The DeFi Dilemma

Aron Bodisz
University of Vienna & VGSF

Nikolaus Hautsch
University of Vienna

Stefan Voigt
University of Copenhagen

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The promises and the dilemma of Decentralized Finance

- Decentralized Finance (DeFi) relies on blockchain technology and inherits its key innovations:
  - A *decentralized network of validators* renders trusted intermediation obsolete
  - Transactions contain *smart contracts*, i.e., self-enforcing computer code that promises to overcome frictions, including those related to arbitrage (Gromb and Vayanos, 2010)

- For blockchains to function, (1) information distribution (*pre-trade transparency*) is essential for achieving consensus, and (2) compensation for validators (*transaction fees*) is necessary to incentivize the extension of the chain (Cong and He, 2019; Hinzen et al., 2022)

- (1) + (2) creates the possibility for *front-running transactions*

⇒ *Dilemma*: DeFi eliminates centralization, but with decentralization comes the excessive cost of front-running

A more efficient way of arbitrage?

- Decentralized exchanges (DEXs) serve as the backbone of DeFi (Harvey et al., 2021)
- Transaction fees render HFT market making on DEXs impractical ⇒ arbitrageurs update prices and ensure price informativeness (Park, 2023; Capponi and Jia, 2023)
- *Atomicity:* Blockchain transactions either execute or fail entirely
- **Promise:** Cross-DEX arbitrage utilizes smart-contracts ⇒ eliminates the costs associated with arbitrage (Gromb and Vayanos, 2010)
  - *No execution risk:* only executes if it is profitable
  - *No capital constraints:* capital is borrowed via a *flashloan*

Cross-DEX arbitrageurs remain idle in the presence of front-running risk

- Granular data on DEX liquidity provision and trading reveals
  - Front-running risk has a negative effect on price informativeness
    1) 90.8% of the documented price differences could have been eliminated
    2) Price differences across DEXs could have improved by $7-11\%$
  - Front-running risk has a negative effect on arbitrage activity
    3) Between $85-99\%$ of net arbitrage profit is forgone
    4) On average 64% of the gross profit goes to the validator
- To circumvent front-running risk, arbitrageurs rely on centralized intermediaries
  - *Dark pools:* In 2021 41% and in 2022 53% of the atomic arbitrage transactions were propagated to dark (or private) pools
  - *Statistical arbitrage:* The share of statistical arbitrage transactions increased significantly, rising from 23% in 2021 to 95% in 2022

What is the optimal way of performing cross-DEX arbitrage?

The decision problem of the cross-DEX arbitrageur

1) Calculates the maximal achievable gross arbitrage profit *given* the liquidity on the and trading fee on DEXs

2) Chooses a transaction fee that places the arbitrage transaction *in the front of the queue* in the next block *given* the fees of transactions pending in the mempool (validation demand)

$$\text{Net arbitrage profit} = \underbrace{\text{Gross arbitrage profit}}_{\substack{\text{1) Determined by} \\ \text{DEX states}}} - \underbrace{\text{Transaction fee}}_{\substack{\text{2) Determined by} \\ \text{validation demand}}}$$

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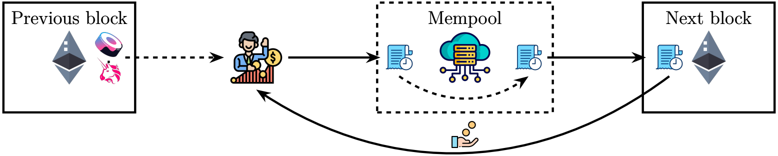
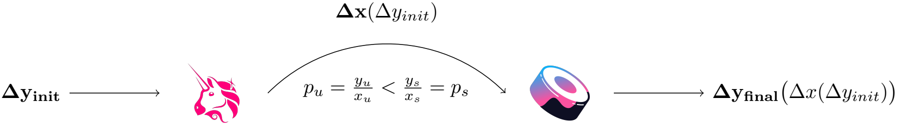


