guard pattern is provably correct in all three directions and the directions are simultaneously load-bearing — has not been established.

**Composition gap.** Even when individual-protocol formalizations exist, the cross-protocol portability of guard-pattern correctness has not been established as a load-bearing meta-theorem. Producing per-protocol proofs in isolation tells reviewers little about the pattern’s correctness as an abstract defense; reviewers reasonably ask whether a guard-pattern proof for Protocol A composes with a guard-pattern proof for Protocol B without modification of either. Absent such a composition theorem, per-protocol claims sit as disconnected lemmas rather than a coherent discipline claim.

## 1.3 Contribution claim summary

We present the first machine-checked correctness proof of the OpenZeppelin reentrancy-guard pattern against a Lean

4 state-machine model of production-deployed Solidity source with a composition meta-theorem spanning multiple production protocols. The proof corpus is organized along three machine-checked directions — a tridirectional discriminating-power structure — across the following layers: (a) a negative-instance attack reproduction on the DAO 2016 vulnerable pattern (Layer 6-A; six theorems), (b) a positive-instance correctness proof against the Compound v2 cToken family (Layer 6-B; three theorems), and (c) a boundary-case proof distinguishing Aave V3’s production flashLoan function — safe by design via CEI-correct implementation — from a minimal-diff mutant flashLoanVulnerable constructed to isolate a single security-critical structural difference (Layer 6-C; three theorems). We apply mutation-testing methodology to formal verification: flashLoanVulnerable is a constructed minimal-diff mutant isolating a single security-critical structural difference — a controlled experiment that naturally-occurring near-misses rarely provide — demonstrating the methodology’s sensitivity to single-line regressions in production-grade logic. Our proofs operate against a Lean 4 state-machine model of this source; the faithfulness of that model to Solidity semantics is a trust assumption in the sense of §3.3.

The negative instance demonstrates that the methodology catches the most famous historical reentrancy attack (the DAO predates the OpenZeppelin guard library, so this leg establishes that the methodology recognizes the vulnerability class the guard targets — a guard-absent baseline distinct from the two guard-correctness legs); the positive instance demonstrates that the methodology clears a production contract currently securing billions in user funds; the boundary case is a constructed mutation-testing experiment that distinguishes syntactically-similar safe and vulnerable variants at the structural-adjacency boundary where pattern recognition tends to degrade — complementing the negative and positive instances rather than serving as independent evidence of natural near-miss discrimination. The full proof corpus is continuously verified under a four-block CI configuration that re-checks each theorem and its axiom record on every push, ensuring claims hold against ongoing dependency drift; complete Lean 4 source plus lake build reproduction commands are provided in Appendix A.

A single capstone meta-theorem at Layer 6-D composes the three protocol instantiations under a no-retrofit composition discipline: the three protocol-instantiation proofs were sealed prior to capstone authoring, and the capstone is proven by direct conjunction of three already-proven prior-layer theorems without modification of any underlying proof, certifying that the guard invariant holds uniformly across structurally divergent host protocol architectures. This is a stronger empirical claim than “composition succeeds when proofs are co-developed,” because the discipline forbids the most common composition move — adjusting an underlying lemma’s hypotheses to fit the desired composition target. The result is a machine-checked composition meta-theorem demonstrated under a no-retrofit composition discipline against three production protocols. To our knowledge, no prior smart-contract formal verification work has produced this combination — discriminating power against production source plus cross-protocol composition validated under a discipline that forbids retrofitting of underlying proofs. Each conjunct has partial prior art — guard correctness on

simplified models, attack feasibility on isolated vulnerable instances, per-protocol proofs in isolation; the contribution is their machine-checked conjunction, against production-deployed source, under a no-retrofit composition discipline — a combination not previously assembled, distinguished from prior co-developed compositional FV (CompCert, Iris; §8.3) by the no-retrofit constraint. Both live instantiations (Compound v2, Aave V3) are lending-family, so the cross-protocol claim is scoped to within-lending portability plus the DAO 2016 exemplar; cross-domain extension is future work (§9.4). (Full methodology framework details, including the operational labels for the patterns this discipline embodies, in Appendix B.)

#### 1.4 Approach summary

The methodology rests on four load-bearing choices. Lean 4 with mathlib4. All thirteen theorems are stated and machine-checked in Lean 4; type-theoretic foundations support the discriminating-power claim without SMT-solver dependence, and mathlib4 supplies standard tactic infrastructure. No-retrofit composition discipline. Each protocol-instantiation contract is sealed against modification before capstone authoring; the Layer 6-D capstone composes the three instantiations only from outside, by direct conjunction, with no modification of any underlying proof during composition (§4.2). Axiom-record-minimal wrapper composition. The capstone discharges its target inside a thin top-level wrapper whose own axiom footprint is exactly [propext]; absorption preserves the strongest available axiom-record claim at the capstone layer (§4.3). Continuous-integration axiom-record verification. The thirteen theorems are gated by a four-block CI configuration that verifies axiom records on every push (§4.4; Appendix A.3 reproduction commands); the repository is tagged at substantive substrate closure and methodology framework canonization, enabling reviewers to reproduce the entire corpus from a single tagged commit.

#### 1.5 Results summary

Thirteen theorems machine-checked. Six Layer 6-A theorems formalize the negative-instance DAO 2016 attack reproduction; three Layer 6-B theorems formalize the positive-instance Compound v2 cToken correctness proof; three Layer 6-C theorems formalize the boundary-case pair distinguishing Aave V3 flashLoan from the flashLoanVulnerable mutant; one Layer 6-D capstone meta-theorem (tridirectionalDiscriminatingPower\_certificate) composes the three protocol instantiations under the no-retrofit composition discipline at [propext]-only axiom dependence.

Informally: the Layer 6-A representative theorem states that the reentrancy attack on the DAO contract is formally derivable from its source semantics; the Layer 6-B representative states that the Compound v2 cToken family’s withdrawal function correctly implements the OpenZeppelin guard pattern under our formal definition of reentrancy; the Layer 6-C representative states that the minimal-diff mutant flashLoanVulnerable fails the formal discriminating-power property that production flashLoan satisfies; and the Layer 6-D capstone states (informally) that if the OpenZeppelin guard pattern is correct on Compound v2 cTokens, correct on Aave V3 flashLoan, and discriminating between Aave V3’s safe

and vulnerable variants, then the composed discriminating-power claim holds across all three. Precise theorem statements appear in §5.

Four protocol instantiations exercised. DAO 2016 (negative); Compound v2 cToken (positive; the Compound v2 cToken family — canonical mainnet markets including cUSDC at 0x39AA39c021dfbaE8faC545936693aC917d5E7563 and cDAI at 0x5d3a536E4D6DbD6114cc1Ead35777bAB948E3643 — secures multi-billion-USD lending TVL across multiple markets per public on-chain accounting at submission time); Aave V3 flashLoan paired with the flashLoanVulnerable mutant (boundary; the Aave V3 Pool contract (Ethereum mainnet) at 0x87870bca3f3fd6335c3F4ce8392D69350B4fA4E2 is among the most-deployed flash-loan venues by single-protocol TVL); and the composition across the three (Layer 6-D capstone meta-theorem).

First cross-protocol PASS under no-retrofit composition discipline. The no-retrofit composition discipline held across the Compound v2  $\rightarrow$  Aave V3 protocol-instantiation boundary at the first empirical instance in the trajectory where the discipline was stress-tested under non-trivial protocol-semantics divergence — and passed without retrofitting either underlying proof. We separate observed (composition was not prevented at this boundary; N=1 empirical), argued (the sealed-before-capstone discipline forecloses the co-development explanation), and conjectured (broader portability pending further cross-pair validation). Both live protocols are lending-family: the instance crosses a within-lending, not a between-domain, boundary (§9.4). (Internal methodology framework labels for this discipline are documented at Appendix B.)

Build state and axiom record. lake build is green at 901 jobs; the axiom-record check (§4.4) is green across every theorem. Zero sorry. Zero introduced axioms. Axiom footprint bounded by [propext] across the entire corpus (Appendix A.2 ground truth; §4.3 wrapper composition).

## 2 Background

This section establishes the context that subsequent sections build on: the smart contract security setting in which reentrancy vulnerabilities arise, the attack class itself, the OpenZeppelin guard pattern’s defensive role, the production contracts in scope for the tridirectional discriminating-power claim, and the Lean 4 + formal verification foundations on which the machine-checked proofs rest.

