A solution to Multiple Withdrawal Attack in ERC20 token

Abstract—**ERC20 standard[1] defines set of functions for implementation of tokens in Ethereum blockchain. Tokens are subset of smart contracts that standardize creation of digital assets. These digital assets could aimed for representation of financial instrument (e.g., stocks, bonds, futures, etc), financial commodities (e.g., gold, oil, rice, etc) or even a new type of digital currency differs from Ether. ERC20 standard makes it possible for ERC20-compliant applications (e.g., online exchanges, automated payment systems, or decentralized games) to reuse ERC20 tokens. There are two functions in ERC20 standard (i.e., *approve* and *transferFrom*) that allow token transfer on behalf of the owner. In case of race condition, these two functions could be used in "Multiple Withdrawal Attack" that allows a spender to transfer more tokens than the owner ever wanted. This issue was initially raised on GitHub and is still open since October 2017. In this paper, 10 suggested solutions have been analyzed in terms of compatibility with the standard and mitigate the attack. Ultimately, new solution is proposed while adhering specifications of ERC20 standard and keeping backward compatibility with already deployed smart contracts.**

Index Terms—**Cryptocurrency; Multiple Withdrawal Attack; ERC20; Token; Ethereum; Blockchain; Vulnerability;**

1. Introduction

Ethereum blockchain project[1] launched in 2014 by announcing Ether as its protocol-level cryptocurrency. It is ranked second in terms of market value after Bitcoin[2] in 2019 and has the biggest development community to track enhancement and introduce new ideas[3]. Ethereum offers an ecosystem to implement any type of distributed applications (or DApps for short) on the blockchain that work together consistently. Tokens are essential part of this ecosystem that define common set of rules (known as API[4]) for standardizing behavior of smart contracts[5]. As a result, any ERC20-compliant application is aware of functionality of deployed tokens to employ them for exchanging, trading, transferring, etc. For example, shares of company X can be represented as ERC20 token. This makes it possible for other smart contracts to trade or exchange shares in form of digital assets. As shown in the below diagram, leveraging ERC20 tokens facilitate implementation of left side of the trading model on the blockchain:

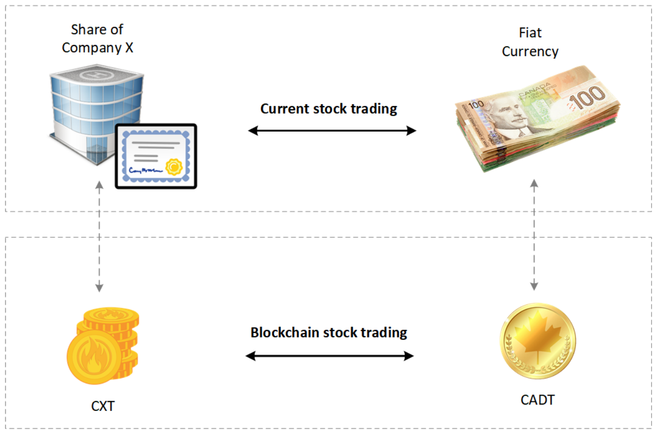


Figure 1. A blockchain trading model using ERC20 tokens.

Correspondingly, the right side of the model needs a financial asset which is equivalent to a fiat currency (like USD or CAD). Stablecoins[6] provide this functionalities in blockchain and could also be represented as ERC20 token. Representing both share of company X and fiat currency as ERC20 tokens, give us two ERC20 tokens with different values to trade. This shows the importance of tokens in Ethereum ecosystem for digitizing tangible assets to digital equivalents. By using ERC20 tokens in the above example, we are able to migrate current centralized trading systems to the blockchain and taking advantage of a distributed trading system.

As mentioned before, ERC20 tokens are technically standardized version of smart contracts that could be vulnerable to security flaws. Some of these vulnerabilities have been already discovered and addressed by Ethereum community while there are few issue still open. In this paper,

[1]ERC20 is the title of standard and it should be referred as EIP20 (which is the actual proposal for improvement). In this paper we use both ERC20 and EIP20 in one sense for simplicity.

[2]CoinMarketCap - Ethereum currency - Accessed: 2019-02-11 https://coinmarketcap.com/currencies/ethereum/

[3]CoinDesk Crypto-Economics Explorer - Accessed: 2019-02-11 https://www.coindesk.com/data

[4]Advanced Programming Interface

[5]Or smart transaction: Types of transactions that execute as they are programmed by a scripting language (like Solidity or Viper)

[6]Types of digital assets that value of it will be stable over time and people be able to count on its value since it is pegging to something that has a stable value (like gold or USD).

we analyze proposed community approaches and introduce new solution to one of these open issues that is known as "Multiple Withdrawal Attack". The issue is originally opened on GitHub[2] and raised as separate thread[3] for making it easy to follow. It is security issue in protocol-level and originating from definition of APIs in ERC20 standard for approving and transferring tokens. According to the standard specifications:

1- *approve*[7] allows *_spender* to withdraw up to the *_value* amount of tokens from token pool of the approver. If this function is called again, it has to overwrites the current allowance with the new *_value*.
2- *transferFrom*[8] grants required rights to the spender (accounts, wallets or other smart contracts) for transferring *_value* amount of tokens from address *_from* to address *_to*.

Security issues at the protocol-level may impact already deployed ERC20 tokens and functionality of smart contracts based on them. In fact, using these functions (i.e., *approve* and *transferFrom*) in an undesirable situation could result in conditions that tokens being spent by another third party on behalf of the owner. Authors of the standard [4], provided two sample codes from OpenZeppelin[5] and ConsenSys[6] as generic implementations. OpenZeppelin implementation uses two additional methods that initially proposed by MonolithDAO[7] and ConsenSys has not attempted to work around the issue. This issue is still open since October 2017 and several suggestions have been made that needs to be analyzed in term of compatibility with the standard and mitigation against the attack.