Maximal gross arbitrage profit and optimal transaction fee

- Two DEXs allow trading a blockchain-based asset X against a numéraire Y

- DEXs work as a *constant product market makers* (CPMMs) with certain liquidity and trading fees

1) *Maximal gross arbitrage profit*: $\Pi^* = \max_{\Delta y_{init}} \Delta y_{final}(\Delta y_{init}) - \Delta y_{init}$



$\mathbf{\Delta x}(\Delta y_{init})$

$\boldsymbol{\Delta}\mathbf{y_{init}} \longrightarrow$ $p_u = \frac{y_u}{x_u} < \frac{y_s}{x_s} = p_s$ $\longrightarrow \boldsymbol{\Delta}\mathbf{y_{final}}(\Delta x(\Delta y_{init}))$

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1) *Maximal gross arbitrage profit*: $\Pi^* = \max_{\Delta y_{init}} \Delta y_{final}(\Delta y_{init}) - \Delta y_{init}$

2) The *optimal transaction fee* is the *lowest fee that guarantees the execution* of the transaction given the level of validation demand

Is it optimal for the arbitrageur to submit the transaction?

Under front-running risk it's not

- Consider the possible two cases:

Bid the value of the arbitrage profit (scaring off front-runners) and earn 0 net profit (optimal strategy Easley and Tenorio (2004); Daniel and Hirshleifer (2018))

OR

Deviate and bid a lower transaction fee in hopes of a positive profit. If front-run, earn a 0 gross profit and pay a reversion fee $r > 0$, yielding a *loss*

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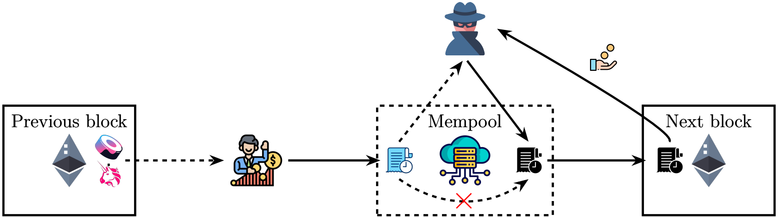
$\Rightarrow$ With front-running risk, cross-DEX arbitrageurs earn non-positive expected profit



Granular dataset on DEXs and transaction fees

- Data on DEXs from Dune Analytics covers the period from December 7, 2020, to August 31, 2022
  - DEXs that use (1) CPMMs and (2) account for $80 - 85\%$ of the trading volume on the Ethereum blockchain at the beginning of the sample period: *Uniswap V2, Sushiswap, and Shibaswap*
  - Arbitrage across the economically most significant pools that trade the token pairs: *WETH-USDC, WETH-USDT, WETH-DAI, and WETH-WBTC*

- Transaction fee is chosen based on where it would place the transaction in the queue of the next block: 1*st*, $\leq$ 10th or the $\leq$ 25th *in the queue*

Arbitrageurs could close price differences by ≈ 10%

Pool pair	Average price improvement (%)	Average arbitrageur's share from price improvement (transaction placed < 25th in the queue) (%)	Average arbitrageur's share from price improvement (transaction placed 1st in the queue) (%)	Share of blocks with positive effective price differences (%)
Uniswap v2-Sushiswap WETH-USDT	7.77	2.37	1.43	0.34
Uniswap v2-Shibaswap WETH-USDT	10.09	0.26	0.07	2.58
Sushiswap-Shibaswap WETH-USDT	10.98	0.42	0.14	3.61
Uniswap v2-Sushiswap WETH-WBTC	7.88	2.60	1.57	0.39
Uniswap v2-Shibaswap WETH-WBTC	9.87	0.73	0.24	1.58
Sushiswap-Shibaswap WETH-WBTC	10.44	0.98	0.37	1.60
Uniswap v2-Sushiswap WETH-USDC	8.28	3.45	2.24	0.24
Uniswap v2-Shibaswap WETH-USDC	10.48	0.24	0.07	2.42
Sushiswap-Shibaswap WETH-USDC	10.94	0.34	0.09	3.14
Uniswap v2-Sushiswap WETH-DAI	9.35	2.49	1.36	0.71
Uniswap v2-Shibaswap WETH-DAI	10.40	0.63	0.19	3.25
Sushiswap-Shibaswap WETH-DAI	9.92	0.72	0.26	3.81