### 2.1 Smart contract security context

Smart contract platforms execute programmable on-chain logic under a tightly-constrained operational model — deterministic execution against globally-replicated state, transaction-atomic semantics with deterministic intra-block ordering, and synchronous external-call semantics that interleave control flow across contract boundaries within a single transaction. Ethereum is the dominant platform by value locked; Layer-1 chains and Layer-2 rollups extend the model with varying compatibility. Decentralized finance TVL has ranged from roughly US\$30B to US\$100B over the past four years, with individual protocols holding multi-billion-dollar

deposit balances and annual losses across all attack classes ranging US\$1B–2B+ in documented incidents. Reentrancy is one of several leading attack classes by aggregate loss; it is among the most enduring, recurring annually since 2016 despite near-universal industry awareness. Smart contracts are uniquely vulnerable relative to traditional software because execution is code-is-law (no operator can revert a mined transaction absent multi-month chain-governance processes), transactions are irreversible, deployed bytecode is immutable absent upgrade-pattern infrastructure, and the composable-interface model encourages cross-contract calls that interleave state mutation across mutually-distrusting authors — a single missed defensive boundary can drain a multi-billion-dollar contract in one transaction.

## 2.2 The reentrancy attack class

Reentrancy refers to a family of vulnerabilities in which a smart contract is re-entered — its functions invoked again — while a prior invocation of the same contract is still mid-execution, in a way the contract’s authors did not anticipate. The category subsumes several sub-patterns that share the underlying mechanism but differ in the specific path of state mutation and re-entry.

Classical (single-function) reentrancy is the original DAO 2016 attack pattern. The vulnerable contract performs an external call (typically a withdrawal of native ETH or an ERC-20 transfer) before updating its internal accounting state. The external call is a `CALL` opcode that transfers execution to a callee contract; if the callee is attacker-controlled, the callee can re-invoke the original contract’s withdrawal function before the original invocation has updated its state. The state update — typically a decrement of the user’s recorded balance — has not yet occurred when the recursive withdrawal begins, so the recursive withdrawal succeeds against the same (undecremented) balance. Recursion proceeds until the contract is drained or until a gas limit halts execution.

Cross-function reentrancy generalizes the pattern across multiple functions of the same contract. One function mutates state; an external call during that function’s execution allows the attacker to invoke a different function on the same contract that depends on the not-yet-updated state. The attack works even when the originally-invoked function follows the checks-effects-interactions (CEI) pattern internally, because the cross-function state coupling is not visible at the single-function level.

Read-only reentrancy is a more recent variant. A view function (one declared as not mutating state) is invoked during a reentrant call window; the view function returns stale state because the broader transaction has not yet updated the relevant storage slot. Downstream contracts that consume the view function’s return value can be deceived into accepting stale data. The attack does not require the view function itself to be vulnerable in the traditional sense; it requires only that a consumer of the view function executes during the reentrant window.

Reentrancy is fundamental to the smart contract execution model rather than incidental to any particular language. The Ethereum `CALL` opcode is synchronous: external calls transfer execution to the callee and return to the caller; the caller’s local state at the moment of the `CALL` is preserved across the synchronous transition, but global storage is

shared with the callee. Combined with the atomic-transaction guarantee, this produces a setting where mutually-distrusting contracts can observe and act on each other’s mid-transaction state. Any defense pattern that relies on storage-based gating must contend with the fact that storage is observable to reentrant callees, and any defense that relies on call-stack state must contend with the fact that the call stack includes contracts authored by attackers.

Static analysis tools — including Slither, Mythril, Securify, and academic-leaning prototypes — have made substantial progress on detecting classical single-function reentrancy patterns. Pattern-recognition heuristics flag candidate violations of the CEI pattern; constraint-solver-based tools encode storage access ordering and reachability properties. Performance on classical reentrancy is now reasonable. Performance on cross-function and read-only variants is weaker; these patterns require reasoning across function boundaries and across views vs mutators, which static analysis tools have historically struggled with at production-source scale.

## 2.3 OpenZeppelin guard pattern

The OpenZeppelin `ReentrancyGuard` contract is a single-storage-slot mutex that has become the de facto reentrancy defense across most production DeFi protocols. The contract exposes a `nonReentrant` modifier applied to externally-callable functions performing state-mutating work involving external calls. A storage slot — historically a `uint256` taking values `_NOT_ENTERED` (typically 1) and `_ENTERED` (typically 2) under varying field names — holds the current reentrancy state. The modifier requires the slot to be `_NOT_ENTERED` at function entry (reverting otherwise), sets it to `_ENTERED`, executes the function body, and resets it on exit. Any reentrant invocation of any function carrying the same modifier — same function or different function on the same contract instance — fails at the entry guard. The pattern is defensive-coding discipline rather than language-level enforcement: the Solidity compiler does not insert the guard; the developer must add the modifier to each function that requires protection, and a missed modifier produces no warning. The guard is one ingredient in a broader checks-effects-interactions discipline; production contracts adopting both are well-defended against the classical reentrancy class. Adoption is widespread (Compound, Aave, Uniswap-style AMMs, and the bulk of TVL-significant DeFi protocols use `ReentrancyGuard` or a near-identical variant), so the pattern’s correctness is load-bearing at ecosystem scale.

## 2.4 Real-contract instances in scope

The tridirectional discriminating-power claim is established against four production-relevant contract instances spanning negative, positive, and boundary cases.

DAO 2016 (negative instance). The Decentralized Autonomous Organization (the DAO) was a 2016 Ethereum smart contract that raised approximately 11.5M ETH ( $\approx$ US\$150M at the time) through token sales and aimed to operate as an investor-directed venture fund. In June 2016, an attacker exploited a classical single-function reentrancy vulnerability in the DAO’s `splitDAO` function to drain approximately 3.6M ETH ( $\approx$ US\$60M at attack-time price; substantially higher at current ETH prices). The Ethereum

community responded with a hard fork that reverted the attack’s effects, splitting the chain into Ethereum (with the hard fork) and Ethereum Classic (without). The DAO attack is the canonical reentrancy incident; reproducing its core mechanism is the natural negative-instance test of any guard-pattern verification methodology.

Compound v2 cToken family (positive instance). Compound v2 is one of the longest-running and largest production lending protocols on Ethereum. The cToken family — interest-bearing tokens representing deposits in Compound’s lending markets — uses the OpenZeppelin guard pattern correctly across its withdrawal and redemption paths. The Compound v2 cTokens currently secure approximately US\$2.5B in lending TVL across multiple markets, depending on market conditions. The cToken family is a strong positive-instance test: a real production contract holding multi-billion-dollar deposits, with a guard-pattern implementation that the community has stress-tested for years without a confirmed reentrancy incident against the pattern itself.

Aave V3 flashLoan (boundary case, safe). Aave V3 is one of the largest production lending protocols. Its Pool contract — deployed on Ethereum mainnet at address `0x87870bca3f3fd6335c3F4ce8392D69350B4fA4E2` — implements a flashLoan function that issues uncollateralized loans repayable within the same transaction. The flashLoan body is checks-effects-interactions-correct by design: the function records the loan, transfers funds to the borrower, invokes the borrower’s `IFlashLoanReceiver.executeOperation` callback, then verifies repayment plus fee on return. The body prevents reentrancy by checks-effects-interactions execution ordering — the borrower callback cannot observe uncommitted intermediate state — rather than by an OpenZeppelin-style storage-mutex modifier; the formalization (§5.5) models this CEI ordering at an abstract body-shape layer. flashLoan is the canonical protocol-by-design CEI-correct exemplar in the boundary-case layer.

Aave V3 flashLoanVulnerable (boundary case, vulnerable). For the boundary case to test discriminating power, we author a structurally-adjacent vulnerable variant — flashLoanVulnerable — that differs from flashLoan in a single security-critical respect: the variant fails to engage the guard pattern’s body invariant correctly, leaving a reentrancy window during the callback. The variant is structurally adjacent to the safe version: same function signature, same borrower-callback shape, near-identical control flow, identical surface API. Pattern recognition operating at code-shape level would treat the two variants as the same; the methodology presented here distinguishes them at the body-shape layer where the guard-engagement invariant differs.

The four contracts together exercise the tridirectional discriminating-power claim. The negative instance demonstrates that the methodology catches the most famous historical reentrancy attack. The positive instance demonstrates that the methodology clears a production contract currently securing billions in user funds. The boundary case demonstrates that the methodology distinguishes between syntactically-similar safe and vulnerable variants at the structural-adjacency boundary — the place where pattern recognition tends to degrade and where a verification methodology’s discriminating power is most consequential.

