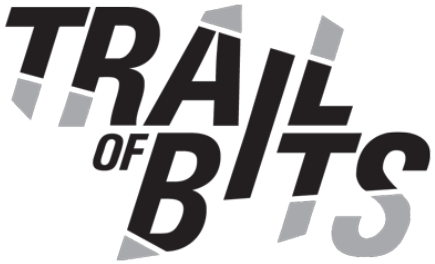

Compound v2

Security Assessment

April 8, 2019

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Changelog:

April 8, 2019:	Public release
March 22, 2019:	Week 3 results delivered to Compound

Executive Summary

Between March 4th and March 22nd and again during the week of April 1st, 2019 Trail of Bits assessed the smart contracts of the Compound v2 Ethereum codebase. Two engineers conducted this assessment over the course of eight person-weeks. Trail of Bits had assessed the prior release of Compound in late July of 2018.

The first week consisted of a high level architectural review. However, the extant code was consulted to fill in gaps and provide context for portions of the specification that were in flux. The second week initiated an in-depth assessment of release `v2.1-Beta1` of the codebase[1]. The third week concluding the general manual analysis of a slightly newer release[2]. The fourth week specifically focused on the contract upgrade mechanisms of yet another slightly newer release[3].

Ten new findings were discovered, four of which are high severity. The majority are related to either untrusted calls to external contracts or gas-usage inefficiencies. Several bugs stem from logical errors and design decisions necessitated by Compound's error reporting mechanism and avoidance of reverts. Additional code-quality recommendations that are not necessarily related to security have been added to Appendix B.

[1] `git` commit `9e6e50320dacc93b9f9f834f5dffbaa8727550ad`
[2] `git` commit `4c93c9363d5f554717e5a880b74c052acaee7558`
[3] `git` commit `b7475c1a7c04f8a558d21db672f82ba42cae531f`

Engagement Goals & Scope

The goal of the engagement was to evaluate the security of the Compound v2 system and answer the following questions:

- Can attackers use leverage within the system to undermine the stability of the market?
- Can the system handle wildly fluctuating assets while maintaining a bounded increase/decrease percentage?
- Do the contracts calculate prices, swings, and basis points correctly?
- Does the new Comptroller contract pattern introduce any vulnerabilities in its interaction with the token markets?
- Is the Unitroller/Comptroller upgrade proxy pattern implemented correctly?

Coverage

We reviewed:

- Compound v2 whitepaper and protocol specification
- `money-market` `v2.1-Beta1`
- `money-market` commit `4c93c9363d5f554717e5a880b74c052acaee7558`
- `money-market` commit `b7475c1a7c04f8a558d21db672f82ba42cae531f`

This review included all Solidity smart contracts, JavaScript tests, as well as their requisite configuration files and environments.

Contracts were reviewed for common Solidity flaws, such as integer overflows, re-entrancy vulnerabilities, and unprotected functions. Furthermore, contracts were reviewed with special consideration for high-level logical flaws and unhandled edge cases in the interaction between the new `Comptroller` and `CToken` contracts.

The contract upgradability mechanism implemented in commit `b7475c1a7c04f8a558d21db672f82ba42cae531f` was specifically analyzed during the final week of the assessment. Special care was placed in checking for variable shadowing, function shadowing, initialization, and slot ordering errors.

Project Dashboard

Application Summary

Name	Compound v2
Type	Money Market, ERC20 Token, and Protocol
Platform	Solidity

Engagement Summary

Dates	March 4th through March 22nd, 2019 April 1st through April 5th, 2019
Method	Whitebox
Consultants Engaged	2
Level of Effort	8 person-weeks

Vulnerability Summary

Total High Severity Issues	4	■■■■
Total Medium Severity Issues	0	
Total Low Severity Issues	0	
Total Informational Severity Issues	4	■■■■
Total Issues of Undetermined Severity	2	■■
Total	10	

Category Breakdown

Access Controls	2	■■
Data Validation	3	■■■
Denial of Service	1	■
Error Reporting	1	■
Timing	1	■
Undefined Behavior	2	■■
Total	10	

Recommendations Summary

Short Term

❑ **Carefully employ error handling.** The pattern used for error propagation and handling is inefficient and dangerous. Be diligent about usage of functions that return an error state.