Identifying arbitrage transactions

- We use the granular Flashbots MEV dataset to identify executed cross-DEX arbitrage transactions

- Amongst others, the dataset includes the
  - gross arbitrage profits
  - transaction fees/and direct payments (for dark pool transactions) to the validators

- We merge the identified hashes on DEX trading data and filter for atomic arbitrage transactions that have only two legs

85% to 99% of arbitrage opportunities are *not* exploited

Pool pair	Actual arbitrage (mUSD)		Hypothetical arbitrage (mUSD)	
	Cumulative net profit from actual arbitrage transactions	Cumulative payments to validators	Cumulative net profit from hypothetical arbitrage transactions (transaction placed < 25th in the queue)	Cumulative net profit from hypothetical arbitrage transactions (transaction placed 1st in the queue)
Uniswap v2-Sushiswap WETH-USDT	0.072	0.112	1.262	1.160
Uniswap v2-Shibaswap WETH-USDT	0.005	0.004	0.082	0.062
Sushiswap-Shibaswap WETH-USDT	0.007	0.006	0.136	0.112
Uniswap v2-Sushiswap WETH-WBTC	0.002	0.006	0.701	0.682
Uniswap v2-Shibaswap WETH-WBTC	0.001	<0.001	0.042	0.037
Sushiswap-Shibaswap WETH-WBTC	<0.001	<0.001	0.011	0.007
Uniswap v2-Sushiswap WETH-USDC	0.041	0.110	1.343	1.239
Uniswap v2-Shibaswap WETH-USDC	0.001	0.003	0.107	0.085
Uniswap v2-Shibaswap WETH-USDC	0.004	0.003	0.113	0.093
Uniswap v2-Sushiswap WETH-DAI	0.059	0.111	0.723	0.638
Uniswap v2-Shibaswap WETH-DAI	0.004	0.002	0.067	0.053
Sushiswap-Shibaswap WETH-DAI	0.008	0.003	0.078	0.055