## 2.5 Lean 4 and formal verification context

Lean 4 is a dependently-typed proof assistant with type-theoretic foundations based on the Calculus of Inductive Constructions with universes. Theorems are propositions, proofs are programs constructing evidence, and type-checking confirms that proof terms have the type stated in the theorem (Curry-Howard). We selected Lean 4 over Coq, Isabelle/HOL, and HOL Light because Lean’s tactic framework suits the structural reasoning the discriminating-power claim requires; mathlib4 supplies standard data structures, finiteness reasoning, and tactic libraries reducing proof-engineering overhead; and Lean 4’s tooling, semantics, and proof-term sizes remain stable and manageable for the theorem shapes used here.

The proof corpus depends on a pinned mathlib4 version specified in `lakefile.lean` and locked via `lake-manifest.json`; `lean-toolchain` pins the Lean compiler version. Standard imports include `Mathlib.Tactic`, natural-number infrastructure, `Mathlib.Data.List.*` modules for trace semantics, and `Mathlib.Logic` for propositional reasoning. Axiom record discipline is enforced at the CI level (§4.4); acceptable records are kernel-only (provable in pure intensional type theory) and `[propxt]`-only (propositional extensionality only — no choice or excluded middle). No theorem is admitted with `sorry`, `admit`, or any user-introduced axiom.

## 3 Threat Model

This section specifies the formal threat boundary against which the discriminating-power claim of §1.3 is established. We make adversary capabilities, the state-machine abstraction level at which formalization operates, the trust assumptions on which our proofs depend, and the explicit out-of-scope items all visible up-front. Doing so allows reviewers to evaluate the contribution claim’s scope precisely and serves as the canonical reference point for the substantive material in §5 about what is and is not proved.

### 3.1 Adversary model

The adversary controls one or more Externally-Owned Accounts (EOAs) on the target chain and may deploy and call arbitrary smart contracts. The adversary is permitted to compose cross-protocol interactions via the callable-contract pattern that underlies the reentrancy attack class — that is, to deploy contracts conforming to the callback interfaces (`receive`, `fallback`, `tokensReceived`, `IFlashLoanReceiver.executeOperation`, etc.) that the protocols under analysis use to invoke external behavior during the execution of a guarded function. The adversary may also coordinate sequences of transactions across blocks where coordination across atomic-transaction boundaries is permitted by the underlying chain semantics.

The adversary has no special protocol-level privileges. The adversary is not a protocol owner, is not on a whitelist, is not a validator or block proposer, and holds no role-based access-control credentials at the protocols under analysis. In particular, the adversary cannot pause the protocol, change interest-rate parameters, replace the implementation behind an upgradeable proxy, or otherwise exercise governance-mediated authority. Where a protocol exposes a nonReentrant-guarded function, the adversary’s only routes to that

function are the publicly callable interfaces; the adversary cannot bypass the guard pattern by privileged means.

The adversary may control multiple addresses. Sybil-resistance analysis is not in scope; for the purposes of this threat model, all adversary-controlled addresses are treated collectively as the adversary, and a defense that holds against a single adversary-controlled address holds against multiple coordinated addresses under the same control. The adversary’s computation is bounded by standard EVM gas-limit constraints (per-transaction block gas limit and per-call sub-budgets); no quantum-computational, oracle-prediction, or non-classical computational assumptions are made on either side.

### 3.2 State-machine abstraction level

The formalization operates at Solidity-level semantics rather than raw EVM bytecode. The state machine captures storage layout at slot granularity, call-stack-aware function-call sequencing, the boundary semantics of external CALL op-codes (synchronous-return-with-shared-storage — the property that produces the reentrancy setting), and atomic-transaction guarantees (whole-transaction rollback on revert; observable mutations only on success). The OpenZeppelin guard pattern’s correctness claim is precisely that the entry-time storage check on `_status` blocks every re-entry into any function carrying the `nonReentrant` modifier on the same contract instance, regardless of whether the original invocation has returned. Several abstraction-level details are deliberately out of scope at the model layer: gas accounting is assumed sufficient for analysis-relevant operations (we model neither gas exhaustion mid-call as a separate failure mode nor denial-of-service via gas, since the discriminating-power claim concerns reachability of attacker-favorable states under successful execution); precompile semantics and `SELFDESTRUCT` are abstracted (the in-scope protocols do not exercise them on reentrancy-relevant paths); Solidity-source-to-bytecode compilation correctness is a separate trust assumption (§3.3). Model fidelity. The model captures features load-bearing for reentrancy (storage at slot granularity, call-stack-aware sequencing, external-CALL boundary semantics, atomic-transaction guarantees, modifier composition) and abstracts precompile internals, `SELFDESTRUCT`, and coarse gas accounting — each benign for the reentrancy class. The faithfulness of this model to Solidity semantics for the modeled features is an explicit trust assumption (§3.3).

### 3.3 Trust assumptions

Five trust assumptions underpin the discriminating-power claim, all standard in the formal-verification literature for smart-contract source-level proofs. The first two concern translation soundness in opposite directions from the source-level pivot; the third concerns computational-substrate correctness; the remaining two scope the threat model.

Solidity compiler correctness. Our proofs operate at the Solidity source level. Deployed bytecode correctness derives from the Solidity compiler’s correct compilation of that source (specifically, the solc version in each protocol’s deployment metadata — pre-0.4.x lineage for DAO 2016, 0.5.x for Compound v2 cToken, 0.8.x for Aave V3 Pool). Compiler-correctness verification is itself an active research area; we

do not attempt to subsume that work within the present scope. Reviewers may treat our results as conditional on sole correctness for the specific source files analyzed.

Lean-model fidelity for the modeled features. Our proofs operate against the Lean 4 state-machine model of §3.2, not raw Solidity source or compiled bytecode directly. We assume this model is a sound abstraction of the relevant Solidity-semantics fragment for the analyzed contracts (the captured features of §3.2). The model targets the logic semantics of the storage-slot-mutex guard pattern (`_status` slot, `_NOT_ENTERED/_ENTERED` transitions, modifier-entry/exit), which are invariant across source-level and compiled-bytecode representations; this is an intentional design choice rather than a verification gap. Deriving such model-to-source soundness mechanically — a verified-translation pipeline in the KEVM/F\*-EVM-semantics line of §8.1 — is active research, out of scope here; results are conditional on this fidelity. This assumption is distinct from solc compiler correctness above: it concerns the source→Lean-model direction.

Lean 4 kernel and mathlib4 correctness. As is standard for any Lean 4 formalization, the proofs are mechanically checked under the assumption that the Lean 4 kernel correctly implements its type theory and that the imported mathlib4 modules correctly state the mathematical results they claim. Lean 4’s kernel is small and has received community scrutiny; the imported mathlib4 modules (general tactic infrastructure, finite-data-structure reasoning, propositional logic) are pinned via `lakefile.lean` dependency declarations and locked through `lake-manifest.json`, with the Lean compiler version pinned separately via `lean-toolchain`. The exact dependency graph is reproducible from the tagged commit.

Honest borrower assumption per real-contract instance. For the Compound v2 cToken positive instance, the discriminating-power claim concerns the guard pattern’s correctness against reentrancy; it does not require borrowers to behave honestly in any economic sense (interest-rate solvency, collateral maintenance, liquidation responsiveness). Borrowers may be adversarial in the §3.1 sense; what is assumed is that the protocol-level invariants the cToken family relies on (such as correct accrual of interest at withdrawal time) are computed by the protocol’s own accounting code rather than supplied by the caller. The same holds for the Aave V3 boundary case: the borrower is assumed adversarial, the flash-loan protocol’s repayment-verification logic is assumed to execute as written.

No miner or validator behavior assumption. The properties proved are not contingent on miner or validator behavior. We do not assume timing constraints, transaction-ordering constraints, reorg-resistance constraints, or proposer honesty. The reentrancy attack class is mediated by smart-contract execution within a single transaction, not by consensus-layer behavior; our claim therefore inherits no consensus-layer trust requirement.

### 3.4 Out-of-scope items and boundary summary

The discriminating-power claim addresses the reentrancy attack class against contracts that adopt (or fail to adopt) the OpenZeppelin guard pattern. Several attack classes that have produced significant losses in production DeFi are explicitly

out of scope: oracle manipulation (flash-loan-enabled price-feed attacks, structurally distinct from re-entering a guarded function); MEV and transaction-ordering attacks (sandwich extraction, mempool-ordering arbitrage operating above the contract-execution layer); governance attacks (proposal-passing exploits, vote-buying, timelock bypasses, assuming each protocol’s governance configuration is correctly set); cross-chain bridge attacks (chain-boundary trust assumptions absent from single-chain analysis); front-running (mempool-level user-transaction frontrunning); centralization risks (admin keys, upgradeable-proxy privileged operations, role-based pauses — our claim concerns the publicly callable surface only); and economic attacks not mediated by reentrancy (liquidation cascades, interest-rate manipulation, collateral-ratio exploits). The methodology’s potential extension to these classes is future work (§9, §7.2); no broader claim is made by the present paper.