❑ **Fix the potential for reentrancy.** Either adhere to the checks-effects-interactions pattern or use reentrancy guards.

❑ **Document redundant data storage in the Comptroller.** Improve source code comments and sanity checks to reinforce the importance of keeping the data structures synchronized.

❑ **Evaluate the costs and benefits of Solidity optimizations.** Measure the gas savings from optimizations, and carefully weigh that against the possibility of an optimization-related bug.

❑ **Add a mitigation for orphaned balances.** Consider adding an admin-only function to the CToken contract to withdraw unexpected or unsupported ERC20 tokens.

❑ **Implement a mitigation for the ERC20 race condition.** For example, implement the increaseApproval and decreaseApproval functions of OpenZeppelin's ERC20 implementation.

❑ **Remove unnecessary nonReentrant modifiers.** Weigh the value of avoiding view functions against the cost of higher gas overhead. Consider refactoring the checks-effects-interactions pattern wherever possible.

❑ **Do not allow CTokens as an underlying asset of another CToken.** Consider the implications of this edge case.

❑ **Fix the admin or initializing check.** Either convert the adminOrInitializing function to a modifier, or pass in the sender address to verify as a function argument.

❑ **Document storage variable shadowing between the Unitroller and Comptroller.** All future implementations of the Comptroller must extend from UnitrollerAdminStorage (via ComptrollerV1Storage) in order to preserve the storage layout. New Comptroller instances must always be constructed from the same account that is listed as admin in the Unitroller.

Long Term

❑ **Consider abandoning the error-handling pattern.** This will serve to make the code more maintainable, succinct, and less expensive.

❑ **Consider refactoring redundant storage in the Comptroller.** Carefully measure the gas benefit of reduced iterations versus the cost of additional storage. Consider removing one of the data structures so that there is no chance of desynchronization.

❑ **Monitor the development and adoption of Solidity compiler optimizations.** Continually assess the maturity of Solidity optimizations.

❑ **Document procedures for changes to external contracts.** What happens when the token backing an asset performs a migration?

❑ **Monitor the progress of alternative reentrancy protections.** For example, EIP 1153 introduces a much less expensive ephemeral storage opcode that could be used for reentrancy protection.

❑ **Consider whether CTokens should ever be listed.** If so, investigate potential side effects and document procedures for updating their parameters. Also, clearly document the necessary criteria for a token to be listed on Compound. This will be especially important if the protocol transitions to a decentralized governance model in the future.

❑ **Avoid variable shadowing between proxies and implementations.** For example, the ZeppelinOS implementation of the delegatecall proxy pattern uses a custom storage slot to store the admin address in order to avoid such collisions; the implementation can safely use storage starting at slot zero. Alternatively, consider the contract migration upgrade pattern.

Issues Addressed Since the First Assessment

This is a summary of issues uncovered during the first assessment by Trail of Bits of Compound Release Candidate 1.1 in August of 2018. The table lists whether each finding has been addressed in version 2.1 of the protocol. Only findings related to the protocol and smart contracts are included.

#	Title	Severity	Addressed?
1	CarefulMath error handling is inefficient and dangerous	Informational	No
2	Authentication check replication	Informational	No
3	ERC20 interface undefined behavior	High	Yes
4	Frontrunning can be used to weaken collateral requirements	Medium	In theory, yes, but it is unclear if the new model can react fast enough
8	MoneyMarket should be pausable	Informational	Yes, in development
12	Missing error-handling defaults	Informational	No

Findings Summary

#	Title	Type	Severity
14	Error propagation instead of reverting is inefficient and dangerous	Error Reporting	Informational
15	Potential reentrancy from malicious tokens	Data Validation	High
16	Redundant data storage in the Comptroller can lead to desynchronization	Data Validation	Informational
17	Solidity compiler optimizations can be dangerous	Undefined Behavior	Undetermined
18	Token migration results in orphaned balances	Access Controls	High
19	Race condition in the ERC20 approve function may lead to token theft	Timing	High
20	Unnecessary nonReentrant modifiers waste gas	Denial of Service	Informational
21	Using CTokens as underlying assets may have unintended side effects	Data Validation	Undetermined
22	A malicious contract can reentrantly bypass administrative checks in the Comptroller	Access Controls	High
23	Variable shadowing between the Unitroller and Comptroller	Undefined Behavior	Informational

