AAVE

Protocol Whitepaper V1.0

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Abstract

This document describes the definitions and theory behind the Aave Protocol explaining the different aspects of the implementation.

Contents

1 Introduction

The birth of the Aave Protocol marks Aave's shift from a decentralized P2P lending strategy (direct loan relationship between lenders and borrowers, like in ETHLend) to a pool-based strategy. Lenders provide liquidity by depositing cryptocurrencies in a pool contract. Simultaneously, in the same contract, the pooled funds can be borrowed by placing a collateral. Loans do not need to be individually matched, instead they rely on the pooled funds, as well as the amounts borrowed and their collateral. This enables instant loans with characteristics based on the state of the pool. A simplified scheme of the protocol is presented in figure 1 below.

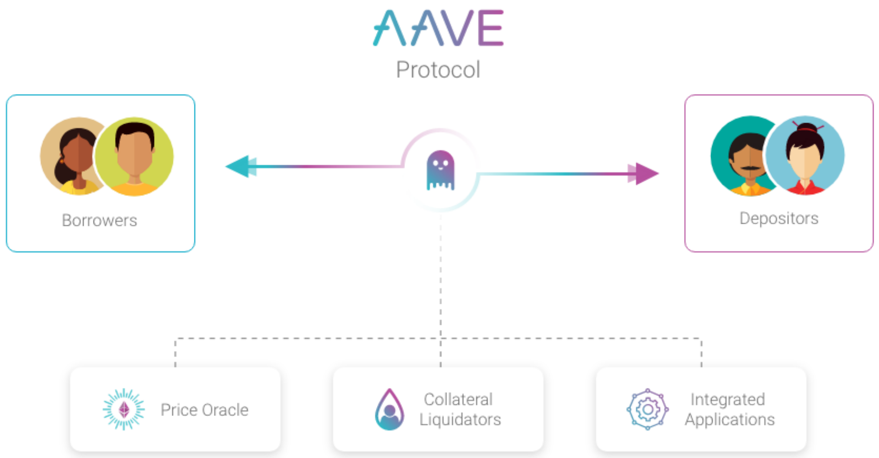


Figure 1: The Aave Protocol

The interest rate for both borrowers and lenders is decided algorithmically:

- For borrowers, it depends on the cost of money - the amount of funds available in the pool at a specific time. As funds are borrowed from the pool, the amount of funds available decreases which raises the interest rate.
- For lenders, this interest rate corresponds to the earn rate, with the algorithm safeguarding a liquidity reserve to guarantee withdrawals at any time.

1.1 Basic Concepts

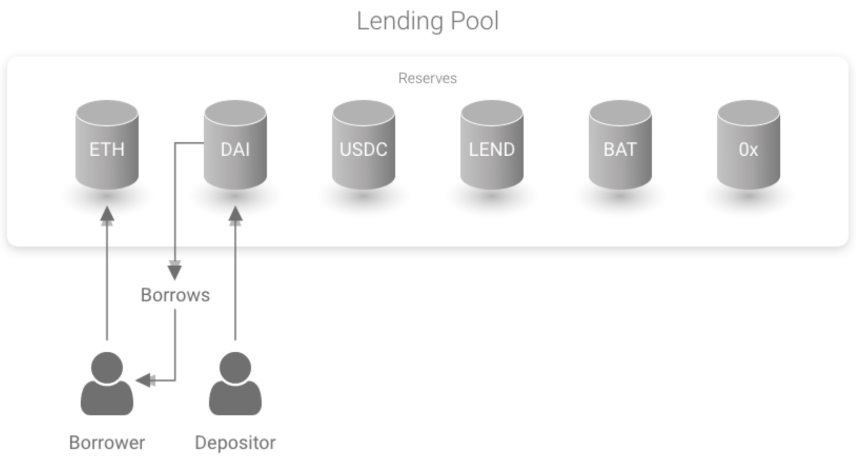


Figure 2: Lending Pool Basics

At the heart of a **lending pool** is the concept of **reserve**: every pool holds reserves in multiple currencies, with the total amount in Ethereum defined as **total liquidity**. A reserve accepts **deposits** from lenders. Users can

borrow these funds, granted that they lock a greater value as **collateral**, which backs the borrow position. Specific currencies in the pooled reserves can be configured as collateral or not for borrow positions, only low risk tokens should be considered. The amount one can borrow depends on the currencies deposited still available in the reserves. Every reserve has a specific **Loan-To-Value (LTV)**, calculated as the **weighted average** of the different LTVs of the currencies composing the collateral, where the weight for each LTV is the **equivalent amount of the collateral in ETH**; figure 3 shows an example of parameters.

Every borrow position can be opened with a **stable or variable rate**. Borrows have infinite duration, and there is no repayment schedule: partial or full repayments can be made anytime.

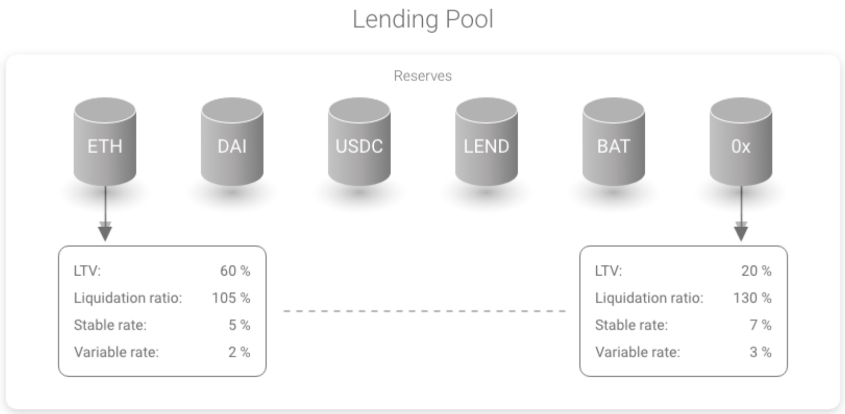


Figure 3: Lending Pool Parameters

In case of price fluctuations, a borrow position might be **liquidated**. A liquidation event happens when the price of the collateral drops below the threshold, L_Q, called **liquidation threshold**. Reaching this ratio channels a **liquidation discount**, which incentivizes liquidators to buy the collateral at a discounted price. Every reserve has a specific liquidation threshold, following the same approach as for the LTV. Calculation of the average liquidation threshold L_Q^a is performed dynamically, using the weighted average of the liquidation thresholds of the collateral's underlying assets.

At any point in time, a borrow position is characterized by its health factor H_f, which determines if a loan is **undercollateralized**:

$$H_f = \frac{TotalCollateralETH * L_Q^a}{TotalBorrowsETH} \ \textit{when } H_f < 1, \textit{ a loan is considered undercollateralized and can be liquidated}$$

Further details on liquidation can be found in section 3.6.