In scope: the reentrancy attack class against the OpenZeppelin guard pattern, formalized at Solidity source level for the three production protocol instantiations of §1.3 — DAO 2016 (negative), Compound v2 cToken (positive), Aave V3 flashLoan paired with the flashLoanVulnerable minimal-diff mutant (boundary). Within that scope the methodology catches the negative instance, clears the positive instance, and distinguishes the boundary pair, machine-checked end-to-end.

## 4 Methodology Overview

This section describes the formalization approach and the methodological discipline under which the proofs were authored, presented at the level of operational consequence rather than internal-framework labels. The full methodology framework — including its sub-pattern catalog, graduation criteria, and cross-protocol stress-test history — is the subject of a companion arXiv paper; the present section gives reviewers what they need to evaluate the substantive smart-contract-verification claims of this paper.

### 4.1 Formalization approach

The formalization is conducted in Lean 4 with mathlib4 as the supporting mathematical library. Lean 4’s dependent type theory, with the propositions-as-types correspondence sketched at §2.5, allows propositions and their proofs to be first-class type-theoretic objects: a theorem statement is a type, a proof is a program of that type, and the type-checker’s confirmation that the proof has the stated type is the verification. Tactic proof scripts produce these proof terms; the kernel re-checks them whenever the corpus is built.

Mathlib4 modules are imported as needed. The dependency graph is recorded explicitly: the Lean compiler version is pinned in lean-toolchain; the mathlib4 dependency version is pinned in lakefile.lean and locked at lake-manifest.json. Standard tactic infrastructure (Mathlib.Tactic), natural-number reasoning (Mathlib.Data.Nat.Basic), list manipulation underlying the trace semantics (modules under Mathlib.Data.List), and propositional reasoning (Mathlib.Logic modules) constitute the bulk of the imported surface.

The proof discipline is theorem-statement-first. Each theorem statement is authored and sealed prior to any proof body

authoring; statement modifications during proof work are prohibited under the methodology framework’s discipline. This forecloses the most common failure mode of co-developing statement and proof — the unconscious weakening of a statement’s hypotheses or strengthening of its assumptions to fit the partial proof one has constructed. When the proof of a sealed statement turns out to be impossible as written, the disciplined response is to escalate (the statement was the wrong claim) rather than silently adjust the statement to match the proof.

Per-theorem axiom-record verification is gated in continuous integration on every push. Lean 4’s #print axioms introspection produces, for any named theorem, the list of axioms its proof transitively depends on. The CI configuration runs this introspection over each theorem in the corpus and fails the build if any theorem’s axiom record drifts from the claimed record. This converts axiom-minimality from an author’s assertion into a continuously checked invariant: a future change that silently introduces a dependency on (say) classical choice would be caught by the CI gate at the next push, not by reviewer inspection at submission time.

### 4.2 The compose-from-outside discipline

The capstone meta-theorem at Layer 6-D is proven under a strict no-retrofit composition discipline: the three protocol-instantiation theorems are conjoined directly to produce the capstone, with no modification of any underlying protocol-instantiation proof during composition. The phrase compose from outside names the operational consequence: composition operates on the prior-layer theorems as black-box facts rather than reaching inside their proofs to adjust hypotheses, conclusions, or supporting lemmas.

The discipline is enforced procedurally rather than by a single language-level mechanism. The three protocol-instantiation files — DAOContract.lean, CompoundContract.lean, AaveBoundaryCase.lean — were authored, proven, and sealed prior to any work on the capstone meta-theorem. Once a file was sealed, modifications to that file were prohibited under the methodology discipline; any subsequent change required explicit re-authorization with documented rationale. The capstone author thereby faced a hard constraint: prove the meta-theorem from the sealed prior layers as they stand, or escalate.

Three classes of modification are forbidden under this discipline. Adjusting an underlying lemma’s hypotheses to fit a desired composition target — the most common composition move in formal-verification work — is prohibited. Weakening a prior theorem’s conclusion to make it easier to compose is prohibited. Adding unstated hypotheses to underlying theorems to discharge intermediate proof obligations is prohibited. The capstone proof either composes the underlying theorems exactly as they were sealed, or it does not compose at all.

The first cross-protocol stress test of this discipline occurred at the Compound v2 → Aave V3 boundary in the Layer 6-D capstone. The two protocols differ in non-trivial ways at the semantic level: Compound’s cToken family operates on a balance-update-and-transfer pattern with persistent user accounting; Aave’s flashLoan operates on a repay-within-transaction pattern with no persistent user accounting beyond the loan window. A retrofit-permissive workflow could have

produced a capstone proof by adjusting either protocol’s underlying lemmas to fit a common composition shape. The no-retrofit discipline forbade that path. The capstone nevertheless composed: a direct conjunction of the three sealed prior-layer theorems discharged the meta-theorem at [propxt]-only axiom dependence. We treat that successful composition as observed  $N=1$  evidence — and, given the sealed-before-capstone discipline that forecloses the co-development explanation, as an argument that the guard pattern’s correctness is portable across the observed boundary; broader portability is conjectured pending further cross-pair validation (the observed/argued/conjectured separation of §1.5), not asserted from  $N=1$ .

This is a methodologically stronger claim than “composition succeeds when proofs are co-developed.” The latter is consistent with each underlying proof having been silently shaped to fit the eventual composition target. The no-retrofit discipline rules out that path of explanation: the underlying proofs cannot have been shaped by the composition target, because they were sealed before the composition target’s proof was authored. The internal label and broader pattern context for this discipline within our methodology framework appear at Appendix B; the operational property described above is the load-bearing one for the present paper.

#### 4.3 Axiom-record-minimal wrapper composition

The Layer 6-D capstone is structured as a thin wrapper module that imports the three sealed protocol-instantiation theorems and discharges its target proposition by directly conjoining them; the wrapper introduces no new axioms, and its `#print` axioms record is exactly the union of the underlying theorems’ records. This wrapper-layer pattern preserves axiom-record minimality at the capstone: each underlying protocol-instantiation theorem carries its own kernel-only or [propxt]-only record (verified at the per-layer CI block), and the wrapper only conjoins existing facts. The capstone therefore inherits the strongest available axiom-record claim — [propxt]-only, the standard `mathlib4` axiom of propositional extensionality, a single classical extension fully compatible with the Lean 4 kernel. No user-introduced axioms appear at any layer of the corpus. The broader pattern context (related patterns, cross-protocol empirical history) is documented at Appendix B and elaborated in the companion methodology paper.

#### 4.4 CI verification and axiom-record discipline

Continuous integration consists of four parallel verification blocks at `build.yml` lines 287, 356, 408, and 464, gating the thirteen theorems on every push: one block each for Layer 6-A (DAO 2016 negative-instance, 6 theorems + supporting lemmas), Layer 6-B (Compound v2 `cToken` positive-instance, 3 theorems), Layer 6-C (Aave V3 boundary-case pair, 3 theorems), and Layer 6-D (capstone meta-theorem). The `#print` axioms introspection emits each theorem’s transitively required axioms; the CI compares against recorded expectations per theorem and fails the build on any mismatch. The capstone records [propxt]-only; each Layer 6-A/B/C theorem records kernel-only (no axioms beyond Lean 4’s intensional type theory) or [propxt]-only. No theorem is admitted with sorry, admit, or any user-introduced axiom. Reproducibility

is anchored at tagged commits: the substantive substrate at `v1.3-layer6-closure`, the methodology framework canonization at `v1.7-methodology-housekeeping`. Reviewers reproduce the verification by checking out either tag and running `lake build plus lake env lean QanaryContracts/PrintAxioms.lean` against the pinned dependency graph. The manuscript content corresponding to this paper version is sealed at intermediate tag `v1.6-phase7-closure` (the abstract’s reproducibility anchor); the substrate at `v1.6` is identical to `v1.3`, so reviewers may equivalently check out `v1.6` for end-to-end reproduction.

#### 4.5 Manuscript audit and transparency

The manuscript was developed with generative-AI assistance (Claude, Grok, and Gemini) used for editorial purposes including adversarial audit of drafts, prose drafting under author direction, and methodology-framework review during preparation. All model outputs were inspected by the author; the substantive contributions of this paper — the thirteen machine-checked theorems and their axiom records — are verified by the Lean 4 kernel and CI-reproducible per Appendix A.3. The audit framework itself is not a claimed research contribution of this paper and is presented in the companion methodology paper (separate arXiv track per the boundary discipline of §1). This paragraph satisfies the generative-AI-usage disclosure required by the venue’s call for papers.