2. Attack analysis

Usually, *transferFrom* function will be called after *approve* method. The attack could happen in case of race condition[9], that allows a spender to transfer more tokens than the owner ever wanted. This is possible since the *approve* method overrides current allowance regardless of whether spender already transferred any tokens or not. Moreover, transferred tokens are not trackable and only *Transfer*[10] event will be logged (which is not sufficient in case of transferring tokens to a third parity). Here could be a possible attack scenario:

1- Alice allows Bob to transfer N tokens by calling *approve(_Bob, N)*.
2- After a while, Alice decides to change Bob's approval from N to M by executing *approve(_Bob, M)*.
3- Bob notices Alice's second transaction before it was mined and quickly sends another transaction that runs *transferFrom(_Alice, _Bob, N)*. This will transfer N Alice's tokens to Bob.
4- Bob's transaction will be executed before Alice's transaction (because of higher transaction fee, miner's policy or other prioritization techniques) and Bob front-runs Alice's transaction.
5- Alice's transaction will be executed after Bob's and allows Bob to transfer more M tokens.
6- Bob successfully transferred N Alice's tokens and gains ability of transferring another M tokens.
7- Before Alice notices that something went wrong, Bob calls *transferFrom* method again and transfers M Alice's tokens by executing *transferFrom(_Alice, _Bob, M)*.

As its details are shown in the figure below, Alice attempted to change Bob's allowance from N to M, but she made it possible for Bob to transfer N+M of her tokens at most, while Alice never wanted to allow so many transfers to be occurred by Bob:

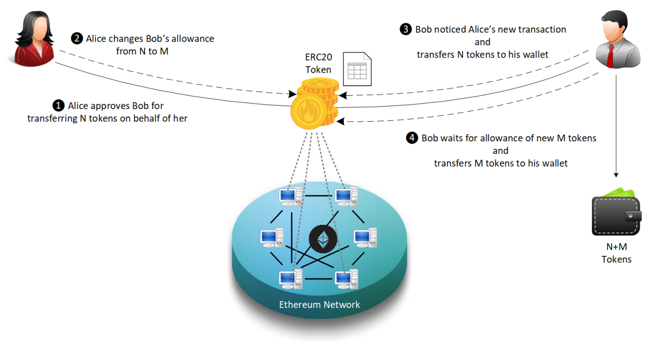

❷ Alice changes Bob's allowance from N to M
❶ Alice approves Bob for transferring N tokens on behalf of her
ERC20 Token
❸ Bob noticed Alice's new transaction and transfers N tokens to his wallet
❹ Bob waits for allowance of new M tokens and transfers M tokens to his wallet
Ethereum Network
N+M Tokens

Figure 2. Possible multiple withdrawal attack in ERC20 tokens.

It should be noted that the assumption here is to prevent Bob from withdrawing Alice's tokens multiple times. If he could withdraw N tokens after the initial Alice's approval, this would be considered as legitimate transfer since Alice has already approved it. In other words, it is Alice's responsibility to make sure before approving anything to Bob. In short, we are looking for a solution to prevent multiple withdrawal (N+M) by Bob presuming that Alice has more than N+M tokens in her wallet.

3. Mitigation

Several solutions have been suggested by Ethereum community (mostly from developers on GitHub) to address this attack. There would be some considerations for each solution that needs to be evaluated in term of compatibility with ERC20 standard and attack mitigation. We have examined technical aspects of each solution in the following sections.

[7]approve(address _spender, uint256 _tokens)

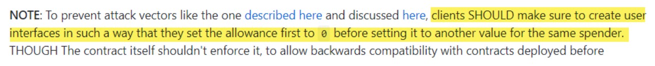
[8]transferFrom(address _from, address _to, uint256 _tokens)

[9]Execution of two transactions at the same time with undesirable situation or priority.

[10]Transfer(address indexed _from, address indexed _to, uint256 _value)

3.1. Enforcement by User Interface (UI)

ERC20 standard recommends to set allowance to zero before any non-zero values and enforce approval processing check in UI instead of smart contract:



NOTE: To prevent attack vectors like the one described here and discussed here, clients SHOULD make sure to create user interfaces in such a way that they set the allowance first to `0` before setting it to another value for the same spender. THOUGH The contract itself shouldn't enforce it, to allow backwards compatibility with contracts deployed before

Figure 3. Recommendation of ERC20 standard to mitigate multiple withdrawal attack.

However, if Alice does not use UI and connects directly to the blockchain, there would be a good chance of impacting by this attack. Furthermore, as discussed on Github[8], this approach is not sufficient and still allows Bob to transfer N+M tokens:

1- Bob is allowed to transfer N Alice's tokens.
2- Alice publishes transaction that changes Bob's allowance to 0.
3- Bob front runs Alice's transaction and transfers N Alice's tokens (*transferFrom* sets Bob's allowance to 0).
4- Alice's transaction is mined and Bob's allowance is set to 0 by *approve* method. This is exactly what she would see if Bob would not transfer any tokens, so she has no reason to think that Bob actually used his allowance before it was revoked.
5- Now Alice publishes a new transaction that changes Bob's allowance to M.
6- Alice's second transaction is mined, Bob now is allowed to transfer M Alice's tokens.
7- Bob transfers M Alice's tokens and in total N+M.

At step 3, Bob is able to transfer N tokens and consequently his allowance becomes 0. This is a legitimate transaction since Alice has already approved it. The issue occurs after Alice's new transaction to set Bob's allowance to 0. In case of front-running by Bob, Alice needs to check Bob's allowance for the second time before setting any new value. However, she will find out Bob's allowance 0 in either case. In other words, she can not distinguish whether Bob's allowance is set to 0 because of her transaction or Bob already transferred token on her behalf. Someone may point out that Alice notices this by checking *Transfer* event logged by *transferFrom* function. However, if Bob had transferred tokens to someone else (like Carol), then *Transfer* event will not be linked to Bob, and, if Alice's account is busy and many people are allowed to transfer from it, Alice may not be able to distinguish this transfer from a legitimate one performed by someone else. Overall, this solution does not prevent the attack while tries to follow ERC20 recommendations for setting Bob's allowance to zero before any non-zero value. Additionally, There is no way to see from UI if setting Bob's allowance to 0 is processed before the subsequent non-zero approval [9]. This is because of current methods in Web3.js[11] that do not support such checking[10]. Hence, enforcement should be considered at contract level not UI.[12]

[11] JavaScript UI library for interacting with Ethereum blockchain

3.2. Using Minimum viable token

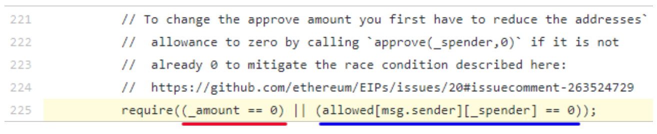
As suggested by[10], we can boil down ERC20 standard to a very basic functionalities by implementing only essential methods. this will prevent effecting of the attack by skipping implementation of vulnerable functions. While removing *approve* and *transferFrom* functions prevent the attack, it makes the token partially-ERC20-compliant. Golem Network Token (GNT[13]) is one of these examples since it does not implement the *approve*, *allowance* and *transferFrom* functions. According to ERC20 specifications, these methods are not OPTIONAL and must be implemented. Moreover, ignoring them will cause failed function calls from standard smart contracts that expect to interact with these methods. Therefore, we would not consider this solution as a compatible fix although mitigates the attack.