14. Error propagation instead of reverting is inefficient and dangerous

Severity: Informational
Type: Error Reporting
Target: All smart contracts

Difficulty: Low
Finding ID: Compound-TOB-014

Description
The contracts in Compound version 2.1 retain the unusual error handling pattern from the prior version in which errors are reported as a second return argument rather than immediately throwing an assertion.

```
function sub(uint a, uint b) internal pure returns (Error, uint) {
    if (b <= a) {
        return (Error.NO_ERROR, a - b);
    } else {
        return (Error.INTEGER_UNDERFLOW, 0);
    }
}
```

Figure 14.1: Error handling in the `CarefulMath` subtraction function.

This can be very useful and informative for debugging purposes, and allows callers the opportunity to gracefully handle certain errors. However, it suffers from three major shortcomings:

1. This implementation requires the caller to check for the error (*q.v.* Figure 14.2). This not only bloats the calling usages, but allows for a careless caller to mishandle the error at the callsite.

```
(Error err0, uint blockDelta) = sub(blockEnd, blockStart);
if (err0 != Error.NO_ERROR) {
    return (err0, 0);
}
```

Figure 14.2: Example usage of the `CarefulMath` subtraction function.

2. Additional control flow logic and branching is required at each callsite, drastically increasing the complexity of the code, and thereby the number of resulting EVM opcodes, and thereby the gas cost of executing the code.

3. Using the Checks-Effects-Interactions pattern to avoid reentrancy attacks becomes difficult if the interactions return an error instead of reverting, since all of the effects would have to be unwound manually.

Our calculations suggest that each call to a function using this pattern incurs up to *three times* the gas of an alternative that uses a standard `require` statement. This can constitute a significant gas expenditure.

Exploit Scenario
A future refactor causes a function to be called without checking for its resulting error condition.

Recommendation
In the short term, be extremely careful and diligent about usage of functions that return an error state.

In the long term, consider abandoning this error-handling pattern. Not only will this serve to make the code more maintainable, succinct, and less expensive, but it will enable you to use the canonical

`“using SafeMath for uint256;”`

idiom that will ensure that all arithmetic will be handled using SafeMath. This should be relatively straightforward since it appears that all usages of CarefulMath functions either blindly pass on errors to their caller or ignore the specific error.

15. Potential reentrancy from malicious tokens

Severity: High
Type: Data Validation
Target: `CToken.sol` and `MoneyMarket.sol`

Difficulty: High
Finding ID: Compound-TOB-015

Description
Functions that make external calls to underlying token assets fail to use the "Checks-Effects-Interactions" pattern. This is presumably related to Compound-TOB-014, since properly adhering to the pattern *without* using a revert would make the code more complex and significantly increase the gas cost. For example, Figure 15.1 is an excerpt from the `withdraw` function in `MoneyMarket.sol`.

```
//////////////////////////
// EFFECTS & INTERACTIONS
// (No safe failures beyond this point)

// We ERC-20 transfer the asset into the protocol (note: pre-conditions already checked
above)
err = doTransferOut(asset, msg.sender, localResults.withdrawAmount);
if (err != Error.NO_ERROR) {
    // This is safe since it's our first interaction and it didn't do anything if it failed
    return fail(err, FailureInfo.WITHDRAW_TRANSFER_OUT_FAILED);
}

// Save market updates
market.blockNumber = getBlockNumber();
market.totalSupply =  localResults.newTotalSupply;
market.supplyRateMantissa = localResults.newSupplyRateMantissa;
market.supplyIndex = localResults.newSupplyIndex;
market.borrowRateMantissa = localResults.newBorrowRateMantissa;
market.borrowIndex = localResults.newBorrowIndex;

// Save user updates
localResults.startingBalance = supplyBalance.principal; // save for use in `SupplyWithdrawn`
event
supplyBalance.principal = localResults.userSupplyUpdated;
supplyBalance.interestIndex = localResults.newSupplyIndex;
```

Figure 15.1: Code using a pattern that allows reentrancy.

The call to `doTransferOut` will interact with the underlying asset contract. That contract can do whatever it wants, including calling back into the Compound contracts with a reentrancy attack. This all happens *before* the effects of the withdrawal, like the supply changes, are recorded.