### 5 Formalization

This section presents the substantive substrate of the discriminating-power claim: the formal definitions and predicates, the inventory of the thirteen machine-checked theorems, per-layer presentation of negative/positive/boundary proofs, the capstone meta-theorem, and the reproducibility anchor. Full theorem statements, axiom records, and proof-skeleton excerpts are deferred to Appendix A.

#### 5.1 Formal definitions and predicates

The formalization rests on three load-bearing predicates over the Solidity-source state-machine model of §3.2. The reentrancy predicate characterizes the attack class: a contract execution exhibits reentrancy if there exists a call trace in which an external `CALL` from function `f` of contract `A` transfers execution to an attacker-controlled callee that, before `f`’s frame returns, invokes a function `g` of `A` (where `g` may be `f` itself) and observes storage state `f` has modified but not yet completed updating. The predicate is call-stack-aware, storage-mutation-aware, and external-call-boundary-aware, capturing classical single-function, cross-function, and the storage-observation aspect of read-only reentrancy. The guard-pattern correctness predicate characterizes the OpenZeppelin guard’s correct application: function `f` of contract `A` carries the guard correctly if its entry condition checks `_status == _NOT_ENTERED`, its body sets `_status = _ENTERED` before any external `CALL`, its exit resets to `_NOT_ENTERED`, and these accesses target the same storage slot as other guarded functions on `A`; a function carrying the guard correctly cannot exhibit reentrancy under the model. The discriminating-power predicate is the meta-level claim: a verification methodology discriminates between



guard-protected and guard-vulnerable instances if it derives the reentrancy predicate for vulnerable instances, derives the guard-pattern correctness predicate for protected instances, and distinguishes structurally-adjacent vulnerable variants from safe counterparts. The tridirectional claim of §1.3 is the assertion that our formalization satisfies this meta-predicate against the three production instantiations of §2.4 plus the minimal-diff mutant of §5.5. Full predicate definitions appear in Appendix A.

## 5.2 Theorem inventory

Thirteen theorems machine-check the discriminating-power claim. The inventory below summarizes each theorem at the level of an informal one-line statement; the precise Lean 4 statements (with full type signatures, hypothesis lists, and the `#print` axioms output) appear in Appendix A.

Each layer’s theorems are gated by an independent CI block (§4.4), mechanically verifying both that the theorems still type-check against the pinned `mathlib4` dependency graph and that their axiom records match the expectations recorded in Appendix A on every push. No theorem is admitted with `sorry`, `admit`, or any user-introduced axiom declaration; the corpus axiom footprint is bounded by `[propxt]` (Appendix A.2).

### 5.3 Layer 6-A: negative instance (DAO 2016)

The Layer 6-A negative instance reproduces the classical reentrancy attack against the DAO 2016 contract. The `splitDAO` function performs an external transfer of native ETH to a user-controlled recipient before decrementing the user’s recorded balance, opening a window in which a recipient contract can re-invoke `splitDAO` against the same undecremented balance until the contract is drained.

Our formalization models the relevant subset of the DAO contract source — the `splitDAO` function’s storage layout, balance accounting, and external-call structure — at the abstraction level of §3.2. The Layer 6-A capstone theorem (one of six in this layer) states that under the reentrancy predicate of §5.1, the attacker-controlled re-entry path is derivable from the DAO contract source: there exists a constructible call trace, expressible in our state-machine model, in which the re-entry succeeds and the contract’s invariant (balance-sum equals total-deposits) is broken. The five supporting lemmas decompose the derivation into the load-bearing pieces — call-stack interleaving, storage-observation, balance-update sequencing, and the absence of any guard-pattern protection — that together discharge the capstone.

The DAO contract predates the OpenZeppelin guard library. Its inclusion as the negative instance is therefore not a guard-pattern failure but a guard-pattern target: the DAO formalization demonstrates that the methodology recognizes the vulnerability class the guard pattern was created to address, even where the guard itself is absent. This complements the Layer 6-B and 6-C results, which establish recognition of the guard’s behavior when present. Full theorem statements, hypothesis structure, and proof-skeleton outline appear in Appendix A.

### 5.4 Layer 6-B: positive instance (Compound v2 cToken family)

Compound v2’s `cToken` family represents the largest and longest-running production deployment of the OpenZeppelin guard pattern within DeFi lending. Each `cToken`’s withdrawal-path functions (`redeem`, `redeemUnderlying`, the underlying transfer flows) carry a `nonReentrant` modifier implementing the OpenZeppelin guard pattern. Compound v2’s deployment uses a structurally-equivalent custom in-contract realization rather than the literal library import — same `_status` slot semantics, same `_NOT_ENTERED/_ENTERED` integer encoding, same modifier-entry guard, same modifier-exit reset — authored before the OpenZeppelin library API stabilized; our formalization targets this custom realization, and the discriminating-power claim transfers to OZ-library-importing protocols because the formalization predicate (§5.1) abstracts over the realization at the storage-slot-mutex level. (Source-level terminology may vary across “OpenZeppelin guard pattern,” “structurally-equivalent custom guard,” and “mutex-modifier pattern” depending on commit; all refer to the same storage-slot mutex semantics formalized here.) The protocol has stress-tested this pattern in production for years without a confirmed reentrancy incident against the guard itself.

The Layer 6-B target theorem (one of three in the layer) states that the `cToken` withdrawal path correctly implements the OpenZeppelin guard pattern under our predicate of §5.1: any execution trace conforming to the `cToken` withdrawal path satisfies the guard-pattern correctness predicate, and consequently no reentrancy trace is constructible against it. Two supporting lemmas decompose the result: a guard-invariant lemma showing that the storage slot tracking guard state is consistently set before any external call and reset after, and a cross-function safety lemma showing that the guard’s protection extends across the multiple functions of the `cToken` interface that share the same `_status` slot.

The Layer 6-B capstone is structured as a thin wrapper module that imports the supporting lemmas and discharges the target theorem by composition without modifying either lemma — an instance of the axiom-record-minimal wrapper composition of §4.3, which preserves axiom-record minimality through the composition. The capstone records minimal axiom dependence (no propositional extensionality required at this layer; the result is provable in the pure intensional fragment of Lean 4’s type theory). Full theorem statements, the wrapper module’s structure, and the per-lemma proof skeletons appear in Appendix A.

### 5.5 Layer 6-C: boundary case (Aave V3 flashLoan vs flashLoanVulnerable)

The Layer 6-C boundary case is the methodological core of the discriminating-power claim. Aave V3’s `Pool` contract implements `flashLoan` according to a checks-effects-interactions discipline that is guard-pattern correct by construction: the loan is recorded, funds are transferred, the borrower’s `IFlashLoanReceiver.executeOperation` callback is invoked, and repayment plus fee is verified on return. The borrower-supplied callback cannot exploit reentrancy because the body commits all security-relevant state before the callback executes; the Layer 6-C predicate discriminates on this `SSTORE-before-`

TABLE 1  
Inventory of thirteen theorems across four protocol-instantiation layers.

Layer	Count	Theorem(s)	Informal statement	Axiom record
6-A	1 + 5	DAO reentrancy derivation + supporting lemmas	The DAO 2016 attack trace is derivable from the contract’s source semantics under the reentrancy predicate	[propext]-only master/wrapper; kernel-only inner lemmas
6-B	1 + 2	Compound v2 cToken correctness + supporting lemmas	The cToken family’s withdrawal path correctly implements the OpenZeppelin guard pattern under our reentrancy predicate	[propext]-only master/wrapper; kernel-only inner lemmas
6-C	2 + 1	Aave V3 flashLoan correctness + flashLoanVulnerable failure + CEI lemma	Production flashLoan satisfies guard-pattern correctness; the minimal-diff mutant flashLoanVulnerable fails it	[propext]-only master/wrapper; kernel-only inner lemmas
6-D	1	Tridirectional discriminating-power capstone	Composed: methodology catches the negative instance, clears the positive instance, and distinguishes the boundary pair	[propext]-only (union of prior-layer records)

CALL body-shape ordering (the abstract guard-engagement pattern), which production flashLoan satisfies.

To exercise discriminating power against structurally-adjacent variants — where pattern recognition is known to degrade per §1.2 — we construct flashLoanVulnerable as a minimal-diff mutant of production flashLoan. The mutant differs in a single security-critical respect: its body fails to engage the guard correctly at the callback boundary, leaving a reentrancy window. All other aspects — signature, callback interface, control flow, surface API — are identical. This is mutation testing for formal proofs: where naturally-occurring near-misses combine multiple structural differences with confounding context, the minimal-diff mutant isolates the precise security-critical structural difference. A single hand-constructed minimal-diff mutant is a principled choice over an operator-derived corpus [9], [10] — a security-critical semantic regression test specifically optimized for formal specification boundary detection, distinct from the random syntactic perturbations automated mutation operators typically produce against production DeFi code.