1.2 Formal Definitions

Variable	Description	
T, **current timestamp**	Current number of seconds defined by `block.timestamp`.	
T_l, **last updated timestamp**	Block height of the last update of the reserve data. B_l is updated every time a borrow, deposit, redeem, repay, swap or liquidation event occurs.	
T_Δ, **delta time**	Period, with $T_{year} = 31536000$ the number of seconds in a year.	$T_\Delta = \frac{T-T_l}{T_{year}}$
L_t, **total liquidity**	Total amount of liquidity available in the reserve. The decimals of this value depend on the decimals of the currency.	
B_f, **total stable borrows**	Total amount of liquidity borrowed at a stable rate. The decimals of this value depend on the decimals of the currency.	
B_v, **total variable borrows**	Total amount of liquidity borrowed at a variable rate. The decimals of this value depend on the decimals of the currency.	
B_t, **total borrows**	Total amount of liquidity borrowed. The decimals of this value depend on the decimals of the currency.	$B_t = B_f + B_v$
U, **utilization rate**	Representing the utilization of the deposited funds.	$U = \begin{cases} 0, \text{ if } L_t = 0 \\ \frac{B_t}{L_t}, \text{ if } L_t > 0 \end{cases}$
R_{vb}, **base variable borrow rate**	Constant for $B_t = 0$. Expressed in ray.	
R_{vs}, **base variable rate scaling**	Constant representing the scaling of the variable rate versus the utilization. Expressed in ray.	
R_v, **current variable borrow rate**	Expressed in ray.	$R_v = R_{vb} + UR_{vs}$
R_f, **current stable rate**	Implemented in section 4.2. Expressed in ray.	
R^t_{fa}, **average stable rate borrow rate**	When a stable borrow of amount B_{new} is issued at rate R_f:	$\mathrm{R}^t_{fa} = \frac{B_f R^{t-1}_{fa} + B_{new} R_f}{B_f + B_{new}}$
	When a stable borrow of a user x is repaid for an amount B_x based on the borrow rate R_{fx}:	$\mathrm{R}^t_{fa} = \begin{cases} 0, \text{ if } B_f - B_x = 0 \\ \frac{B_v R_v + B_x R_x}{B_f + B_x}, \text{ if } B_f - B_x > 0 \end{cases}$
	In `LendingPoolLibrary.sol` check the methods `decreaseTotalBorrowsFixedAndUpdateAverageRate()` and `increaseTotalBorrowsFixedAndUpdateAverageRate()`. Expressed in ray.	

Variable	**Description**	
R_O, **overall borrow rate**	Overall borrow rate of the reserve, calculated as the weighted average between the total variable borrows B_v and the total stable borrows B_f.	$R_O = \begin{cases} 0, \text{ if } B_t = 0 \\ \frac{B_v R_v + B_f R_{fa}}{B_t}, \text{ if } B_t > 0 \end{cases}$
R_Δ, **borrow or liquidity rate delta**	Constant representing the delta between the total income of the reserve represented by R_O and the Liquidity Rate R_Δ. Expressed in ray.	
R_l, **current liquidity rate**	Function of the overall borrow rate R_O and the utilization rate U.	$R_l = R_O U - R_\Delta$
C_i^t, **cumulated liquidity index**	Interest cumulated by the reserve during the time interval T_Δ, updated whenever a borrow, deposit, repay, redeem, swap, liquidation event occurs.	$C_i^t = (R_l T_\Delta + 1) C_i^{t-1}$ $C_i^0 = 1 \times 10^{27} = 1\ ray$
I_n^t, **reserve normalized income**	Ongoing interest cumulated by the reserve.	$I_n^t = (R_l T_\Delta + 1) C_i^{t-1}$
B_{vc}^t, **cumulated variable borrow index**	Interest cumulated by the variable borrows B_v, at rate R_v, updated whenever a borrow, deposit, repay, redeem, swap, liquidation event occurs.	$B_{vc}^t = (R_v T_\Delta + 1) B_{vc}^{t-1}$ $B_{vc}^0 = 1 \times 10^{27} = 1\ ray$
B_{vcx}^t, **user cumulated variable borrow index**	Variable borrow index of the specific user, stored when a user opens a variable borrow position.	$B_{vcx}^t = B_{vc}^t$
B_x, **user principal borrow balance**	Balance stored when a user opens a borrow position. In case of multiple borrows, the compounded interest is cumulated each time and it becomes the new principal borrow balance.	
B_{xc}, **user compounded borrow balance**	Principal B_x plus the cumulated interests. For a variable position: For a stable position:	 $B_{xc} = \frac{(R_v T_{\Delta x}) + 1}{B_{vcx}} B_{xc} B_x$ $B_{xc} = (R_f T_{\Delta x} + 1) B_x$

2 Protocol Architecture

The current implementation of the protocol is as follows:

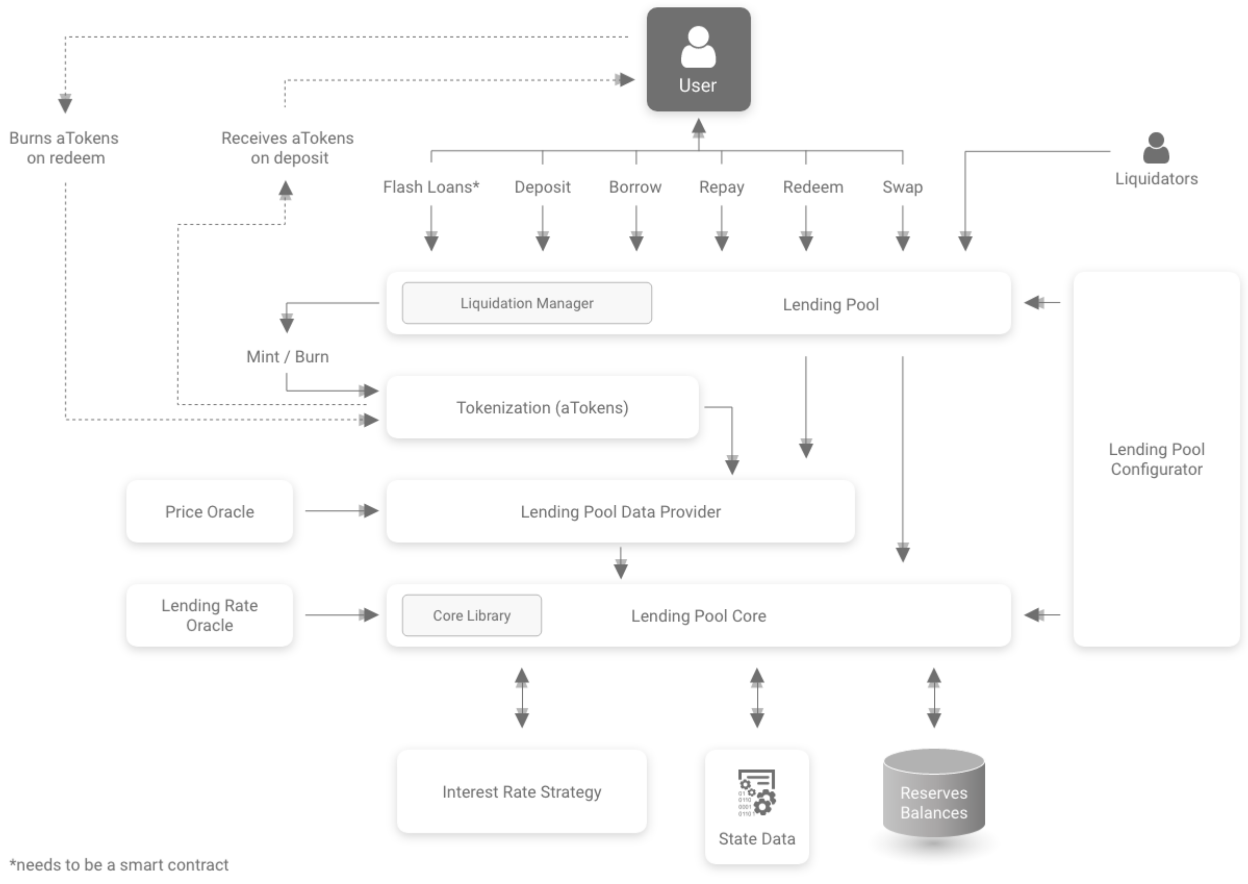


Figure 4: Protocol Architecture

2.1 Lending Pool Core

The `LendingPoolCore` contract is the center of the protocol, it:

- holds the state of every reserve and all the assets deposited,
- handles the basic logic (cumulation of the indexes, calculation of the interest rates...).

2.2 Lending Pool Data Provider

The `LendingPoolDataProvider` contract performs calculations on a higher layer of abstraction than the `LendingPoolCore` and provides data for the `LendingPool`; specifically:

- Calculates the ETH equivalent a user's balances (Borrow Balance, Collateral Balance, Liquidity Balance) to assess how much a user is allowed to borrow and the health factor.
- Aggregates data from the `LendingPoolCore` to provide high level information to the `LendingPool`.
- Calculate of the Average Loan to Value and Average Liquidation Ratio.

2.3 Lending Pool

The `LendingPool` contract uses the `LendingPoolCore` and `LendingPoolDataProvider` to interact with the reserves through the actions:

- Deposit
- Redeem
- Borrow
- Repay
- Rate swap
- Liquidation
- Flash loan

One of the advanced features implemented in the `LendingPool` contract is the **tokenization** of the lending position. When a user deposits in a specific reserve, he receives a corresponding amount of **aTokens**, tokens that map the liquidity deposited and accrue the interests of the deposited underlying assets. Atokens are minted upon deposit, their value increases until they are burned on redeem or liquidated. Whenever a user opens a borrow position, the tokens used as collateral are locked and cannot be transferred. Further details on the tokenization are in section 3.8.

2.4 Lending Pool Configurator

The `LendingPoolConfigurator` provides main configuration functions for `LendingPool` and `LendingPoolCore`:

- Reserve initialization
- Reserve configuration
- Enable/disable borrowing on a reserve
- Enable/disable the usage of a specific reserve as collateral.

The `LendingPoolConfigurator` contract will be integrated in Aave Protocol governance.

2.5 Interest Rate Strategy

The `InterestRateStrategy` contract holds the information needed to update the interest rates of a specific reserve and implements the update of the interest rates. Every reserve has a specific `InterestRateStrategy` contract. Specifically, within the base strategy contract `DefaultReserveInterestRateStrategy` the following are defined:

- Base variable borrow rate R_{vb}
- Variable borrow rate scaling R_{vs}
- Stable borrow rate scaling R_{fs}
- Borrow to liquidity rate delta $R_{\triangle}$

2.6 Governance

The rights of the protocol are controlled by the LEND token. Initially, the Aave Protocol will be launched with a decentralized on-chain governance based on the DAOStack framework which will evolve to a fully autonomous protocol. On-chain implies all votes are biding: actions that follow a vote are hard-coded and must be executed.

To understand the scope of the governance it's important to make the distinction:

- The **Aave Protocol** is bound to evolve and will allow the creation of multiple lending pools with segregated liquidity, parameters, permissions, and type of assets.
- The **Aave Lending Pool** is the first pool of the Aave protocol until the "Pool Factory" Update is released and anyone can create their own pool.

Within the Aave Protocol, the governance will take place at two level :

1. The **Protocol's Governance** voting is weighted by LEND for decisions related to protocol parameters and upgrades of the smart contract. It can be compared to MakerDAO's governance where stakeholders vote on current and future parameters of the protocol.
2. The **Pool's Governance** where your vote is weighted based on your share of pool liquidity expressed in aTokens. The votes cover pool specific parameters such as assets used as collateral or to be borrowed.

   Each Pool will have its own governance, under the umbrella of the Protocol's Governance.

More details on the Governance will be published in a Governance Proposal to the community.

3 The `LendingPool` Contract

The actions implemented within `LendingPool` allow users to interact with the reserve. All the actions follow this specific sequence:

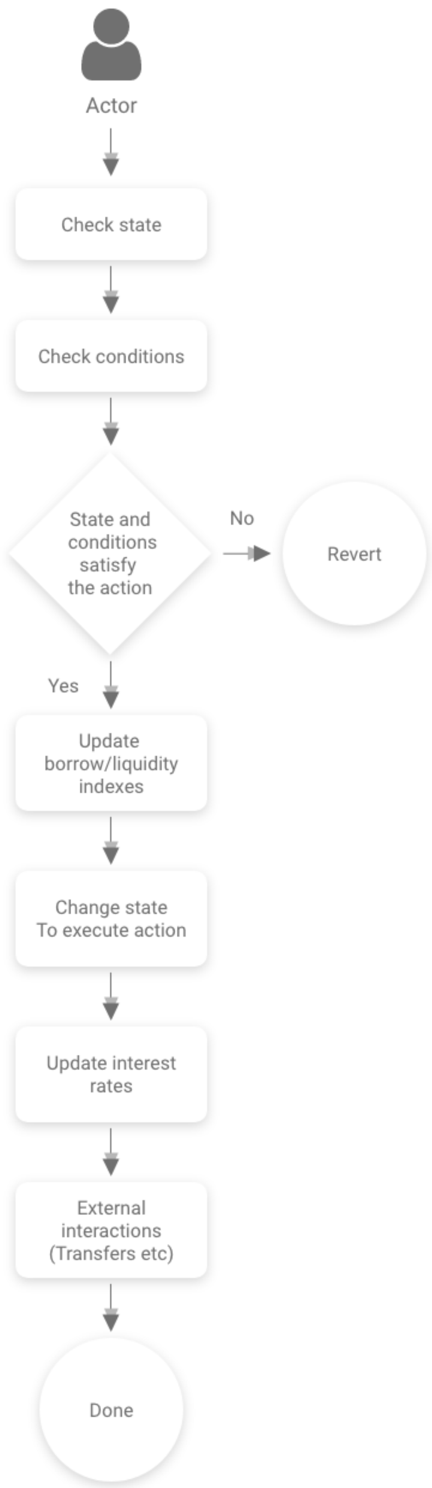

Actor
Check state
Check conditions
State and conditions satisfy the action
No
Revert
Yes
Update borrow/liquidity indexes
Change state To execute action
Update interest rates
External interactions (Transfers etc)
Done