3.3. Approving trusted parties

Approving token transfer to non-upgradable smart contracts can be considered safe. Because they do not contain any logic to take advantage of this vulnerability. However, upgradable smart contracts may add new logic to a new version that needs re-verification before approving token transfer. Similarly, approving token transfer to people that we trust could be considered as a mitigation plan. Nonetheless, this solution would have limited use cases and it could not be considered as a comprehensive mitigation for the attack.

3.4. MiniMeToken solution

MiniMeToken[11] also follows ERC20 recommendation by reducing allowance to zero before non-zero values. They added a line of code to the *approve* method. The red clause allows setting approval to 0 and blue condition checks allowance of *_spender* to be 0 before setting to other values (i.e., If *_spender* allowance is 0 then allows non-zero values):



```
        // To change the approve amount you first have to reduce the addresses`
        //  allowance to zero by calling `approve(_spender,0)` if it is not
        //  already 0 to mitigate the race condition described here:
        //  https://github.com/ethereum/EIPs/issues/20#issuecomment-263524729
        require((_amount == 0) || (allowed[msg.sender][_spender] == 0));
```

Figure 4. MiniMeToken suggestion for adding new codes to approve method.

[12] Interestingly, OpenZeppelin example implements a workaround in contract level that makes it inconsistent with the recommendations of ERC20.

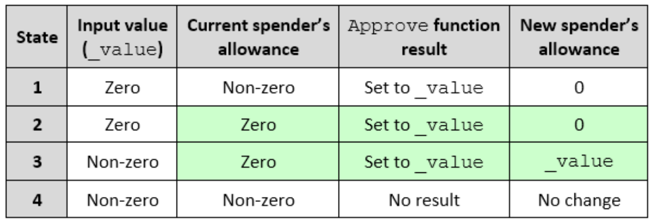
[13] https://etherscan.io/address/0xa74476443119A942dE498590Fe1f2454d7D4aC0d#code

Similar to "Enforcement by User Interface (UI)", this will not prevent Bob from transferring N+M tokens. Because Alice would not be able to distinguish whether N tokens have been already transferred or not. It is more clear in this scenario:

1- Alice decides to set Bob’s allowance to 0.
2- Bob front-runs Alice’s transaction and his allowance sets to 0 after transferring N tokens.
3- Alice’s transaction is executed and sets Bob’s allowance to 0 (Red clause passes sanity check).
4- Alice checks Bob’s allowance and she will find it 0, so, she can not determine whether this was because of her transaction or Bob already transferred N tokens.
5- By considering that Bob has not been transferred any tokens, Alice allows Bob for transferring new M tokens.
6- Bob would be able to transfer new approved tokens.

3.5. MonolithDAO solution

MonolithDAO[7] Token suggests two additional functions for increasing or decreasing allowance. *approve* function will also have an additional code to set allowance to zero before non-zero values. In this case, the default *approve* function should be called when spender’s allowance is zero (No approval has been made). If spender’s allowance is non-zero, increase and decrease functions will be used:



State	Input value (`_value`)	Current spender’s allowance	`Approve` function result	New spender’s allowance
1	Zero	Non-zero	Set to `_value`	0
2	Zero	Zero	Set to `_value`	0
3	Non-zero	Zero	Set to `_value`	`_value`
4	Non-zero	Non-zero	No result	No change

Figure 5. Functionality of *approve* method with new added code in MonolithDAO token.

These two functions can address race condition and prevent allowance double-spend exploit:

1- Alice allows Bob to transfer N tokens by calling *approve(_Bob, N)*. This will be executed by *approve* function since current Bob’s allowance is 0.
2- After a while, Alice decides to decrease Bob’s approval by M by running *decreaseApproval(_Bob, M)*.
3- Bob notices Alice’s second transaction and front runs it by executing *transferFrom(_Alice, _Bob, N)*.
4- Bob’s transaction will be executed first and transfers N token to his account and the his allowance becomes 0 as result of this transfer.
5- Alice’s transaction is mined after Bob’s transaction and tries to decrease Bob’s allowance by M. If Bob had already transferred more than M tokens, new Bob’s allowance becomes negative and it fails the transaction. So, the transaction does not change Bob’s remaining allowance and he would be able to transfer the rest (which is legitimate transfer since Alice has already approved it). If Bob had transferred less than M tokens, the new allowance will be applied and reduces Bob’s allowance by M.

Although these two new functions will prevent the attack, they have not been defined in the initial specifications of ERC20. Therefore, they can not be used by smart contracts that are already deployed on the Ethereum network since they will still use approve method for setting new allowance and not *increaseApproval* or *decreaseApproval*. Moreover, ERC20 specifications does not define any increase or decrease of allowance. It only defines new allowance. For example, if Alice has approved Bob for 100 tokens and wants to set it to 80, the new allowance should be 80 while using decrease methods will set it 20 (100 - 80 = 20). Comparatively, increase method will set new allowance to 180 while it has to set to 80 again. For these reasons, this solution would not be compatible with ERC20 standard and only is usable if approver or smart contract are aware of these supplementary methods.

3.6. Alternate approval function

Another suggestion[12] is to move security checks to another function like *safeApprove* that sets allowance if it has not been already changed. By using this function, Alice uses the standard *approve* function to set Bob’s allowance to 0 and for new approvals, she has to use *safeApprove*. It takes the current expected approval amount as input parameter and calls *approve* method if previous allowance is equal to current expected approval. So, Alice will have one step more and it is reading the current allowance and passing it to the new *safeApprove* method. As mentioned in the last section, this approach is not backward compatible with already implemented smart contracts. The new *safeApprove* method that is not defined in ERC20 standard and existing code would not be able to use this safety feature.