The Layer 6-C theorems formalize discriminating power against this pair: production flashLoan satisfies guard-pattern correctness under the §5.1 predicate; flashLoanVulnerable fails it (a reentrancy trace is constructible against the mutant); a supporting CEI-pattern preservation lemma underwrites the first theorem and is consumed by the second’s failure proof at the structural-adjacency boundary where the mutant deviates. The methodology thereby distinguishes safe flashLoan from structurally-adjacent vulnerable flashLoanVulnerable at the precise boundary the boundary case is designed to probe. Full theorem statements and the mutant’s diff specification appear in Appendix A.

## 5.6 Layer 6-D: tridirectional capstone

The Layer 6-D capstone meta-theorem composes the three protocol-instantiation results into the tridirectional discriminating-power claim: if the Layer 6-A derivation, the Layer 6-B correctness theorem, and the Layer 6-C boundary-case pair all hold, then the methodology satisfies the discriminating-power predicate of §5.1 against the production protocol instantiations of §2.4 plus the minimal-diff mutant of §5.5. The capstone is proven by direct conjunction of the three prior-layer theorems — a wrapper construction in the sense of §4.3 — without modification of any underlying proof.

This composition shape is the operational signature of the no-retrofit discipline of §4.2. The three protocol-instantiation files were sealed prior to capstone authoring; capstone construction had no path to modify them; the capstone composed by direct conjunction nevertheless. We treat this as the first cross-protocol stress-test PASS against non-trivial protocol-semantics divergence: Compound v2’s persistent-accounting model and Aave V3’s repay-within-transaction model differ in ways a retrofit-permissive workflow could have used to shape underlying lemmas toward a common composition target — the discipline forbade that path and the composition succeeded anyway. Mathematically the capstone is conjunction-introduction; the contribution is the demonstrated environmental-contract uniformity of the guard invariant across protocol architectures that do not share an accounting model, made non-vacuous by foreclosing the co-development confound.

The capstone’s axiom record is [propext]-only and equals the union of the three prior-layer records (§4.3 wrapper preserves axiom-record minimality); no choice, no excluded middle, no user-introduced axiom declarations anywhere in the corpus. In the Lean formalization, the safe contract instance carrying production flashLoan is named aaveContract,

and the structurally-adjacent vulnerable contract carrying flashLoanVulnerable is named aaveContractAdjacent; the paper-body flashLoan vs flashLoanVulnerable distinction is the function-level view of the contract-level objects below. The capstone’s Lean 4 statement and proof term illustrate the direct-conjunction wrapper composition concretely:

```
theorem tridirectionalDiscriminatingPower_certificate :
  (¬ OZGuardDisciplineGeneral daoContract) ∧
  (OZGuardDisciplineGeneral compoundContract) ∧
  (OZGuardDisciplineGeneral aaveContract ∧
   ¬ OZGuardDisciplineGeneral aaveContractAdjacent) :=
  ⟨daoContract_violates_OZGuardDisciplineGeneral,
   compoundContract_satisfies_OZGuardDisciplineGeneral,
   aaveBoundaryCase_certificate⟩
```

The proof term is exactly the triple  $\langle h\_dao, h\_compound, h\_aave \rangle$  of the three sealed prior-layer theorems — no rewriting, no hypothesis adjustment, no auxiliary lemma. Full prior-layer theorem statements and `#print` axioms output appear in Appendix A.

## 5.7 Reproducibility

The corpus is reproducible end-to-end from a tagged commit per §4.4; full git checkout invocations, lake build commands, and expected axiom-record outputs appear in Appendix A.3.

# 6 Implementation and Reproducibility

This section presents the practitioner-facing evidence base for the discriminating-power claim: the size of the formalization corpus, the CI gating discipline that re-checks the corpus on every push, and the tagged-commit reproducibility procedure that allows reviewers to verify the verification. We do not report head-to-head comparison against heuristic detectors (Slither, Mythril, Certora-style checking): foundational machine-checked verification establishes a different guarantee layer than heuristic detection, so the comparison is qualitative by construction (per §1.2).

## 6.1 Repository structure

The repository is organized at three top-level locations: paper/ (manuscript source, arXiv submission package, and supporting artifacts), QanaryContracts/ (Lean 4 source mapping to Layer 6-A/B/C/D — DAOContract.lean (Layer 6-A negative instance), CompoundContract.lean (Layer 6-B positive instance), AaveBoundaryCase.lean (Layer 6-C boundary case), CrossProtocolAudit.lean (Layer 6-D capstone) — plus supporting modules), and methodology/ (canonical artifacts pointer-tabled at Appendix B). The continuous-integration configuration sits at build.yml. All artifacts are reachable from any tagged commit, so a reviewer who checks out a single tag obtains consistent state across manuscript, source, and CI configuration.

## 6.2 Corpus size

The formalization corpus is approximately 8,538 lines of Lean 4 source across the four protocol-instantiation layers and supporting infrastructure: Layer 6-A formalizes the DAO 2016 negative instance across ~656 lines (6 theorems); Layer 6-B Compound v2 across ~517 lines (3 theorems); Layer 6-C Aave V3 across ~770 lines (3 theorems including the

minimal-diff mutant); Layer 6-D the capstone in ~260 lines (1 theorem); supporting modules and lemmas total ~6,335 lines. Per-file contribution and full theorem-to-file mapping appear in Appendix A (approximate per-layer counts; exact per-file counts reproducible at the tagged commit per Appendix A.3).

## 6.3 CI verification

The CI configuration of §4.4 — four parallel verification blocks, one per Layer 6-A/B/C/D — runs on every push. lake build compiles and type-checks the corpus at 901 jobs; the axiom-record introspection of §4.4 verifies each theorem against its recorded expectation. Wall-clock verification runs in the order of minutes per push on standard runners. CI failure on any block — type-check failure, axiom-record drift, or supporting-lemma regression — surfaces immediately in the pull-request status. Full per-theorem axiom records appear in Appendix A.

## 6.4 Reproducibility posture

Every proof-authoring session is recorded as a tagged-commit-anchored artifact; the directive + closure-report discipline is documented in the companion methodology paper. The corpus is reproducible end-to-end from a tagged commit: the substantive substrate is sealed at v1.3-layer6-closure; the methodology framework canonization is sealed at v1.7-methodology-housekeeping. The manuscript content corresponding to this paper version is sealed at intermediate tag v1.6-phase7-closure (the abstract’s reproducibility anchor); see §4.4 for the relationship between these three tags. Full reproduction commands and the pinned dependency graph appear in Appendix A.

# 7 Discussion

## 7.1 Implications

The result extends machine-checked verification for smart-contract security beyond the pattern-recognition layer at which auditors operate and beyond the toy-example layer that has constrained much prior academic verification work. The tridirectional discriminating-power claim is established against production-deployed Solidity source for the OpenZeppelin guard pattern — Compound v2 and Aave V3 production sources plus the historical DAO 2016 contract — rather than against simplified models. The contracts addressed collectively secure substantial production deposits (§2.4, §5.4); economic significance is ecosystem-load-bearing rather than research-prototype. The no-retrofit composition discipline (§4.2) establishes a stronger empirical claim than co-developed composition: the three protocol-instantiation proofs were sealed before the capstone meta-theorem was authored, the capstone composed by direct conjunction without modification of any underlying proof, and we read this as evidence that the OpenZeppelin guard pattern’s correctness is portable across the observed protocol-instantiation boundary rather than an artifact of co-developed proofs.

The empirical meaning of the cross-protocol PASS under  $N=1$ . The single observed composition (Compound v2  $\rightarrow$  Aave V3) is  $N=1$ ; its significance is not that composition occurred but what occurred under the no-retrofit constraint.

While  $N=1$  at the protocol-family level, the composition proofs exercise two fundamentally divergent financial state architectures — persistent ledger balance accounting on Compound v2 vs. transient intra-transaction flash-lending on Aave V3 — making the boundary a rigorous qualitative stress test of guard-invariant portability despite the low protocol count. A retrofit-permissive workflow admits an explanation — the underlying proofs were silently shaped toward a common target — that the sealed-before-capstone discipline forecloses by construction. What remains as an explanation for the observed PASS is genuine portability of the guard pattern’s correctness across structurally-divergent lending-family architectures, within the scope qualified at §9.4.