Figure 5: The `LendingPool` Contract

3.1 Deposit

The deposit action is the simplest one and does not have any particular state check. The sequence of action is:

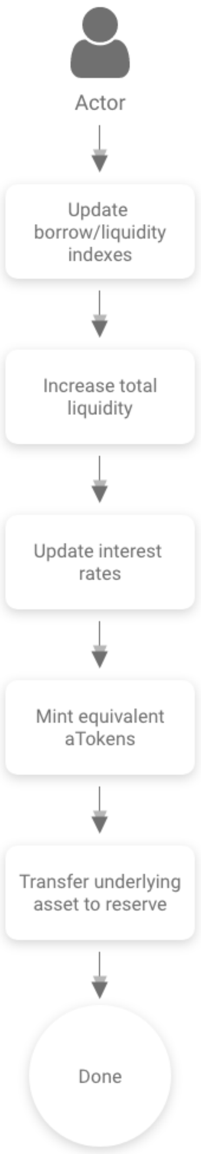
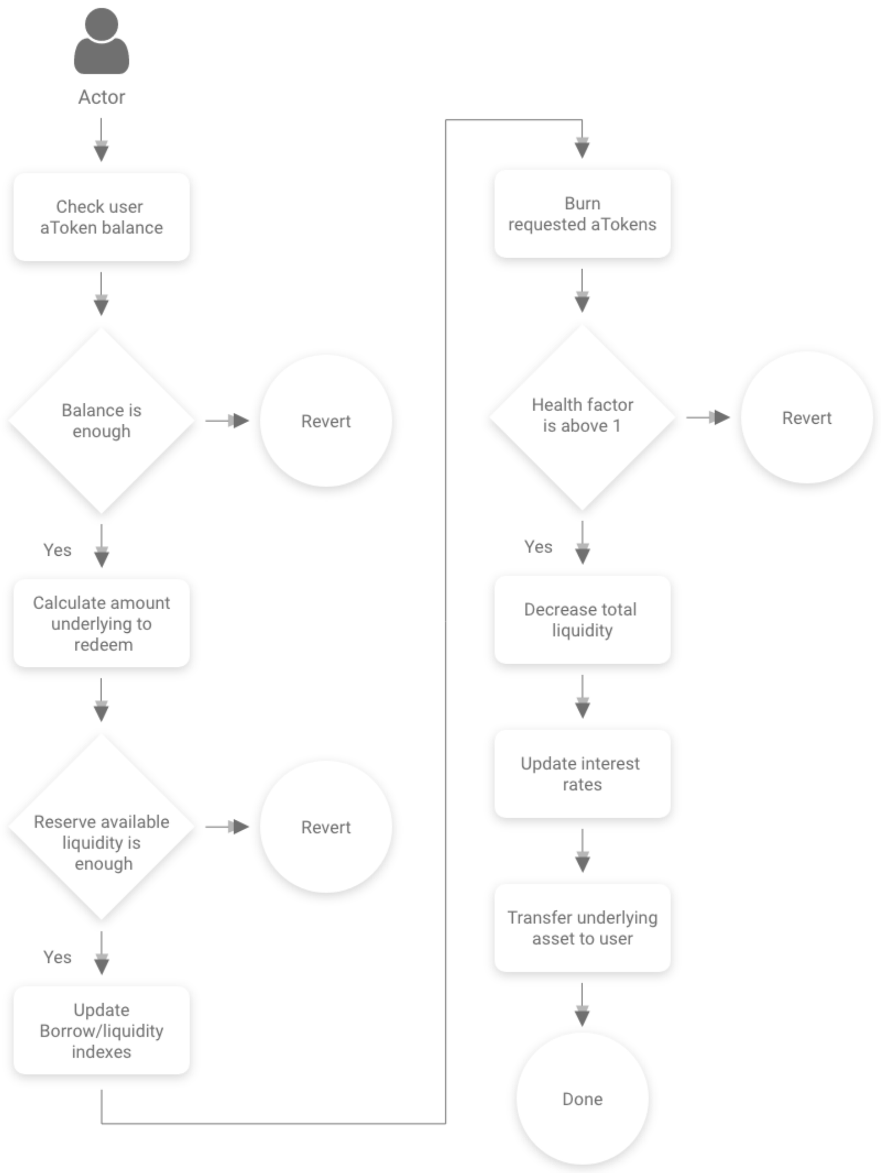


Figure 6: Deposit funds

3.2 Redeem

The redeem action allows users to exchange an amount of aTokens for the underlying asset. The actual amount to redeem is calculated using the aToken/underlying exchange rate E_i in section 3.8. The action is defined as follows:



Actor
Check user aToken balance
Balance is enough
Revert
Yes
Calculate amount underlying to redeem
Reserve available liquidity is enough
Revert
Yes
Update Borrow/liquidity indexes
Burn requested aTokens
Health factor is above 1
Revert
Yes
Decrease total liquidity
Update interest rates
Transfer underlying asset to user
Done

Figure 7: Redeem funds

3.3 Borrow

The borrow action transfers to the user a specific amount of underlying asset, in exchange of a collateral that remains locked. The flow of action can be described as follows:

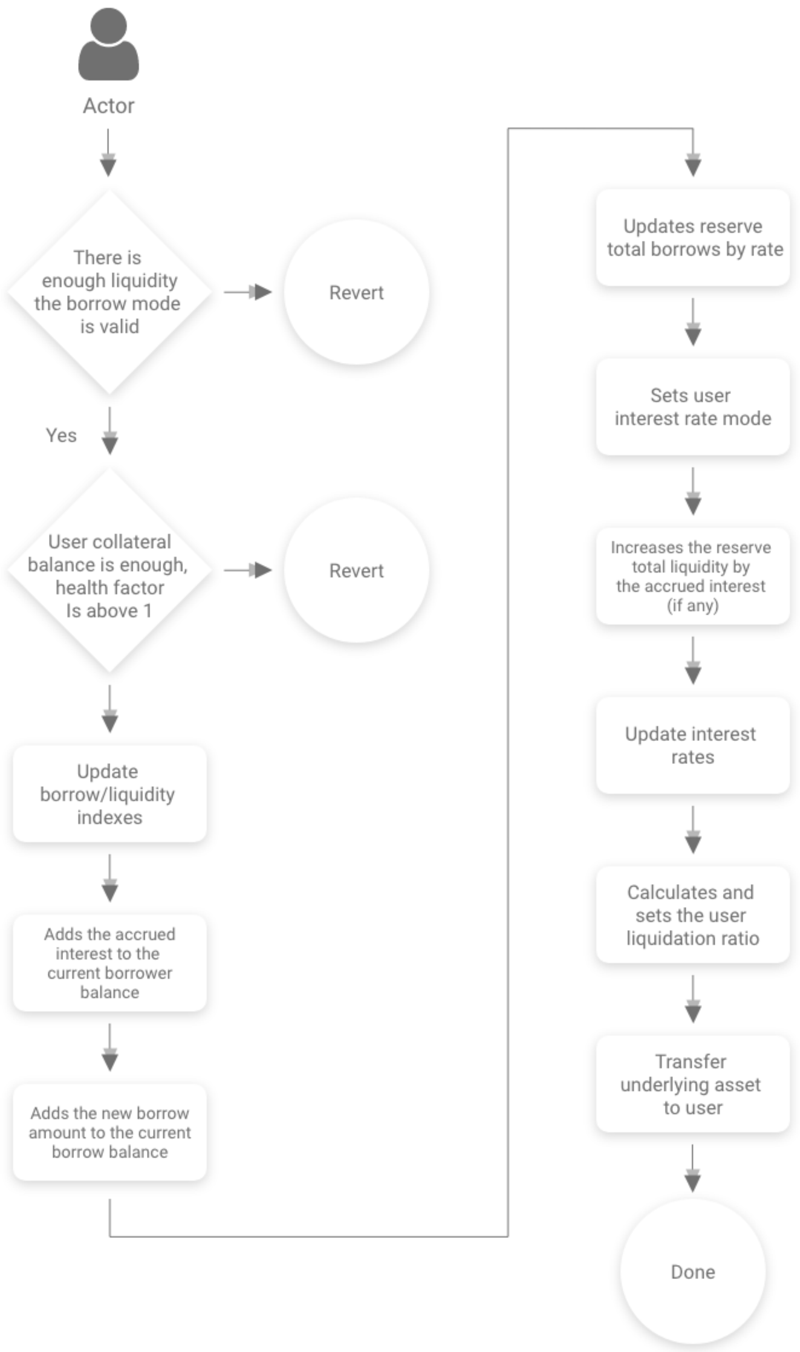

Actor
There is enough liquidity the borrow mode is valid
Revert
Yes
User collateral balance is enough, health factor Is above 1
Revert
Update borrow/liquidity indexes
Adds the accrued interest to the current borrower balance
Adds the new borrow amount to the current borrow balance
Updates reserve total borrows by rate
Sets user interest rate mode
Increases the reserve total liquidity by the accrued interest (if any)
Update interest rates
Calculates and sets the user liquidation ratio
Transfer underlying asset to user
Done

Figure 8: Borrow funds

3.4 Repay

The repay action allows the user to repay completely or partially the borrowed amount plus the origination fee and the accrued interest.

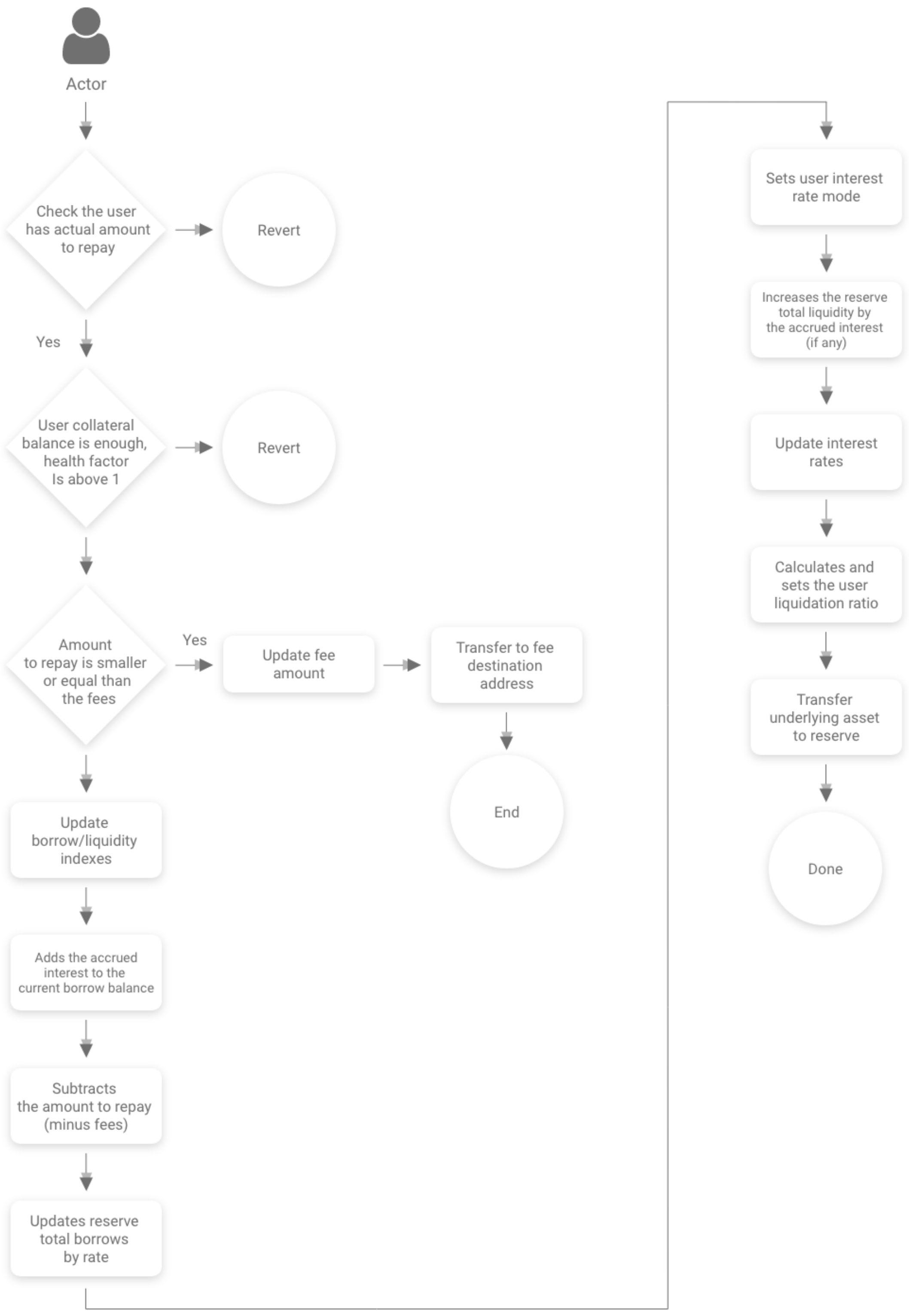
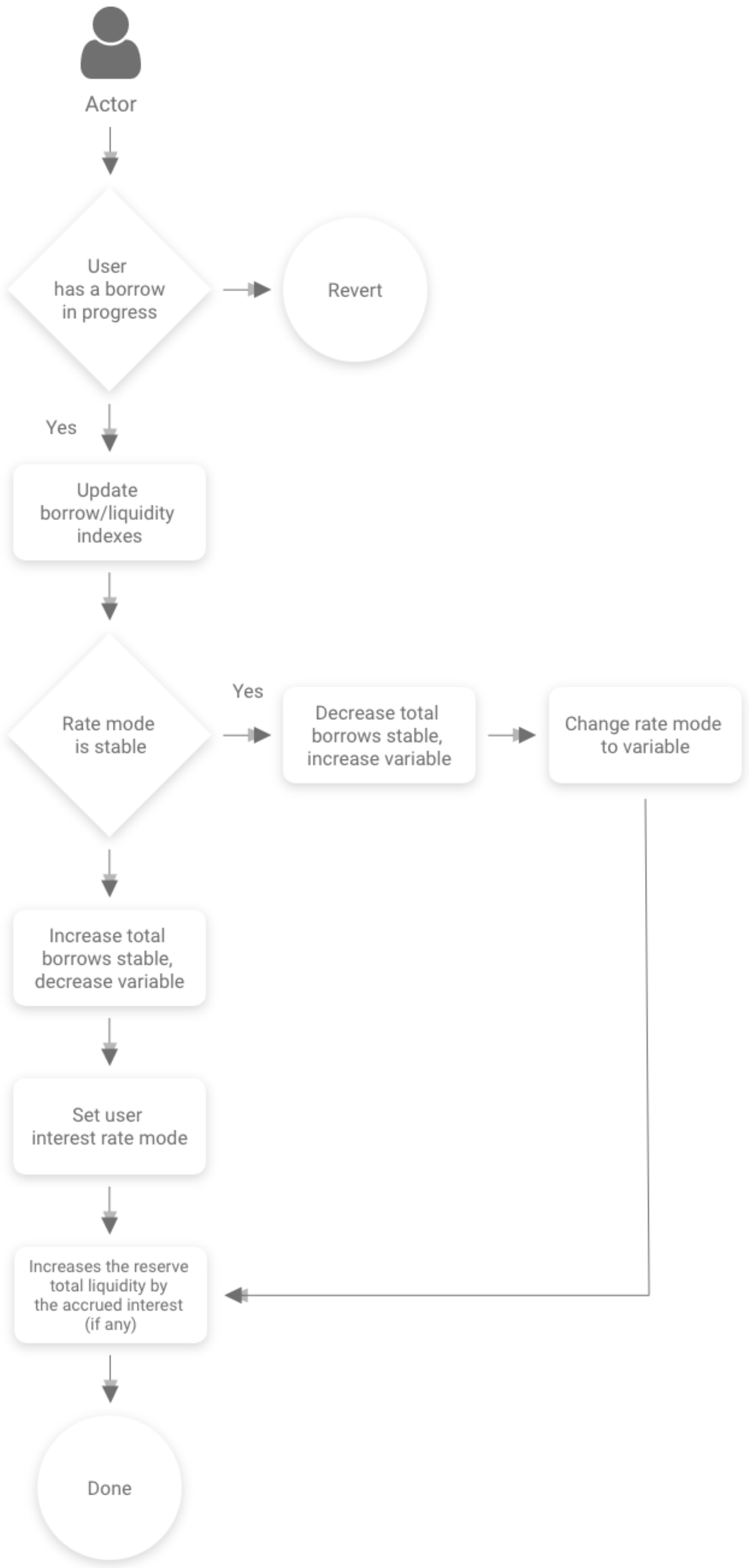