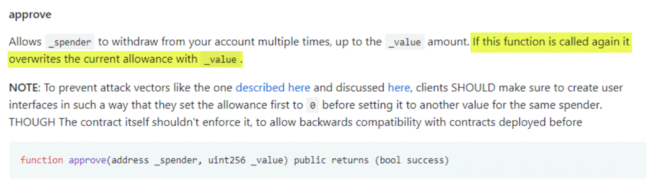
3.7. Detecting token transfers

As suggested by [13],a boolean variable is used to detect whether any tokens have been transferred or not. *transferFrom* method sets a flag to true if tokens are transferred. *approve* method checks the flag to be false before allowing new approvals (i.e., it checks if tokens have been used/transferred since the owner last allowance set). Moreover, it uses a new data structure for keeping track of used/transferred tokens. This approach could prevent race condition as described below:

1- Alice runs *approve(_Bob, N)* to allow Bob for transferring N tokens.
2- Since Bob’s initial allowance is 0 and used flag is false, then sanity check passes and Bob’s allowance is set to N.
3- Alice decides to set Bob’s allowance to 0 by executing *approve(_Bob, 0)*.
4- Bob front-runs Alice’s transaction and transfers N tokens. Then, his used flag turns to *true*.

5- Alice's transaction is mined and passes sanity check (because *_value == 0*).
6- Bob's allowance is set to 0 while used flag is still *true*.
7- Alice changes Bob's allowance to M by executing *approve(_Bob, M)*.
8- Since Bob already transferred number of tokens, used flag is *true* and it fails the transaction.
9- Bob's allowance remains as N and he could transfer only N tokens.

Although this approach mitigates the attack, it prevents any further legitimate approvals as well. Considering a scenario that Alice rightfully wants to increase Bob's allowance from N to M (two non-zero values). If Bob had already transferred number of tokens (even 1 token), Alice would not be able to change his approval. Because used flag is *true* now and does not allow changing allowance to any non-zero values. Even setting the allowance to 0, does not flip used flag and keeps Bob's allowance locked down. In fact, the code needs a line like *allowed[_from][msg.sender].used = false;* in *approve* method. But it will cause another problem. After setting allowance to 0, used flag becomes *false* and allows non-zero values event if tokens have been already transferred. In other words, it resembles the initial values of allowance similar when nothing is transferred. Therefore, it makes attack mitigation functionality ineffective. In short, this approach can not satisfy both legitimate and non-legitimate scenarios and violets ERC20 standard that says:


approve

Allows `_spender` to withdraw from your account multiple times, up to the `_value` amount. If this function is called again it overwrites the current allowance with `_value`.

NOTE: To prevent attack vectors like the one described here and discussed here, clients SHOULD make sure to create user interfaces in such a way that they set the allowance first to `0` before setting it to another value for the same spender. THOUGH The contract itself shouldn't enforce it, to allow backwards compatibility with contracts deployed before

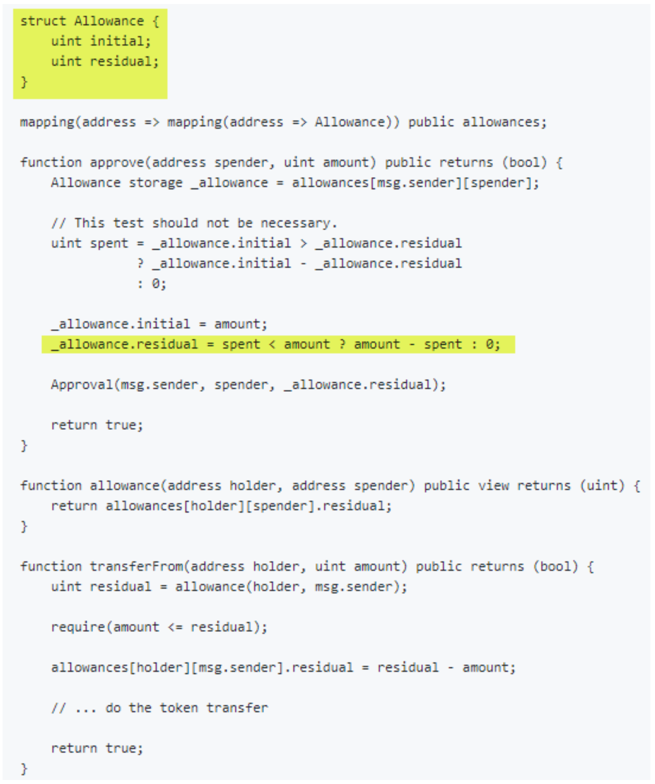
```
function approve(address _spender, uint256 _value) public returns (bool success)
```

Figure 6. ERC20 approve method constraint.

Nevertheless, this solution is a step forward by introducing the need for a new variable to track transferred tokens.

3.8. Keeping track of remaining tokens

Inspired by by the previous solution, [14] keeping track of remaining tokens instead of detecting transferred tokens. It uses modified version of data structure that used in the previous solution for storing residual tokens:


```
struct Allowance {
    uint initial;
    uint residual;
}

mapping(address => mapping(address => Allowance)) public allowances;

function approve(address spender, uint amount) public returns (bool) {
    Allowance storage _allowance = allowances[msg.sender][spender];

    // This test should not be necessary.
    uint spent = _allowance.initial > _allowance.residual
               ? _allowance.initial - _allowance.residual
               : 0;

    _allowance.initial = amount;
    _allowance.residual = spent < amount ? amount - spent : 0;

    Approval(msg.sender, spender, _allowance.residual);

    return true;
}

function allowance(address holder, address spender) public view returns (uint) {
    return allowances[holder][spender].residual;
}

function transferFrom(address holder, uint amount) public returns (bool) {
    uint residual = allowance(holder, msg.sender);

    require(amount <= residual);

    allowances[holder][msg.sender].residual = residual - amount;

    // ... do the token transfer

    return true;
}
```

Figure 7. Keeping track of remaining tokens.