## 7.2 Future work

The methodology is candidate for application to other reentrancy variants — read-only reentrancy at protocols whose view functions feed downstream consumers (the Curve gauges 2022 case), cross-function reentrancy where multiple guarded functions share state — and other OpenZeppelin defense patterns (AccessControl, Pausable, ReentrancyGuardUpgradeable, upgradeable proxy pathways), each carrying its own correctness predicate amenable to the same tridirectional treatment. Beyond reentrancy and OpenZeppelin, the methodology framework canonical artifacts (the subject of the companion methodology paper) enable application to formal verification more broadly, including non-smart-contract targets where the no-retrofit composition discipline addresses the same proof-brittleness pain point. Continuous-integration-driven verification at protocol upgrade events is a final natural extension.

## 8 Related Work

This section positions the discriminating-power result against four bodies of prior literature: prior formal verification of smart contracts at large; reentrancy-specific work; compositional formal verification in adjacent domains; and AI-assisted formal verification context. The compression discipline of §1 + §4 + §5 carries through here: survey breadth across the four categories, with sharp positioning of the present contribution against what the surveyed work has and has not previously demonstrated.

### 8.1 Prior formal verification of smart contracts

Three broad classes of prior work have addressed smart contract correctness at varying levels of foundational rigor.

SMT-based static analysis tools — Slither, Mythril, Securify, and Manticore among the widely deployed — operate at the deployment-scale layer with heuristic pattern-matching against known vulnerability classes (Slither, Securify), symbolic execution (Mythril, Manticore), or declarative property checking (Securify). These tools have driven a substantial fraction of pre-deployment audit workflow and are the de facto baseline for industrial smart contract security. Their strength is scalability; their limitation is that pattern recognition does not establish foundational correctness, and structural-adjacency boundaries are precisely where their precision degrades (per §1.2).

Theorem-prover-based and specification-driven verification has demonstrated foundational rigor on narrower targets. Bhargavan et al. [1] formalized EVM operational semantics in  $F^*$  and Coq (POST 2016 and subsequent); Hildenbrandt et al.’s KEVM [2] (CSF 2018) provided a complete executable EVM semantics in the K framework; Grishchenko, Maffei, and Schneidewind [3] (POST 2018) developed an  $F^*$ -based semantic framework for EVM security analysis; Hirai’s Lem formalization [4] addressed EVM bytecode semantics for proof assistant integration. Subsequent Coq-based work has formalized individual contracts or contract subsets. Certora’s Prover applies SMT-based discharge against specifications expressed in CVL, deployed in production audit workflows; its strength is scale and tool-driven specification discharge rather than foundational machine-checked correctness in the proof-assistant sense. These contributions are foundational at the platform-semantics or specification-discharge layer; cross-protocol composition of guard-pattern correctness against multiple production protocol instantiations has not been previously demonstrated in this line of work.

Property-based testing tools — Foundry fuzz testing and Echidna — have driven substantial bug discovery at deployment scale. Their strength is finding counterexamples; they do not establish foundational correctness. See Appendix C for at-a-glance positioning against Certora, Move Prover, VeriSol, and KEVM.

Prior formal verification of smart contracts has demonstrated theorem-prover-based formalization of platform semantics or isolated contracts at the foundational layer, or scalable SMT-based pattern recognition at the deployment layer; demonstration of foundational correctness against multiple production protocols with no-retrofit composition discipline has remained an open challenge.

### 8.2 Prior reentrancy-specific work

Reentrancy has received targeted attention across runtime, static, and disclosure-driven layers. Sereum [5] introduced runtime monitoring for reentrancy patterns at the EVM execution layer — deployable but not preventive at the source level, not aimed at foundational correctness. Static analyzers including SmartScopy [6] and similar pattern-recognition tools targeted at the reentrancy class apply pattern-recognition discipline; precision is empirically strong for classical reentrancy and weakens at structural-adjacency boundaries (per §1.2) and at cross-function and read-only variants. Mutation testing [9], [10] introduces small syntactic faults to assess sensitivity to structurally-adjacent regressions; the Layer 6-C boundary case (§5.5) applies this methodology to machine-checked proofs of production smart contracts — to our knowledge a first — using a single hand-constructed minimal-diff mutant rather than an operator-derived corpus (defended at §5.5 and §9.2). Read-only reentrancy emerged as a recognized attack class following the Curve Finance gauges 2022 disclosure (callback reentrancy on view functions returning stale state); it is acknowledged here as future-work scope (§7.2). Foundational machine-checked discriminating-power against the OpenZeppelin guard pattern at production protocol scale has not been previously demonstrated.

### 8.3 Related composition discipline work

Compositional formal verification has been extensively developed in adjacent domains. CompCert [7] is the canonical exemplar — compositional correctness proofs for a production-grade C compiler, with subsequent work extending the discipline. Iris [8] developed higher-order concurrent separation logic applied across concurrent program verification targets. These establish that large-scale compositional formal verification is feasible at production-relevant scale when the composition discipline is enforced explicitly. Within smart contract verification specifically, prior work has demonstrated modular proofs at the single-contract scope; cross-protocol composition of guard-pattern correctness at production scale, under a discipline that forbids retrofit of underlying lemmas (the no-retrofit composition discipline of §4.2), has not been previously demonstrated.

### 8.4 AI-assisted formal verification context

Recent AI-assisted formal verification explores LLMs in two roles: proof-tactic synthesis and audit assistance. Specific systems — Baldur [11] (whole-proof generation/repair), Lean-Dojo [12] (retrieval-augmented Lean tactic search), COPRA [13] (in-context-learning theorem-proving agent) — preserve proof-assistant soundness (the LLM proposes; the kernel checks) but operate at per-proof tactic-automation granularity rather than at the verification-architecture or audit-discipline level. AI-assisted audit work has typically operated as single-model review; convergence/divergence analysis across multiple independent reasoning models is novel methodology, subject of the companion methodology paper rather than a claimed contribution here.

## 9 Limitations

This section adds limitations within the discriminating-power claim’s domain that constrain its scope; out-of-scope attack classes are enumerated at §3.4.

### 9.1 Single attack class and single defense pattern

The single-attack-class focus is a principled choice: reentrancy is the canonical class for which the OpenZeppelin guard was constructed and where the structural-adjacency boundary is well-defined and machine-checkable end-to-end. The work addresses the OpenZeppelin reentrancy guard pattern only; other defensive patterns (AccessControl, Pausable, ReentrancyGuardUpgradeable, upgradeable proxy pathways) are not within scope. The no-retrofit composition discipline and axiom-record-minimal wrapper composition (§4.2, §4.3) are applicable to other patterns by construction, but empirical validation across multiple defense patterns at production scale is future work (§7.2).

### 9.2 Constructed mutant boundary case

The Layer 6-C boundary case includes one constructed variant — flashLoanVulnerable, a minimal-diff mutant (§5.5). Per the §1.3 reframing this is mutation testing for formal proofs (grounded in [9], [10]): the hand-constructed minimal-diff mutant is a principled choice, not a concession — it isolates the structural-adjacency boundary in a way naturally-occurring near-misses cannot, with the corpus  $N=1$  by design.

Identifying and formalizing real historical near-miss instances (Curve gauges 2022 read-only-reentrancy class, Lendf.Me 2020 ERC-777 callback class, and similar) is acknowledged future work.

### 9.3 Source-level abstraction and trust assumptions

Operating at Solidity source level (per §3.2) rather than raw EVM bytecode is a deliberate scoping choice: source level is where the guard pattern is expressed and its discriminating-power boundary sharpest, and it keeps the Lean-model-fidelity and solc-compilation assumptions (§3.3) explicit and separable. Recent EVM-level formalization work (§8.1 — KEVM line) is the foundation for a future verified-translation extension closing both gaps. Standard formal-verification trust assumptions apply (§3.3, §6.4): Lean 4 kernel + mathlib4 correctness, pinned dependency graph at the tagged commits. The honest-borrower-at-protocol-invariant-computation-only assumption (§3.3) constrains the claim — borrowers may be adversarial (§3.1) but protocol-internal accounting is assumed to execute as written. Expansion to attacker-controlled-protocol threat models is future work. No consensus-layer behavioral assumption is made.

### 9.4 Cross-protocol claim scope

The cross-protocol composition rests on three instantiations: DAO 2016 (historical exemplar), Compound v2 (lending), Aave V3 (lending / flash-loan facility). The two live protocols are both lending-family; the no-retrofit stress-test crosses a within-lending-family boundary (persistent balance-accounting vs. single-transaction flash-loan architecture), not a between-domain boundary (AMM, CDP, derivatives). The portability claim is therefore scoped to uniformity of the local guard invariant across divergent lending-family host architectures plus the historical reentrancy exemplar; broader-family instantiation is future work (§7.2).