Actor
Check the user has actual amount to repay
Revert
Yes
User collateral balance is enough, health factor Is above 1
Revert
Amount to repay is smaller or equal than the fees
Yes
Update fee amount
Transfer to fee destination address
End
Update borrow/liquidity indexes
Adds the accrued interest to the current borrow balance
Subtracts the amount to repay (minus fees)
Updates reserve total borrows by rate
Sets user interest rate mode
Increases the reserve total liquidity by the accrued interest (if any)
Update interest rates
Calculates and sets the user liquidation ratio
Transfer underlying asset to reserve
Done

Figure 9: Repay a loan

3.5 Swap Rate

The swap rate action allows a user with a borrow in progress to swap between variable and stable borrow rate.

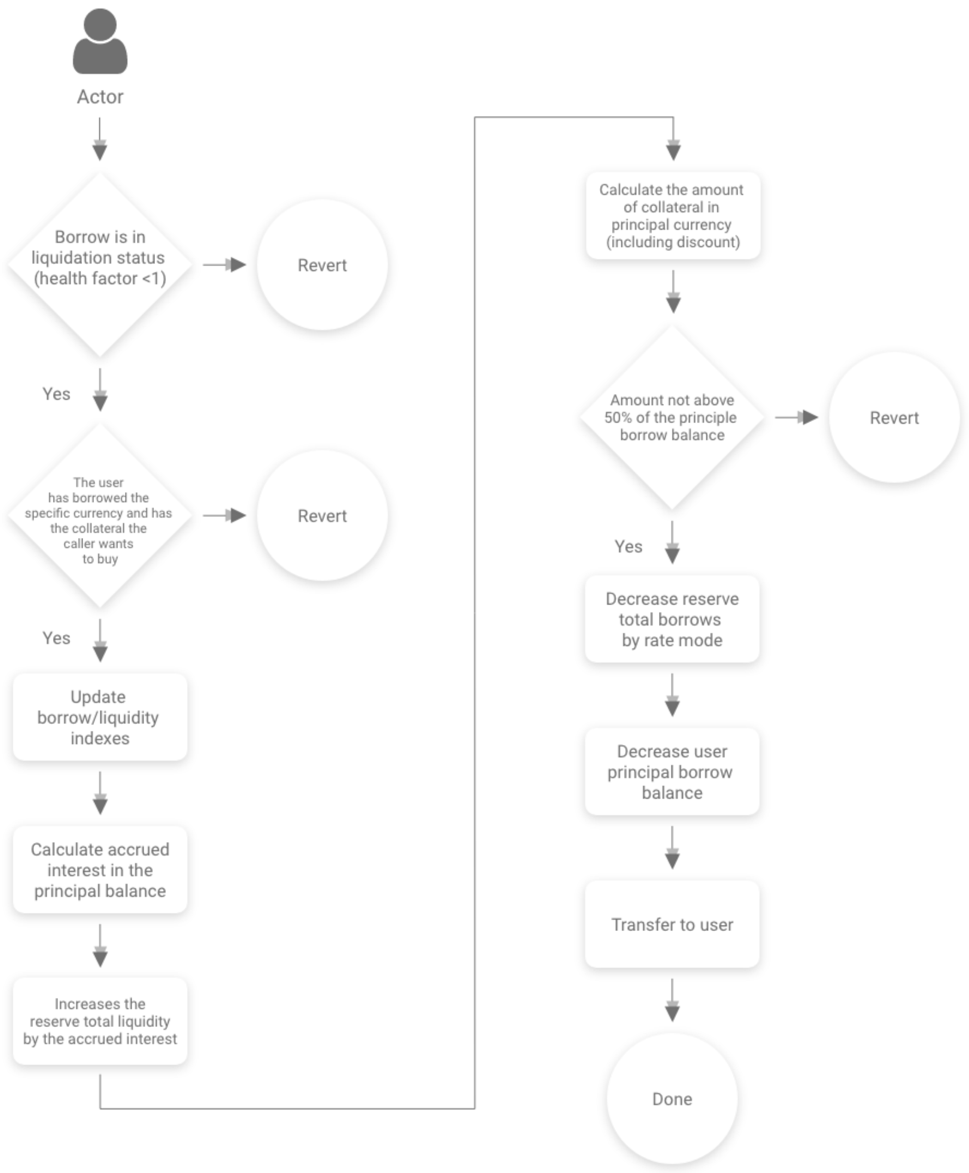


Actor
User has a borrow in progress
Revert
Yes
Update borrow/liquidity indexes
Rate mode is stable
Yes
Decrease total borrows stable, increase variable
Change rate mode to variable
Increase total borrows stable, decrease variable
Set user interest rate mode
Increases the reserve total liquidity by the accrued interest (if any)
Done

Figure 10: Swap Rate

3.6 Liquidation Call

The `liquidationcall` contract allows any external actor to purchase part of a collateral at a discounted price. In case of a liquidation event, a maximum of 50% of the loan can be liquidated, which will bring the health factor back above 1.