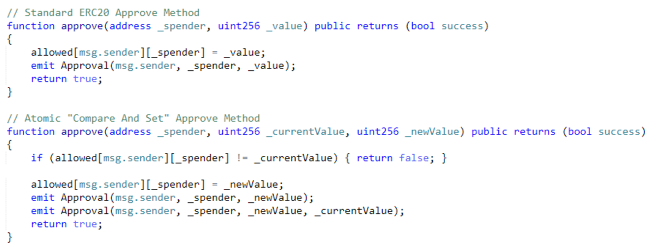
At first, it seems that this solution is a sustainable way to mitigate the attack by setting approval to zero before non-zero values. However, the highlighted code resembles the situation that we explained in "Enforcement by User Interface (UI)":

1- Bob's allowance is initially zero (*allowances[_Alice][_Bob].initial=0*, *allowances[msg.sender][spender].residual=0*).
2- Alice allows Bob to transfer N tokens (*allowances[_Alice][_Bob].initial=N*, *allowances[_Alice][_Bob].residual=N*).
3- Alice decides to change Bob's allowance to M and has to set it to zero before any non-zero values.
4- Bob noticed Alice's transaction for setting his allowance to zero and transfers N tokens in advance. transferFrom sets his allowance (residual) to zero consequently (*allowances[_Alice][_Bob].residual=0*).
5- Alice's transaction is mined and sets *allowances[_Alice][_Bob].initial=0* and *allowances[msg.sender][spender].residual=0* (Similar to step 1). This is like that no token has been transferred. So, Alice would not be able to distinguish whether any token have been transferred or not.
6- Alice approves Bob for spending new M tokens.
7- Bob is able to transfer new M tokes in addition to initial N tokens.

Someone may think of using *Transfer* event to detect transferred tokens or checking approver balance to see any transferred tokens. As explained in "Enforcement by User Interface (UI)", using *Transfer* event is not sufficient in case of transferring tokens to a third party. Checking approver balance also would not be an accurate way if the contract is busy and there are lot of transfers. So, it would be difficult for the approver to detect legitimate from non-legitimate tokens transfers.

3.9. Changing ERC20 API

[9] advised to change ERC20 approve method to compare current allowance of spender and sets it to new value if it has not already been transferred. This allows atomic compare and set of spender allowance to make the attack impossible. So, it will need new overloaded approve method with three parameters:



```
// Standard ERC20 Approve Method
function approve(address _spender, uint256 _value) public returns (bool success)
{
    allowed[msg.sender][_spender] = _value;
    emit Approval(msg.sender, _spender, _value);
    return true;
}

// Atomic "Compare And Set" Approve Method
function approve(address _spender, uint256 _currentValue, uint256 _newValue) public returns (bool success)
{
    if (allowed[msg.sender][_spender] != _currentValue) { return false; }

    allowed[msg.sender][_spender] = _newValue;
    emit Approval(msg.sender, _spender, _newValue);
    emit Approval(msg.sender, _spender, _newValue, _currentValue);
    return true;
}
```

Figure 8. Suggested ERC20 API Change for approve method.

In order to use this new method, smart contracts have to update their codes to provide three parameters instead of current two, otherwise any *approve* call will throw an exception. Moreover, one more call is required to read current allowance value and pass it to the new approve method. New events need to be added to ERC20 specification to log an approval events with four arguments. For backward compatibility reasons, both three-arguments and new four-arguments events have to be logged. All of these changes makes this token contract incompatible with deployed smart contracts and software wallets. Hence, it could not be considered as viable solution.

3.10. New token standards

After recognition of this security vulnerability, new standards like ERC233 [14] and ERC721[15] were introduced to address the issue in addition to improving current functionality of ERC20 standard. They changed approval model and fixed some drawbacks which need to be addressed in ERC20 as well (i.e., handle incoming transactions through a receiver contract, lost of funds in case of calling transfer instead of transferFrom, etc). Nevertheless, migration from ERC20 to ERC223/ERC721 would not be convenient and all deployed tokens needs to be redeployed. This also means update of any trading platform listing ERC20 tokens. The goal here is to find a backward compatible solution instead of changing current ERC20 standard or migrating tokens to new standards. Despite expanded features and improved security properties of new standards, we would not consider them as target solutions.

[14]https://github.com/Dexaran/ERC223-token-standard

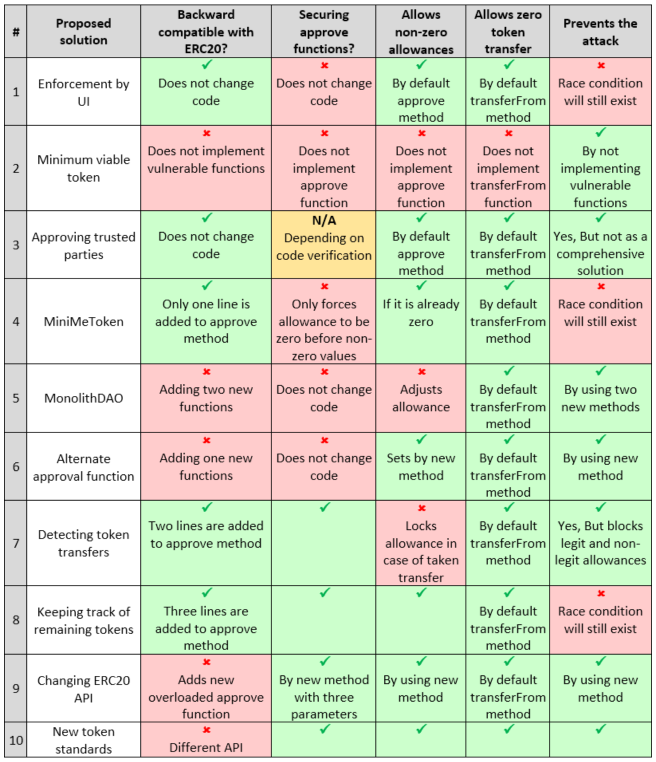
[15]https://github.com/ethereum/EIPs/blob/master/EIPS/eip-721.md

4. Discussion

Analyzing suggested solutions indicate the following constraints to be satisfied for a sustainable solution:

1- Calling *approve* function has to overwrite current allowance with new allowance.
2- *approve* method does not adjust allowance, it sets new allowance.
3- Transferring 0 values by *transferFrom* method MUST be treated as normal transfers and fire the *Transfer* event.
4- Introducing new methods violates ERC20 specifications and it should be avoided for having compatible token with already deployed smart contracts.
5- Spender will be allowed to withdraw from approver account multiple times, up to the allowed amount.
6- Transferring initial allowed tokens is considered as legitimate transfer. It could happen right after approval or before changing it.
7- Race condition MUST not happen in any cases for preventing multiple withdrawal from approver account.