Unfortunately, it is non-trivial to reorder this implementation to conform to the standard checks-effects-interactions pattern, since an error in `doTransferOut` would require the nine changes to `market`, `localResults`, and `supplyBalance` to be unwound to the previous

values, which would also have to be cached. This would result in a significant gas expenditure.

Exploit Scenario
A malicious token is approved as an asset, either surreptitiously or through a future distributed governance mechanism. That token can reentrantly call back into the Compound contracts *before* the effects of the previous action have been recorded, causing the Compound contracts to be in an invalid state.

Recommendation
In the short term, fix the potential of reentrancy by adhering to the checks-effects-interactions pattern.

In the long term, consider abandoning the complex error reporting pattern in favor of standard `require` statements that are guaranteed to revert.

16. Redundant data storage in the Comptroller can lead to desynchronization

Severity: Informational
Type: Data Validation
Target: `Comptroller.sol`

Difficulty: High
Finding ID: Compound-TOB-016

Description
The `accountMembership` and `accountAssets` members of the Comptroller contract store redundant information. The correctness of portions of the code is predicated on those members remaining in sync, since sometimes data is validated against one and not the other. This is a known issue, since a code comment suggests that it is an optimization for alleviating the need to iterate over members.

Exploit Scenario
In a future refactor, checks like this requirement in the Comptroller are removed since it is assumed that `accountMembership` and `accountAssets` will always be synchronized:

```
// paranoid check that we actually found something in the list
// this will always be true and maybe we can delete the if check
// if confident in formal verification of the assets you are in system
require(assetIndex < len);
```

An attacker causes this assumption to be invalidated, *e.g.*, through a reentrancy attack like that of Compound-TOB-015. This will allow the attacker to underflow `accountAssets[msg.sender].length`, gaining the ability to overwrite all of storage.

Recommendation
In the short term, improve source code comments to reinforce the importance of keeping the data structures synchronized. Consider adding more sanity checks like the above `require` example.

In the long term, carefully measure the gas benefit of reduced iterations versus the cost of additional storage. Consider removing one of the data structures so that there is no chance of desynchronization.

17. Solidity compiler optimizations can be dangerous

Severity: Undetermined
Type: Undefined Behavior
Target: `truffle.js`

Difficulty: Low
Finding ID: Compound-TOB-017

Description
Compound has enabled optional compiler optimizations in Solidity.

There have been several bugs with security implications related to optimizations. Moreover, optimizations are actively being developed. Solidity compiler optimizations are disabled by default. It is unclear how many contracts in the wild actually use them. Therefore, it is unclear how well they are being tested and exercised.

High-severity security issues due to optimization bugs have occurred in the past. A high-severity bug in the emscripten-generated `solc-js` compiler used by Truffle and Remix persisted until late 2018. The fix for this bug was not reported in the Solidity CHANGELOG. Another high severity optimization bug resulting in incorrect bit shift results was patched in Solidity 0.5.6.

A compiler audit of Solidity from November, 2018 concluded that the optional optimizations may not be safe. Moreover, the Common Subexpression Elimination (CSE) optimization procedure is "implemented in a very fragile manner, with manual access to indexes, multiple structures with almost identical behavior, and up to four levels of conditional nesting in the same function." Similar code in other large projects have resulted in bugs.

There are likely latent bugs related to optimization, and/or new bugs that will be introduced due to future optimizations.

Exploit Scenario
A latent or future bug in Solidity compiler optimizations—or in the Emscripten transpilation to `solc-js`—causes a security vulnerability in the Compound contracts.

Recommendation
In the short term, measure the gas savings from optimizations, and carefully weigh that against the possibility of an optimization-related bug.

In the long term, monitor the development and adoption of Solidity compiler optimizations to assess its maturity.

18. Token migration results in orphaned balances

Severity: High
Type: Access Controls
Target: `CToken.sol`

Difficulty: High
Finding ID: Compound-TOB-18

Description
The Compound protocol establishes money markets for ERC20 tokens. For a variety of reasons, including security issues or to support new features, these underlying tokens may perform a migration to a new contract in the future. The token balances from the old contract will be transferred as-is to the new contract. All funds deposited on Compound will remain credited to the corresponding `CToken`. However, the functionality of the `CToken` will still refer to the old token address; borrows and redemptions will be impossible to fulfill.