Actor
Borrow is in liquidation status (health factor <1)
Revert
Yes
The user has borrowed the specific currency and has the collateral the caller wants to buy
Revert
Yes
Update borrow/liquidity indexes
Calculate accrued interest in the principal balance
Increases the reserve total liquidity by the accrued interest
Calculate the amount of collateral in principal currency (including discount)
Amount not above 50% of the principle borrow balance
Revert
Yes
Decrease reserve total borrows by rate mode
Decrease user principal borrow balance
Transfer to user
Done

Figure 11: Liquidation

3.7 Flash Loans

The flash loan action will allow users to borrow from the reserves within a single transaction, as long as the user returns more liquidity that has been taken.

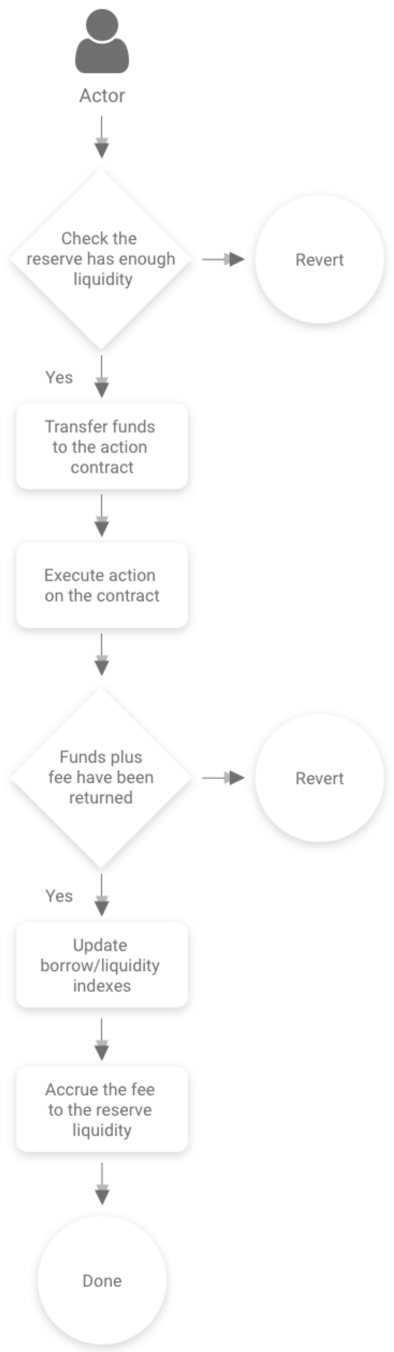

Actor
Check the reserve has enough liquidity
Revert
Yes
Transfer funds to the action contract
Execute action on the contract
Funds plus fee have been returned
Revert
Yes
Update borrow/liquidity indexes
Accrue the fee to the reserve liquidity
Done

Figure 12: Flash Loan

Flash loans temporarily transfer the funds to a smart contract that respects the `IFlashLoanEnabledContract.sol` interface. The address of the contract is a parameter of the action. After the funds are transferred, the method `executeAction()` is executed on the external contract. The contract can do whatever action is needed with the borrowed funds. After the method `executeAction()` is completed, a check is performed to verify that the funds plus fee have been returned to the `LendingPool` contract. The fee is then accrued to the reserve, and the state of the reserve is updated. If less funds than what was borrowed have been returned to the reserve, the transaction is reverted.

3.8 Tokenization

The `Lendingpool` contract generates an ERC20 on every deposit that maps the amount deposited by the users with a specified exchange rate. This exchange rate depends on the initial exchange rate E_i and the normalized income I_n:

$$Exchange\ rate = \frac{E_i}{I_n}$$

4 Stable Rate Theory

The following chapter explains how the stable rates are applied to the system and the limitations.

Implementation of a fixed rate model on top of a pool is complicated. Indeed, fixed rates are hard to handle algorithmically, as the cost of borrowing money varies with market conditions and the liquidity available. There might therefore be situations (sudden market changes, bank runs ...) in which handling stable rate borrow positions would need using specific heuristics based on time or economical constraints. Following this reasoning, we identified two possible ways of handling fixed rates:

1. **Imposing time constraints**: fixed rates might work perfectly fine in a time constrained fashion. If a loan has a stable duration, it should survive extreme market conditions, as the borrower must repay at the end of the loan period. Unfortunately, time constrained fixed rate loans aren't suitable for our specific use case of open ended loan. It would require a certain degree of UX friction where users would need to create and handle multiple loans with different times constraints.

2. **Imposing rates constraints**: An interest rate calculated at the beginning of a loan might be impacted by market conditions, keeping it from staying fixed. If the rate diverges too much from the market, it can be readjusted. This would not be a pure fixed rate, open term loan - as the rate might vary throughout the loan duration – yet users will experience actual fixed rates during specific time periods, or when there is enough liquidity available. This particular implementation has been chosen to be integrated into Aave's Protocol under the name **stable rate**.

4.1 Lending Rate Oracle

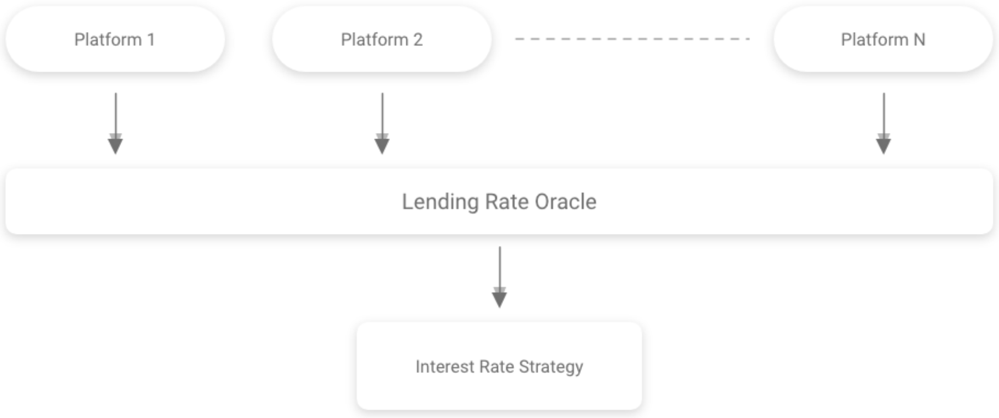


Figure 13: Lending Rate Oracle

The first component to be integrated into the Protocol protocol is a Lending Rate Oracle, which will provide information to the contracts on the actual market rates that other lending platforms, both centralized and decentralized, are providing. The average market lending rate M_r is defined for i platforms with P_r^i the lending rate and P_v^i the borrowing volume:

$$M_r = \frac{\sum_{i=1}^{n} P_r^i P_v^i}{\sum_{i=1}^{n} P_v^i}$$

The market rate will be updated daily, initially by Aave.