85% to 99% of arbitrage opportunities are *not* exploited

Pool pair	Actual arbitrage (mUSD)		Hypothetical arbitrage (mUSD)	
	Cumulative net profit from actual arbitrage transactions	Cumulative payments to validators	Cumulative net profit from hypothetical arbitrage transactions (transaction placed $<$ 25th in the queue)	Cumulative net profit from hypothetical arbitrage transactions (transaction placed 1st in the queue)
Uniswap v2-Sushiswap WETH-USDT	0.072	0.112	1.262 (94%)	1.160 (94%)
Uniswap v2-Shibaswap WETH-USDT	0.005	0.004	0.082 (94%)	0.062 (92%)
Sushiswap-Shibaswap WETH-USDT	0.007	0.006	0.136 (95%)	0.112 (94%)
Uniswap v2-Sushiswap WETH-WBTC	0.002	0.006	0.701 (99%)	0.682 (99%)
Uniswap v2-Shibaswap WETH-WBTC	0.001	$<$0.001	0.042 (98%)	0.037 (98%)
Sushiswap-Shibaswap WETH-WBTC	$<$0.001	$<$0.001	0.011 (99%)	0.007 (98%)
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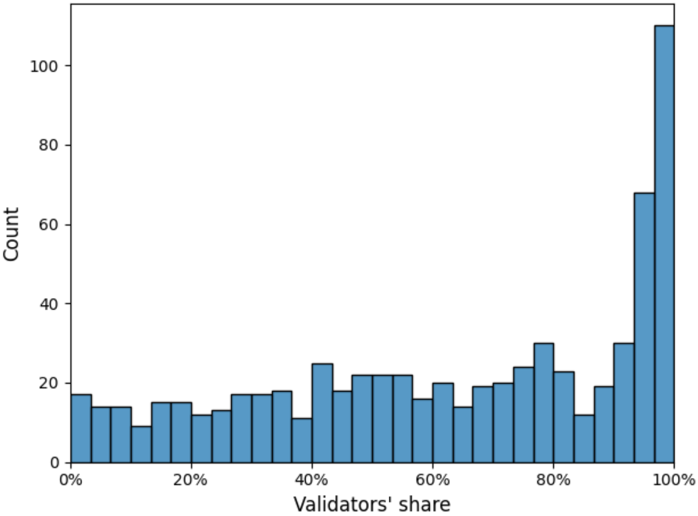
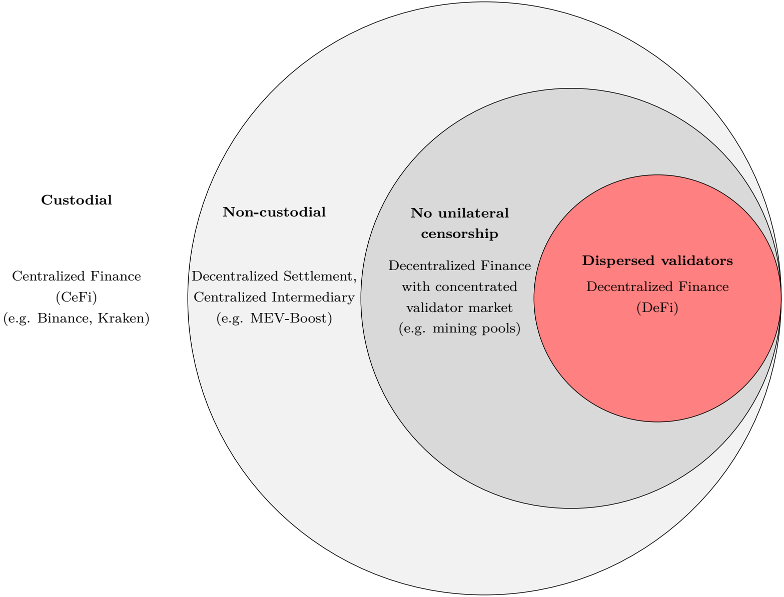
Sushiswap-Shibaswap WETH-DAI	0.008	0.003	0.078 (90%)	0.055 (85%)

Validators claim on average 64% of the arbitrage profits



Do markets come to a halt?

A definition for DeFi (following Qin et al. (2021))



Custodial

Centralized Finance
(CeFi)
(e.g. Binance, Kraken)

Non-custodial

Decentralized Settlement,
Centralized Intermediary
(e.g. MEV-Boost)

No unilateral censorship

Decentralized Finance
with concentrated
validator market
(e.g. mining pools)

Dispersed validators

Decentralized Finance
(DeFi)

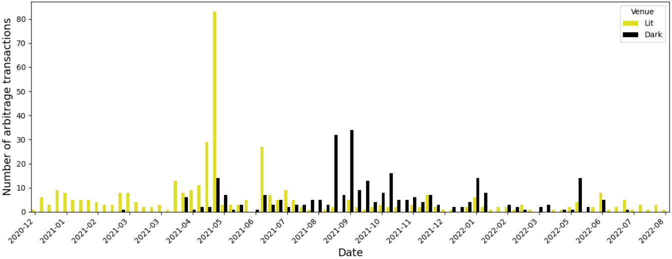
Not, if unilateral censorship is allowed