Exploit Scenario
Compound has an established market for `ZRX`. Alice deposits 1,000 `ZRX` into the Compound ZRX market. The 0x team decides to migrate to a new version of the token contract to add support for a new feature. Alice wishes to withdraw some of her `ZRX` held in Compound but is unable to as the `CToken` contract for the market has no functionality to interact with the new `ZRX` contract.

Recommendation
In the short term, consider adding an admin-only function to the `CToken` contract to withdraw unexpected or unsupported ERC20 tokens. In the event of a migration, the admin will then be able to manually redistribute tokens to Compound users.

In the long term, document procedures for handling changes in the entry point of any external contracts.

References
[How contract migration works]

19. Race condition in the ERC20 approve function may lead to token theft

Severity: High
Type: Timing
Target: `CToken.sol`

Difficulty: High
Finding ID: Compound-TOB-019

Description
Compound markets, implemented as `CToken` contracts, are themselves ERC20 compliant. A known race condition in the ERC20 standard, on the `approve` function, could lead to the theft of tokens.

The ERC20 standard describes how to create generic token contracts. Among others, an ERC20 contract defines these two functions:

- `transferFrom(from, to, value)`
- `approve(spender, value)`

These functions give permission to a third party to spend tokens. Once the function `approve(spender, value)` has been called by a user, `spender` can spend up to `value` of the user's tokens by calling `transferFrom(user, to, value).`

This schema is vulnerable to a race condition when the user calls `approve` a second time on a `spender` that has already been allowed. If the spender sees the transaction containing the call before it has been mined, then the spender can call `transferFrom` to transfer the previous value and still receive the authorization to transfer the new value.

Exploit Scenario
1. Alice calls `approve(Bob, 1000)`. This allows Bob to spend 1,000 tokens.
2. Alice changes her mind and calls `approve(Bob, 500).` Once mined, this will decrease to 500 the number of tokens that Bob can spend.
3. Bob sees Alice's second transaction and calls `transferFrom(Alice, X, 1000)` before `approve(Bob, 500)` has been mined.
4. If Bob's transaction is mined before Alice's, 1,000 tokens will be transferred by Bob. Once Alice's transaction is mined, Bob can call `transferFrom(Alice, X, 500)`. Bob has transferred 1,500 tokens, contrary to Alice's intention.

Recommendations
While this issue is known and can have a severe impact, there is no straightforward solution.

One workaround is to use two non-ERC20 functions allowing a user to increase and decrease the approve (see `increaseApproval` and `decreaseApproval` of StandardToken.sol#L63-L98).

Another workaround is to forbid a call to `approve` if all the previous tokens are not spent by adding a `require` to approve. This prevents the race condition but it may result in unexpected behavior for a third party.

```
require(_approvals[msg.sender][guy] == 0)
```

This issue is a flaw in the ERC20 design. It cannot be fixed without modifications to the standard. It must be considered by developers while writing code.

20. Unnecessary `nonReentrant` modifiers waste gas

Severity: Informational
Type: Denial of Service
Target: `CToken.sol`

Difficulty: Low
Finding ID: Compound-TOB-020

Description
Several functions within the `CToken` contract have been protected with OpenZeppelin's `nonReentrant` modifier from `ReentrancyGuard`. This alone is fine, since it is currently the second-best mitigation against reentrancy, after the checks-effects-interactions pattern. However, some of the functions (*e.g.*, `borrowBalanceCurrent`) could be declared as a `view` (see Appendix B for a comprehensive list). With Solidity 0.5.0 and newer[4], all external calls from a `view` are compiled with the `STATICCALL` opcode introduced in Byzantium, which prevents reentrant storage modifications.

Exploit Scenario
A user unnecessarily spends extra gas or exhausts the block gas limit by interacting with the Compound v2 contracts.

Recommendations
In the short term, weigh the value of avoiding `view` functions (presumably, to enable unit test harnesses) against the cost of higher gas overhead.

In the long term, monitor the progress of EIP 1153, which would introduce a new, much less expensive ephemeral storage opcode that could be used for reentrancy protection. Also consider refactoring to the checks-effects-interactions pattern wherever possible.