4.2 Current Stable Borrow Rate R_f

The current stable borrow rate is calculated as follows:

$$R_f^t = \begin{cases} M_r, \text{ if } U < U_Q \\ R_f^{t-1} + R_{rf}(U - T_r), \text{ if } U > U_Q \end{cases}$$

With:

- U_Q the utilization rate threshold at which the current stable rate B_f starts to rise. Set to $0.25 * 1 \times 10^{27}$, a utilization rate of 25%.
- R_{rf} the stable rate scaling ratio, a linear multiplier that increases the current stable rate as the utilization rate increases.

Note: R_f does NOT impact existing stable rates positions – this is calculated only for new opened positions.

4.3 Limitations on Stable Rate Positions

To avoid abuses on stable rate loans, the following limitations have been applied to the stable rate borrowing model:

1. Users cannot deposit as collateral more liquidity than what they are trying to borrow. Eg. a user deposits 10 Million DAI collateral, tries to borrow 1 Million DAI. This is to prevent the following attack vector:

   Given: $B_f = 18\%APR$, $M_r = 9\%APR$, R$_l = 12\%APR$

   Users might try to artificially lower B_f to the value of M_r by depositing a huge amount of liquidity which would cause B_f to drop, then borrow from the same liquidity at a lower rate, withdraw the liquidity previously deposited to cause B_f and the liquidity rate R_l to raise again; then finally deposit the amount borrowed to earn interest on the previously borrowed funds. Although this attack can still be carried out using multiple accounts, this particular constraint makes the attack more complicated as it requires more money (and a different collateral currency). This works well in combination with the interest rate rebalancing in the next section.

2. Borrowers will only be able to borrow up to T_r of the available liquidity at the current borrow rate. So, for every specific value of B_f, there is only up to T_r of liquidity available for a single borrower. This is to avoid that a specific borrower would borrow too much available liquidity at a too competitive rate.

4.4 Stable Rate Rebalancing

The last and perhaps most important constraint of the stable rate model is the rate rebalancing. This is to work around changes in market conditions or increased cost of money within the pool.
The stable rate rebalancing will happen in two specific situations:

1. **Rebalancing up**. The stable rate of a user x is rebalanced to the most recent value of B_f when a user could earn interest by borrowing:

   $$B_f^x < R_l \text{ with } B_f^x \text{ the fixed borrow rate of user } x$$

2. **Rebalancing down**. The stable rate of a user x is rebalanced to the most recent value of B_f, if:

   $$B_f^x > B_f(1 + \Delta_{Bf})$$

   with Δ_{Bf} a rate delta established by governance which defines the window above B_f to rebalance interest rates. If a user pays too much interest beyond that range, the rate is balanced down.

4.5 The Rebalancing Process

The `LendingPool` contract exposes a function `rebalanceFixedBorrowRate(address reserve, address_user)` which allows to rebalance the stable rate interest of a specific user. Anybody can call this function: however, there isn't any direct incentive for the caller to rebalance the rate of a specific user. For this reason, Aave will provide an agent that will periodically monitor all the stable rates positions and rebalance the ones that will be deemed necessary. The rebalance strategy will be decided offchain by the agent, this means that users that satisfy the rebalance conditions may not be rebalanced immediately. Since those conditions depend on the liquidity available and the state of market, there might be some transitory situations in which an immediate rebalance is not needed.

This does not add any element of centralization to the protocol. Even if the agent stops working, anybody can call the rebalance function of the `LendingPool` contract. Although there isn't any direct incentive in doing it ("why should I do it?") there is an indirect incentive for the ecosystem. In fact, even if the agent should cease to exist, depositors might still want to trigger a rebalance up of the lowest borrow rate positions, to increase the liquidity rate and/or force borrowers to close up their positions, increasing the available liquidity. In case of a rescale down, instead, borrowers have a direct incentive in performing a rebalance of their positions to lower the interest rate.

The following flowchart explains the sequence of actions of the function `rebalanceFixedBorrowRate()`. The compounded balance that is accumulated until the instant at which the rebalance happens, is not affected by the rebalance.

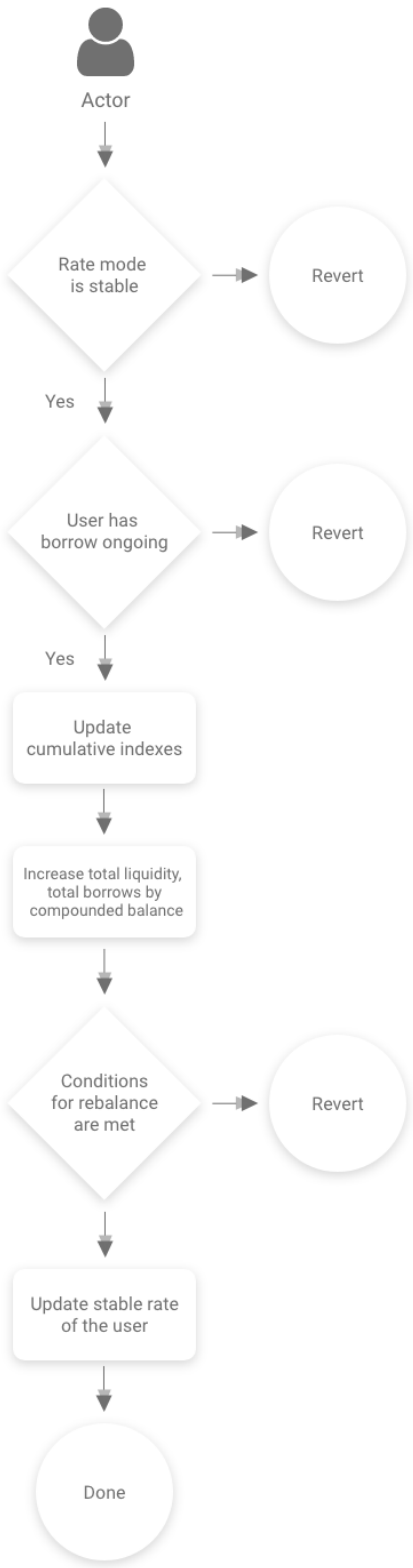

Actor
Rate mode is stable
Revert
Yes
User has borrow ongoing
Revert
Yes
Update cumulative indexes
Increase total liquidity, total borrows by compounded balance
Conditions for rebalance are met
Revert
Update stable rate of the user
Done

Figure 14: Rebalancing