## 10 Conclusion

We presented a machine-checked, tridirectional discriminating-power formal verification of the OpenZeppelin reentrancy guard pattern across three production protocol instantiations: a negative-instance derivation of the classical reentrancy attack from DAO 2016 contract source; a positive-instance correctness proof for the Compound v2 cToken withdrawal path; and a boundary case distinguishing production Aave V3 flashLoan (CEI-correct by construction) from its minimal-diff mutant flashLoanVulnerable under a mutation-testing-for-formal-proofs design. A capstone meta-theorem composes the three prior-layer results by direct conjunction, and all thirteen theorems are machine-checked under continuous CI gating with zero sorry, zero user-introduced axioms, and [propeXt]-only axiom records across the corpus.

The significance is twofold. First, the verified protocols secure substantial deposits at production scale (§2.4, §5.4), grounding the discriminating-power claim in load-bearing real-contract source rather than illustrative models. Second, the capstone composed across the Compound v2 → Aave V3 protocol-instantiation boundary under a no-retrofit

composition discipline that forbids retrofitting underlying proofs toward a composition target — the first such cross-protocol composition demonstrated under this discipline (§7, §8). The verification’s audit trail is inspectable end-to-end; the methodology framework that generalizes this posture is the subject of the companion paper, with the Appendix B pointer summarizing its canonical artifacts. Future work (§7.2, §9) extends the discriminating-power framework to additional attack classes and defense patterns, EVM-bytecode-level formalization, cross-language application, and continuous protocol-upgrade verification.

## Appendix A

### Theorem Statements, Axiom Records, and Reproduction

This appendix is the substantive substrate anchor for the discriminating-power claim. It absorbs the full-statement and axiom-record detail deferred from §5 and §6, so a reviewer can verify the corpus end-to-end. Full Lean 4 source — with exact type signatures, dependent-type declarations, and definitions — is in the repository at the tagged commit v1.3-layer6-closure; the paraphrases below state what each theorem establishes at the level a reviewer needs before consulting the source.

#### A.1 Theorem statements

The corpus comprises thirteen theorems across four layers, matching the §5.2 inventory exactly.

Layer 6-A — DAO 2016 negative instance (1 target + 5 supporting = 6). The target theorem states that, under the reentrancy predicate of §5.1, an attacker-controlled re-entry call trace against the formalized DAO splitDAO source is constructible, and that this trace breaks the contract’s balance-sum invariant. The five supporting lemmas discharge the pieces of the derivation: call-stack interleaving, storage-observation before balance update, balance-update sequencing, external-call-boundary placement, and the absence of any guard-pattern protection.

Layer 6-B — Compound v2 cToken positive instance (1 target + 2 supporting = 3). The target theorem states that every execution trace conforming to the cToken withdrawal path satisfies the guard-pattern correctness predicate of §5.1, so no reentrancy trace is constructible against it. A guard-invariant lemma shows the `_status` slot is set before any external call and reset after; a cross-function safety lemma shows the protection extends across the cToken interface functions sharing that slot. The target is discharged by a thin wrapper that composes the two lemmas without modifying either, preserving axiom-record minimality.

Layer 6-C — Aave V3 boundary case (2 target + 1 supporting = 3). The first target theorem states that production `flashLoan` satisfies guard-pattern correctness under the §5.1 predicate. The second target theorem states that the minimal-diff mutant `flashLoanVulnerable` fails it — equivalently, that a reentrancy trace is constructible against the mutant under the same predicate. A checks-effects-interactions preservation lemma underwrites the first target and is consumed by the

second’s failure proof at the structural-adjacency boundary where the mutant deviates from production.

Layer 6-D — tridirectional capstone (1 target = 1). The capstone meta-theorem states that if the Layer 6-A derivation, the Layer 6-B correctness theorem, and the Layer 6-C boundary pair all hold, then the methodology satisfies the discriminating-power predicate of §5.1 against the §2.4 production instantiations plus the §5.5 mutant. It is proven by direct conjunction of the three prior-layer theorems, with no modification of any underlying proof during composition.

#### A.2 Per-theorem axiom records

Every theorem is verified against an explicit `#print` axioms expectation, re-checked on every push and gated to fail the build on any drift. Across all four layers, the per-function inner lemmas are kernel-only (zero-axiom; no propositional extensionality required), and the master/wrapper/meta theorems carry `[propext]`-only records — no choice, no excluded middle, no user-introduced axioms anywhere in the corpus. The Layer 6-D capstone’s `[propext]` record is exactly the union of the three prior-layer records and introduces no new axiom; the project introduces zero new axioms over the Lean 4 + `mathlib4` baseline. No theorem in the corpus is admitted with `sorry`, `admit`, or any user-introduced axiom declaration. Exact per-theorem records are CI-gated (§6.3) and reproducible per Appendix A.3.

#### A.3 Reproduction commands

The corpus is reproducible end-to-end from the tagged commit:

```
git clone https://github.com/rayiskander2406/qanary-
contracts.git
cd qanary-contracts
git checkout v1.3-layer6-closure
lake build # 901 jobs green
lake env lean QanaryContracts/PrintAxioms.lean # verifies every theorem
```

The dependency graph is pinned and locked:

- Lean compiler version pinned at `lean-toolchain` (`leanprover/lean4:v4.30.0-rc1`).
- `mathlib4` dependency pinned at `lakefile.lean` (input revision `322515540d7f`) and locked to commit `322515540d7fd29ef8992b82c89044f86f02ac10` via `lake-manifest.json`.
- The four parallel CI blocks at `build.yml` lines 287, 356, 408, and 464 re-run on every push and surface any drift in the dependency graph or the corpus.

The methodology-framework canonical artifacts are sealed at the later tag `v1.7-methodology-housekeeping`; a reviewer evaluating the methodology framework rather than the proof substrate should check out that tag.

## Appendix B

### Methodology Framework Pointer

#### B.1 Scope of this pointer

Per the boundary discipline of §1, the methodology framework underpinning this work — the no-retrofit composition discipline of §4.2, the axiom-record-minimal wrapper composition

of §4.3, and the multi-model audit workflow of §4.5 — is canonized as a separate body of work and presented in full in a companion methodology paper (separate arXiv submission). The brief operational presentations in §4 suffice for the substantive smart-contract-verification claims of the present paper. This appendix is deliberately thin: it provides a pointer table mapping the framework labels to their canonical artifact locations, for readers who encounter those labels in the public artifact record (for example, in the project’s commit history). It does not present the framework’s sub-pattern catalog, graduation criteria, or cross-protocol empirical history; those are the scope of the companion paper.

The separation is deliberate length-scoping, not withholding: this paper’s discriminating-power result is fully evaluable on its own terms — the thirteen theorems, their axiom records, and the no-retrofit discipline’s operational consequence (§4.2) are stated and verifiable here. The companion framework adds generalization beyond the present scope and is not load-bearing for this paper’s substantive claims.

## B.2 Canonical artifacts

The methodology framework’s canonical artifacts — the wrapper-layer absorption pattern (axiom-record-minimal composition; §4.3), the compose-from-outside discipline (no-retrofit composition; §4.2), and the family-level authoring-layer-estimation-imprecision meta-pattern — are sealed at the repository tag for methodology-framework canonization and presented in full in the companion methodology paper. Full graduation history, sub-pattern catalog, four-outcome audit-findings triage framework, and the cross-protocol empirical history of the framework’s application appear there.

## Appendix C

### Comparison against industrial FV frameworks

For reviewer at-a-glance positioning, the following table compares the present work against the principal industrial / academic formal verification systems for smart contracts and adjacent verification work (§8.1).

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- 
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TABLE 2  
Positioning against principal industrial / academic formal verification systems for smart contracts and adjacent verification work.

System	Verification target	Composition support	Axiom footprint	Production deployment
QANARY (this paper)	Source-level OZ guard pattern across 3 production protocols	No-retrofit cross-protocol meta-theorem; sealed prior-layer composition	[propext]-only; zero user-introduced axioms; CI-gated	Compound v2, Aave V3 mainnet contracts; tagged-commit reproducible
Certora Prover	CVL specifications discharged via SMT	Per-rule local; no foundational composition discipline	SMT-solver trust; no kernel-level record	Production audit workflows across major DeFi protocols
Move Prover (Dill et al.)	Move-language smart contracts; spec-driven	Modular specs; no cross-protocol meta-claim	SMT trust	Aptos, Sui mainnet runtime checks
VeriSol (Lahiri et al.)	Solidity $\rightarrow$ Boogie translation; spec-driven	Modular contract verification	SMT/Boogie trust	Microsoft (now deprecated)
KEVM (Hildenbrandt et al.)	EVM bytecode operational semantics in K	Platform-semantics layer; no per-contract composition claim	K-framework trust	Foundational artifact; deployed via consumer tools