[4] although the feature appears to have been silently included as early as Solidity 0.4.24

21. Using CTokens as underlying assets may have unintended side effects

Severity: Undetermined
Type: Data Validation
Target: `CToken.sol`

Difficulty: Undetermined
Finding ID: Compound-TOB-021

Description
Compound can support a market for any ERC20 compatible token. These markets are implemented as CToken contracts, which also implement the ERC20 interface. However, using a CToken as the underlying asset of a Compound market may lead to unintended side effects.

Exploit Scenario
A market exists for the `ABC` token, with associated CToken `cABC`. Likewise, a secondary market is created backed by `cABC`, with associated CToken `ccABC`.

These markets both track approximately the same asset. However, their collateral factors (via the Comptroller), interest rate model and other variables are managed independently. They may deviate unintentionally over time.

Recommendations
In the short term, do not enable markets which use a CToken as the underlying asset.

In the long term, consider whether CTokens should ever be listed and if so, investigate potential side effects and document procedures for updating their parameters. Also, clearly document the necessary criteria for a token to be listed on Compound. This will be especially important if the protocol transitions to a decentralized governance model in the future.

22. A malicious contract can reentrantly bypass administrative checks in the Comptroller

Severity: High
Type: Access Controls
Target: `Comptroller.sol`

Difficulty: High
Finding ID: Compound-TOB-022

Description
The `adminOrInitializing()` function checks if `msg.sender` is the comptroller implementation and if the transaction originated from the admin account.

```
/**
 * @dev Check that caller is admin or this contract is initializing itself as
 * the new implementation.
 * There should be no way to satisfy msg.sender == comptrollerImplementaiton
 * without tx.origin also being admin, but both are included for extra safety
 */
function adminOrInitializing() internal view returns (bool) {
    bool initializing = (
            msg.sender == comptrollerImplementation
            &&
            //solium-disable-next-line security/no-tx-origin
            tx.origin == admin
    );
    bool isAdmin = msg.sender == admin;
    return isAdmin || initializing;
}
```

However, `msg.sender` will *always* be equal to `comptrollerImplementation`, because `adminOrInitializing` is declared `internal` (and can thereby only ever be called from other functions in the Comptroller) *and* it is a function, not a modifier. Therefore, `initializing` will be `true` as long as the transaction originated from the admin account.

Exploit Scenario
The admin account executes a transaction that eventually calls a malicious external contract (*e.g.*, a malicious price oracle or underlying asset token). The malicious contract reentrantly calls a privileged function within the Comptroller (*e.g.*, to set the close factor or

change the price oracle). The call to `adminOrInitializing()` will return `true`, allowing the transaction to succeed.

Recommendations
In the short term, there are two potential mitigations:

1. Convert `adminOrInitializing` from a function to a modifier so that `msg.sender` is preserved; or
2. Pass `msg.sender` as a "`sender`" argument into `adminOrInitializing` and perform the validation checks against `sender` instead of `msg.sender`.

Note that the first option will require reverting on failure, deviating from the current error reporting scheme.

In the long term, reevaluate the need for the current error reporting scheme in deference to these sorts of subtle bugs and the relative safety of patterns like modifiers that revert on error.

23. Variable shadowing between the Unitroller and Comptroller

Severity: Informational | Difficulty: Informational
Type: Undefined Behavior | Finding ID: Compound-TOB-023
Target: `Comptroller.sol`, `ComptrollerStorage.sol`, and `Unitroller.sol`

Description
Since the Comptroller extends from `ComptrollerV1Storage` which extends from `UnitrollerAdminStorage`, all of the storage variables and functions defined in `UnitrollerAdminStorage` will be shadowed in the Unitroller proxy contract by the same variables and functions in the Comptroller. If a user calls one such function (*i.e.*, `comptrollerImplementation()`, `admin()`, `pendingAdmin()`, and `pendingComptrollerImplementation()`) on the Unitroller contract, the Unitroller's implementation will be executed. However, if a user calls one such function directly on the Comptroller, the Comptroller's implementation will be executed.

This finding has Informational severity because the shadowed functions do not change contract state.

Exploit Scenario
A future refactor or upgrade causes the Comptroller to have a different admin account address than the Unitroller.

Recommendations
In general, try to avoid state variables in the proxy, particularly public ones.