Comparing suggested solutions shows that they cannot satisfy at least one of the above constraints: As the comparison table shows, a new solution is required to address this security vulnerability while adhering specification of ERC20 standard. The standard advises approvers to change spender allowance from N to 0 and then from 0 to M (instead of changing it directly from N to M). Since there are gaps between transactions, it would be always a possibility of front-running. As discussed in "MiniMeToken soultion", changing allowance to non-zero values after setting to zero, will require tracking of transferred tokens by the spender. If we can not track transferred tokens, we would not be able to identify if any token has been transferred between execution of transactions. Although It would be possible to track transferred token through *Transfer* events (logged by *transferFrom*), it would not be easily trackable in case of transferring to a third-party (Alice -> Bob, Bob -> Carole => Alice -> Carole). The only solution that removes this gap is to use compare and set (CAS) pattern[15]. It is one of the most widely used lock-free synchronization strategy that allows comparing and setting values in an atomic way. It allows to compare values in one transaction and set new values before transferring control.



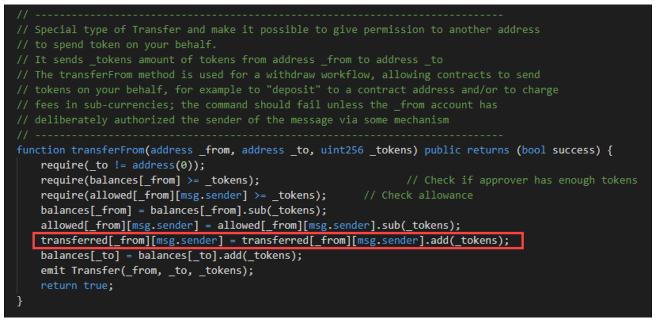
#	Proposed solution	Backward compatible with ERC20?	Securing approve functions?	Allows non-zero allowances	Allows zero token transfer	Prevents the attack
1	Enforcement by UI	✓ Does not change code	✗ Does not change code	✓ By default approve method	✓ By default transferFrom method	✗ Race condition will still exist
2	Minimum viable token	✗ Does not implement vulnerable functions	✗ Does not implement approve function	✗ Does not implement approve function	✗ Does not implement transferFrom function	✓ By not implementing vulnerable functions
3	Approving trusted parties	✓ Does not change code	N/A Depending on code verification	✓ By default approve method	✓ By default transferFrom method	✓ Yes, But not as a comprehensive solution
4	MiniMeToken	✓ Only one line is added to approve method	✗ Only forces allowance to be zero before non-zero values	✓ If it is already zero	✓ By default transferFrom method	✗ Race condition will still exist
5	MonolithDAO	✗ Adding two new functions	✗ Does not change code	✗ Adjusts allowance	✓ By default transferFrom method	✓ By using two new methods
6	Alternate approval function	✗ Adding one new functions	✗ Does not change code	✓ Sets by new method	✓ By default transferFrom method	✓ By using new method
7	Detecting token transfers	✓ Two lines are added to approve method	✓	✗ Locks allowance in case of taken transfer	✓ By default transferFrom method	✓ Yes, But blocks legit and non-legit allowances
8	Keeping track of remaining tokens	✓ Three lines are added to approve method	✓	✓	✓ By default transferFrom method	✗ Race condition will still exist
9	Changing ERC20 API	✗ Adds new overloaded approve function	✓ By new method with three parameters	✓ By using new method	✓ By default transferFrom method	✓ By using new method
10	New token standards	✗ Different API	✓	✓	✓	✓

Figure 9. Comparing suggested solutions.

5. Proposals

5.1. Proposal 1: Securing *approve* method

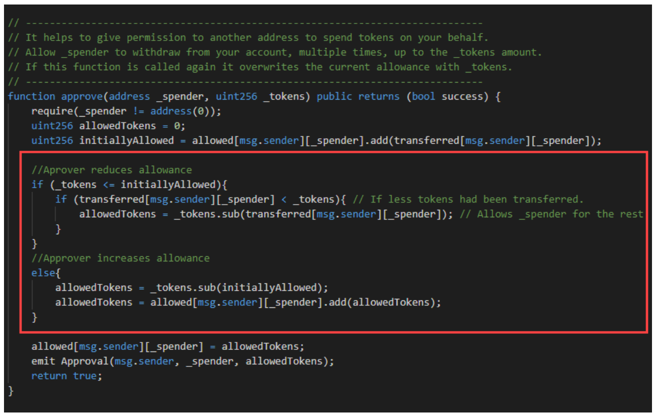
As discussed, a feasible solution would be to use CAS pattern to set new allowance atomically. This needs knowledge of transferred tokens that requires adding a new mapping variable to token code. The code would be still compatible with other smart contracts due to internal usage of the variable. Consequently, *transferFrom* method will have an new line of code for tracking transferred tokens:



```
// ----------------------------------------------------------------------------
// Special type of Transfer and make it possible to give permission to another address
// to spend token on your behalf.
// It sends _tokens amount of tokens from address _from to address _to
// The transferFrom method is used for a withdraw workflow, allowing contracts to send
// tokens on your behalf, for example to "deposit" to a contract address and/or to charge
// fees in sub-currencies; the command should fail unless the _from account has
// deliberately authorized the sender of the message via some mechanism
// ----------------------------------------------------------------------------
function transferFrom(address _from, address _to, uint256 _tokens) public returns (bool success) {
    require(_to != address(0));
    require(balances[_from] >= _tokens);                   // Check if approver has enough tokens
    require(allowed[_from][msg.sender] >= _tokens);      // Check allowance
    balances[_from] = balances[_from].sub(_tokens);
    allowed[_from][msg.sender] = allowed[_from][msg.sender].sub(_tokens);
    transferred[_from][msg.sender] = transferred[_from][msg.sender].add(_tokens);
    balances[_to] = balances[_to].add(_tokens);
    emit Transfer(_from, _to, _tokens);
    return true;
}
```

Figure 10. Modified version of *transferFrom* based on added mapping variable.