- Submitting arbitrage transactions through private pools (e.g. MEV-Boost, Flashbots Relay) ⇒ DeFi settlement, but transactions are received and handled by a centralized intermediary

- *No pre-trade transparency* (excl. validator) and *no reversion fee*

- Private pool transaction data from the largest providers (Flahbots, Eden Network)

- Validators demand an even higher share of the rent: 65% ↗ 75%



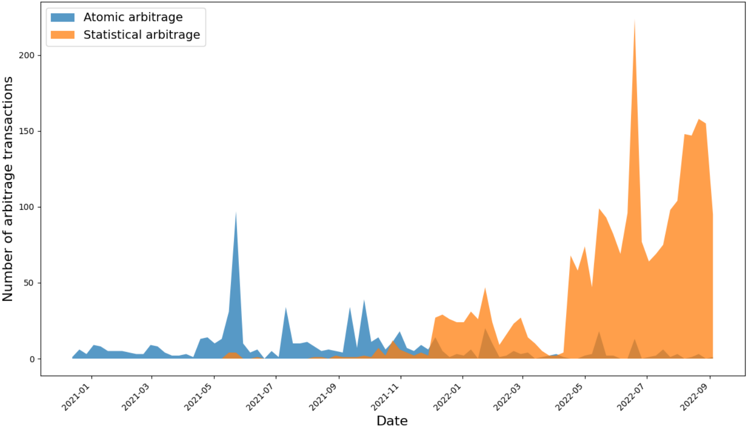
Not, if a custodian controls the assets

- Performing statistical arbitrage between DEX and CEX instead of atomic arbitrage ⇒ Interaction with a custodial centralized intermediary

⇒ Reintroduction of arbitrage costs (Gromb and Vayanos, 2010)
  - The arbitrage transaction is *not* atomic ⇒ execution risk
  - Flashloans cannot be leveraged ⇒ capital constraints

- Using heuristics similar to Heimbach et al. (2024) we find several potential ”legs” of statistical arbitrages

Arbitrageurs turn towards statistical arbitrage



Conclusions

- DeFi relies on blockchain-based settlement, which requires pre-trade transparency and transaction fees, leading to front-running
- We empirically investigate the effects of front-running risk on cross-DEX arbitrage
    - We demonstrate that arbitrage profits are left on the table, and price informativeness across DEXs could be improved
    - To circumvent front-running risk, arbitrageurs interact with centralized intermediaries (dark pools, CEXs)
- *Front-running risk is a major friction* in DeFi that renders arbitrage unprofitable, thereby creating a dilemma
- The only way to overcome this dilemma is to undermine the DeFi ideal by *reintroducing centralization*

References

Capponi, A. and Jia, R. (2023). Liquidity provision on blockchain-based decentralized exchanges. Available at SSRN: `https://ssrn.com/abstract=3805095`.

Cong, L. W. and He, Z. (2019). Blockchain Disruption and Smart Contracts. *Review of Financial Studies*, 32(5):1754–1797.

Daniel, K. D. and Hirshleifer, D. (2018). A theory of costly sequential bidding. *Review of Finance*, 22(5):1631–1665.

Easley, R. F. and Tenorio, R. (2004). Jump bidding strategies in internet auctions. *Management Science*, 50(10):1407–1419.

Gromb, D. and Vayanos, D. (2010). Limits of Arbitrage. *Annual Reviews of Financial Economics*, 2(1):251–275.

Harvey, C. R., Ramachandran, A., and Santoro, J. (2021). *DeFi and the Future of Finance*. John Wiley & Sons.

Heimbach, L., Pahari, V., and Schertenleib, E. (2024). Non-atomic arbitrage in decentralized finance.

Hinzen, F. J., John, K., and Saleh, F. (2022). Bitcoin's Limited Adoption Problem. *Journal of Financial Economics*, 144(2):347–369.

Park, A. (2023). Conceptual Flaws of Decentralized Automated Market

Appendix: Hypothetical transaction fees