In the short term, document this behavior. All future implementations of the Comptroller must extend from `UnitrollerAdminStorage` (via `ComptrollerV1Storage`) in order to preserve the storage layout. New Comptroller instances must always be constructed from the same account that is listed as `admin` in the Unitroller.

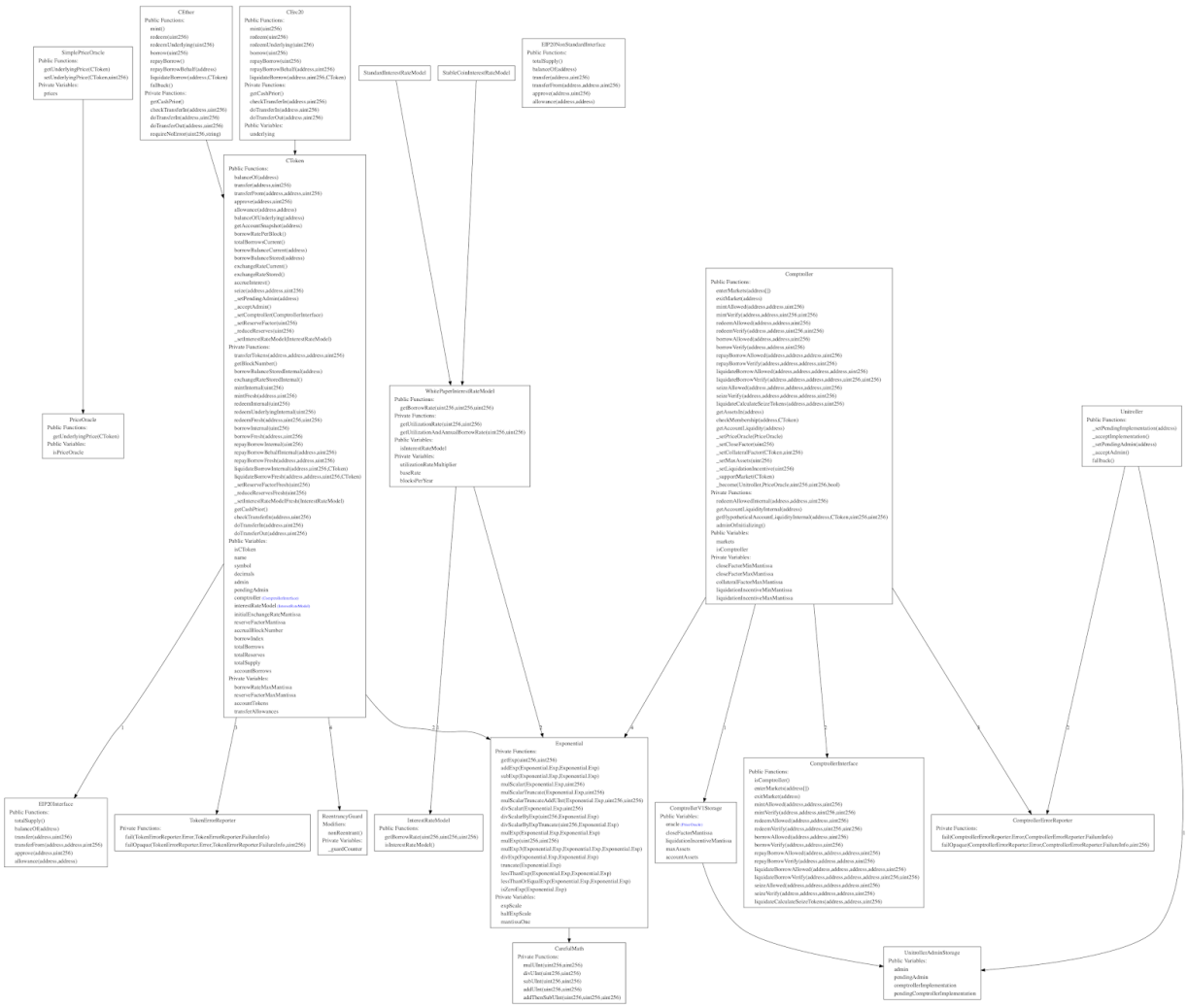
In the long term, consider switching to a different pattern that does not require the Comptroller to shadow the proxy's storage variables. For example, the ZeppelinOS implementation of the `delegatecall` proxy pattern uses a custom storage slot to store the admin address in order to avoid such collisions; the implementation can safely use storage starting at slot zero. Alternatively, consider the contract migration upgrade pattern.