Similarly, a block of code will be added to the *approve* function to compare new allowance with transferred tokens. It has to work in both cases with zero and non-zero allowance set:



```
// ----------------------------------------------------------------------------
// It helps to give permission to another address to spend tokens on your behalf.
// Allow _spender to withdraw from your account, multiple times, up to the _tokens amount.
// If this function is called again it overwrites the current allowance with _tokens.
// ----------------------------------------------------------------------------
function approve(address _spender, uint256 _tokens) public returns (bool success) {
    require(_spender != address(0));
    uint256 allowedTokens = 0;
    uint256 initiallyAllowed = allowed[msg.sender][_spender].add(transferred[msg.sender][_spender]);

    //Aprover reduces allowance
    if (_tokens <= initiallyAllowed){
        if (transferred[msg.sender][_spender] < _tokens){ // If less tokens had been transferred.
            allowedTokens = _tokens.sub(transferred[msg.sender][_spender]); // Allows _spender for the rest
        }
    }
    //Approver increases allowance
    else{
        allowedTokens = _tokens.sub(initiallyAllowed);
        allowedTokens = allowed[msg.sender][_spender].add(allowedTokens);
    }

    allowed[msg.sender][_spender] = allowedTokens;
    emit Approval(msg.sender, _spender, allowedTokens);
    return true;
}
```

Figure 11. Added code block to *approve* function to compare and set new allowance value.

Added code to *approve* function will compare new allowance (*_tokens*) with current allowance of the spender (allowed[msg.sender][_spender]) and with already transferred token (transferred[msg.sender][_spender]). Then it decides to increase or decrease current allowance. If new allowance is less than initial allowance (sum of *allowance* and *transferred* variables), it denotes decreasing allowance, otherwise increasing allowance was intended. For example, we consider these scenarios:

A. Alice approves Bob for spending 100 tokens and then decides to decrease it to 10 tokens.

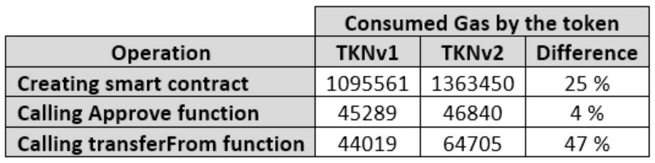
1- Alice approves Bob for transferring 100 tokens.
2- After a while, Alice decides to reduce Bob's allowance from 100 to 10 tokens.
3- Bob noticed Alice's new transaction and transfers 100 tokens by front-running.
4- Bob's allowance is 0 and *transferred* is 100 (set by *transferFrom* function).
5- Alice's transaction is mined and checks initial allowance (100) with new allowance (10).
6- As it is reducing, transferred tokens (100) will be compared with new allowance (10).
7- Since Bob already transferred more tokens, his allowance will be set to 0.
8- Bob is not able to move more than initial approved tokens.

B. Alice approves Bob for spending 100 tokens and then decides to increase it to 120 tokens.

1- Alice approves Bob for transferring 100 tokens.
2- After a while, Alice decides to increase Bob's allowance from 100 to 120 tokens.
3- Bob noticed Alice's new transaction and transfers 100 tokens by front-running.
4- Bob's allowance is 0 and *transferred* is 100.

5- Alice's transaction is mined and checks initial allowance (100) with new allowance (120).
6- As it is increasing, new allowance (120) will be subtracted from transferred tokens (100).
7- 20 tokens will be added to Bob's allowance.
8- Bob would be able to transfer more 20 tokens (120 in total as Alice wanted).

In order to evaluate functionality of the new *approve/transferFrom* functions, we have implemented a standard ERC20 token (TKNv1[16]) along side proposed ERC20 token (TKNv2[17]). Result of tests for different input values shows that TKNv2 can address multiple withdrawal attack by making front-running gain ineffective. Moreover, we compared these two tokens in term of Gas consumption. TokenV2.*approve* function uses almost the same amount of Gas as TokenV1.*approve*, however, gas consumption of TokenV2.*transferFrom* is around 50% more than TokenV1.*transferFrom*. This difference is because of maintaining a new mapping variable for tracking transferred tokens:



	Consumed Gas by the token		
Operation	TKNv1	TKNv2	Difference
Creating smart contract	1095561	1363450	25 %
Calling Approve function	45289	46840	4 %
Calling transferFrom function	44019	64705	47 %

Figure 12. comparison of Gas consumption between TKNv1 and TKNv2.

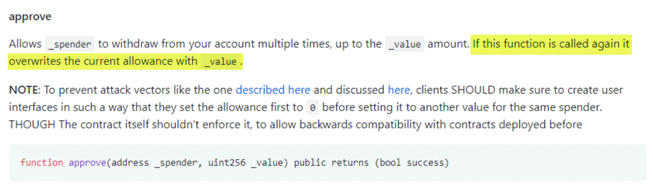
In term of compatibly, working with standard wallets (like MetaMask) have not raised any transfer issue. This shows compatibility of the token with existing wallets.

5.2. Proposal 2: Securing *transferFrom* method

Proposal 1 mitigates the attack in all situations, however it adjusts allowance based on transferred tokens. For example, if Alice allowed Bob for transferring 100 tokens and she decides to increase it to 120 tokens, the allowance will not directly set to 120 and the code adjusts it as below:

- If Bob already transferred 100 tokens, the new allowance will be 20 (100+20 = 120).
- If Bob already transferred 70 tokens, the new allowance will be 50 (70+50 = 120).
- If Bob has not already transferred any tokens, the new allowance will be 120 (0+120=120).

Although the final result will be the same and does not allow Bob to transfer more than intended tokens, but ERC20 standard approve method emphasizes that:



approve

Allows `_spender` to withdraw from your account multiple times, up to the `_value` amount. If this function is called again it overwrites the current allowance with `_value` .