The inheritance hierarchy of the contracts can be analyzed by running

```
slither --print inheritance-graph .
```

This produces a Graphviz file called `contracts.dot` which can be converted to a PDF via

```
dot -Tpdf contracts.dot -o contracts.pdf
```



Appendix A. Vulnerability Classifications

Vulnerability Classes	
Class	**Description**
Access Controls	Related to authorization of users and assessment of rights
Auditing and Logging	Related to auditing of actions or logging of problems
Authentication	Related to the identification of users
Configuration	Related to security configurations of servers, devices or software
Cryptography	Related to protecting the privacy or integrity of data
Data Exposure	Related to unintended exposure of sensitive information
Data Validation	Related to improper reliance on the structure or values of data
Denial of Service	Related to causing system failure
Documentation	Related to documentation accuracy
Error Reporting	Related to the reporting of error conditions in a secure fashion
Patching	Related to keeping software up to date
Session Management	Related to the identification of authenticated users
Timing	Related to race conditions, locking or order of operations
Undefined Behavior	Related to undefined behavior triggered by the program

Severity Categories	
Severity	**Description**
Informational	The issue does not pose an immediate risk, but is relevant to security best practices or Defense in Depth
Undetermined	The extent of the risk was not determined during this engagement
Low	The risk is relatively small or is not a risk the customer has indicated is important

Medium	Individual user's information is at risk, exploitation would be bad for client's reputation, moderate financial impact, possible legal implications for client
High	Large numbers of users, very bad for client's reputation, or serious legal or financial implications

Difficulty Levels	
Difficulty	**Description**
Undetermined	The difficulty of exploit was not determined during this engagement
Low	Commonly exploited, public tools exist or can be scripted that exploit this flaw
Medium	Attackers must write an exploit, or need an in-depth knowledge of a complex system
High	The attacker must have privileged insider access to the system, may need to know extremely complex technical details or must discover other weaknesses in order to exploit this issue

Appendix B: Code Quality Recommendations

The below issues do not pose a direct security risk to Compound, but can still be security-relevant and should be addressed.

- The `allowance` local variable in the `transferTokens` function of `CToken` shadows a function of the same name.
- The `mantissaOne` and `mantissaOneTenth` constants in Exponential.sol are not currently used.
- Use error constants instead of constant literals wherever possible. For example, at the beginning of the `mintFresh` function in `CToken.sol`, the `allowed` result from `comptroller.mintAllowed` should be compared to `Error.NO_ERROR` instead of `0`.
- Many functions do not modify contract state and can therefore be declared as `view` or `pure`. For example, this appears to be the case for *all* of the `*Verify` functions in `Comptroller.sol`.
- A significant number of functions can be declared `external`, which can greatly reduce gas costs for the caller. This is because `external` functions can read arguments directly from the calldata, while `public` functions must first copy the arguments to `memory`. Potential candidates include:
  - In `CToken.sol`
    - `exchangeRateStored`
    - `mint`
    - `redeem`
    - `borrowAsset`
    - `repayBorrow`
    - `repayBorrowBehalf`
    - `borrowBalanceCurrent`
    - `liquidateBorrow`
    - As well as several of the administrative _* functions
  - In `Comptroller.sol`
    - `mintAllowed`
    - `borrowAllowed`
    - `repayBorrowAllowed`
    - `liquidateBorrowAllowed`
    - `seizeAllowed`
    - `getAccountLiquidity`
    - `liquidateCalculateSeizeTokens`
    - As well as several of the administrative _* functions
- Commit 454aaca, which added reentrancy protections, included this note in its commit message:

  ```
  EIP 1283 defines a new refund for set and set-back storage changes. We should probably
  upgrade our re-entry guard to use a process that mimics this as it's now very cheap.
  ```

Unintended consequences of EIP 1283 were the cause of the recent Constantinople hard-fork postponement. It is unlikely that EIP 1283—or any other EIP that permits gas refunds, for that matter—will ever be approved. Instead, we recommend tracking the progress of EIP 1153, which proposes an alternative reentrancy protection mechanism. See the recommendations in Compound-TOB-020 for more information.