NOTE: To prevent attack vectors like the one described here and discussed here, clients SHOULD make sure to create user interfaces in such a way that they set the allowance first to `0` before setting it to another value for the same spender. THOUGH The contract itself shouldn't enforce it, to allow backwards compatibility with contracts deployed before

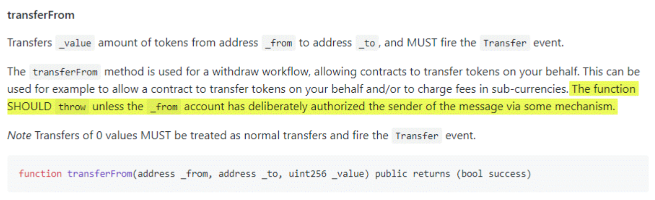
```
function approve(address _spender, uint256 _value) public returns (bool success)
```

Figure 13. ERC20 *approve* method constraint.

Hence, adjusting allowance will violate this constraint. On the other hand, this was the only solution for improving approve method. Because setting allowance securely to new values would need knowledge of transferred tokens. We can get this knowledge by:

1- Tracking what have been transferred and ADJUST allowance accordingly.
2- Passing a new input parameter that is showing what was the allowance before.

We implemented the first approach and the second one would need to modify definition of *approve* method. It seems that there is no feasible implementation to satisfy constraints of ERC20 and mitigating the attack under one solution. Therefore, we would assume API change as final solution of securing *approve* method. As an alternative solution, we can think of securing *transferFrom* method instead of *approve* method. ERC20 standard emphasizes that:



transferFrom

Transfers `_value` amount of tokens from address `_from` to address `_to`, and MUST fire the `Transfer` event.

The `transferFrom` method is used for a withdraw workflow, allowing contracts to transfer tokens on your behalf. This can be used for example to allow a contract to transfer tokens on your behalf and/or to charge fees in sub-currencies. The function SHOULD `throw` unless the `_from` account has deliberately authorized the sender of the message via some mechanism.

Note Transfers of 0 values MUST be treated as normal transfers and fire the `Transfer` event.

```
function transferFrom(address _from, address _to, uint256 _value) public returns (bool success)
```

Figure 14. ERC20 *transferFrom* method constraint.

So, the goal is to prevent spender from transferring more tokens than allowed by the approve. Based on this impression, we should not consider allowance as the main factor. Transferred tokens should be considered as the main variable in calculations. For example:

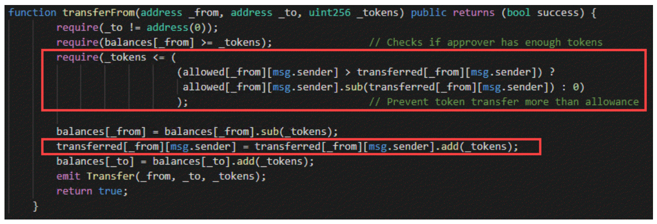
1- Alice allowed Bob for transferring 100 tokens and decides to set it to 70 after a while.
2- Bob front runs Alice's transaction and transfers 100 tokes (legitimate transfer).
3- Alice's transaction is mined and sets Bob allowance to 80.
4- Bob got new allowance and runs *transferFrom(_Bob,80)*. Since he already transferred more than 80, his transaction will fail and prevent multiple withdrawal.
5- Bob's allowance stays as 80, however, he can not use it.

Here allowance can be considered as maximum allowance. It indicates that Bob is eligible to transfer up to specified limit if he has not already transferred any

[16]https://rinkeby.etherscan.io/address/0x8825bac68a3f6939c296a40fc8078d18c2f66ac7

[17]https://rinkeby.etherscan.io/address/0xf2b34125223ee54dff48f71567d4b2a4a0c985[illegible]

tokens. In fact, there is no relation between allowance (*allowed[_from][msg.sender]*) and transferred tokens (*transferred[_from][msg.sender]*). The fist variable shows maximum transferable tokens by a spender and can be changed irrelative to transferred tokens (approve method does not check transferred tokens). If Bob has not already transferred that much of tokens, he would be able to transfer difference of it *allowed[_from][msg.sender].sub(transferred[_from][msg.sender])*. In other words, transferred is life time variable that accumulates transferred tokens regardless of allowance change. So, by this assumption, we can secure *transferFrom* method instead of *approve* method as below:



```
function transferFrom(address _from, address _to, uint256 _tokens) public returns (bool success) {
        require(_to != address(0));
        require(balances[_from] >= _tokens);               // Checks if approver has enough tokens
        require(_tokens <= (
                          (allowed[_from][msg.sender] > transferred[_from][msg.sender]) ?
                           allowed[_from][msg.sender].sub(transferred[_from][msg.sender]) : 0)
                          );                                   // Prevent token transfer more than allowance

        balances[_from] = balances[_from].sub(_tokens);
        transferred[_from][msg.sender] = transferred[_from][msg.sender].add(_tokens);
        balances[_to] = balances[_to].add(_tokens);
        emit Transfer(_from, _to, _tokens);
        return true;
    }
```

Figure 15. Securing *transferFrom* method instead of *approve* method.

This token is implemented as TKNv3 [18] on Rinkby network. Gas consumption of *transferFrom* function is around 37% more than standard implementation which is acceptable for having a secure ERC20 token.

6. Conclusion

Based on ERC20 specifications, token owners should be aware of their approval consequences. If they approve someone to transfer N tokens, the spender can transfer exactly N tokens, even if they change allowance to zero afterward. This is considered a legitimate transaction and responsibility of approver before allowing the spender for transferring any tokens. An attack can happen when changing allowance from N to M, that allows spender to transfer N+M tokens and effect multiple withdrawal attack. This attack is possible in case of front-running by approved side. As we examined possible solutions, all approaches violate ERC20 specifications or have not addressed the attack completely. Proposal 1 uses CAS pattern for checking and setting new allowance atomically. In proposal 2, *transferFrom* function is secured instead of *approve* method. We implemented an ERC20 token for each proposal that solve this security issue while keeping backward compatibly with already deployed smart contracts or wallets. Although these implementations consume more Gas than standard ERC20 implementations, they are secure and could be considered for secure ERC20 token deployment.

[18]https://rinkeby.etherscan.io/address/0x5d148c948c01e1a61e280c8b2ac39fd49ee6d9c6

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