Threshold Encrypted Mempools: Limitations and Considerations

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Abstract. Encrypted mempools are a class of solutions aimed at preventing or reducing negative externalities of MEV extraction using cryptographic privacy. Mempool encryption aims to hide information related to pending transactions until a block including the transactions is committed, targeting the prevention of frontrunning and similar behaviour. Among the various methods of encryption, threshold schemes are particularly interesting for the design of MEV mitigation mechanisms, as their distributed nature and minimal hardware requirements harmonize with a broader goal of decentralization.

This work looks beyond the formal and technical cryptographic aspects of threshold encryption schemes to focus on the market and incentive implications of implementing encrypted mempools as MEV mitigation techniques. In particular, this paper argues that the deployment of such protocols without proper consideration and understanding of market impact invites several undesired outcomes, with the ultimate goal of stimulating further analysis of this class of solutions outside of pure cryptograhic considerations. Included in the paper is an overview of a series of problems, various candidate solutions in the form of mempool encryption techniques with a focus on threshold encryption, potential drawbacks to these solutions, and Osmosis as a case study. The paper targets a broad audience and remains agnostic to blockchain design where possible while drawing from mostly financial examples.

Keywords: MEV, threshold encryption, privacy, market structure, blockchain, markets, mempool, DeFi

1 Introduction

Blockchain networks seek to offer users access to mechanisms for coordination, such as ledgers [Nak09,BCG⁺14] or exchanges [AZS⁺], without requiring users to rely on centralized intermediaries. A deeply related concept, Maximal Extractable Value (MEV) refers to the total amount by which a validator or miner on a blockchain is able to profit from controlling ordering and inclusion of transactions in a block [BDKJ21] and can be seen as a loose measure of the remaining influence of intermediaries which these networks seek to eliminate.

Many current blockchain implementations make use of protocols in which elected block producing nodes are given large degrees of freedom in determining the contents of blocks. The difference between roles in a blockchain (e.g. users, validating nodes and block-producing nodes) creates an asymmetry in information flow. The combination of discretion over transaction execution, asymmetric access to information and the prevalence of financial Decentralized Applications (DApps) on smart-contract chains like Ethereum $[W^+]$ is the core of the recipe for the majority of observed MEV¹.

More concretely, miners (henceforth referred to as 'block producers' to include validators who perform the same role on proof-of-stake networks) are responsible for validating and processing transactions by including them in new blocks. This process generally entails block producers having full visibility of transactions pending inclusion. Consequently, block producers are known to 'front-run' users [KDC23] by observing pending trades, creating transactions based on this information and then prioritizing these over users' pending transactions. Although block production is generally

¹ Despite the fact that theoretically any agent can become a validator/block proposer, this is not necessarily the case in practice. The notion of '1 CPU = 1 vote' was not materialized in Bitcoin and other Proof of Work (PoW) chains as originally envisioned. This is evidenced by the concentration of mining activities in large miners and mining pools. Likewise, Proof of Stake (PoS) chains generally require validators to lock up significant capital (e.g., 32 ETH on Ethereum, which represents approx. \$ 60,000 as of 23/04/2023 to disincentivize malicious behavior. Attached to financial barriers, a high level of technical knowledge is required to operate the necessary software. So, today, widely used PoW and PoS chains have a high barrier of entry for validators, which means that these roles are filled by individuals or institutions with easy access to capital and infrastructure expertise (e.g., market makers, trading firms, etc.)

² Note that the model of block producers extracting MEV is a simplification from reality in which components of the block production process are often outsourced in schemes such as proposer-builder separation. This simplification generally does not impact the analysis provided and is made explicit when relevant.

directly incentivized by the network, MEV in various forms such as frontrunning or privileged access to arbitrage represents a relatively large income stream for block producers [Fla23], often at the expense of users.

This skewed distribution of power, has prompted concern over notions of fairness and economic efficiency in blockchains. Additionally, there is significant concern that unpredictable rewards may impact the consensus rules necessary for the functioning of the chain, such as time-bandit attacks identified in [DGK⁺19]. These concerns have been heightened by increasing adoption and growing numbers of decentralized applications deployed on blockchain networks, especially financial applications such as Decentralized Exchanges (DEX's) [Blo], e.g., Uniswap [AZS⁺].

Despite broad concern over the externalities of MEV-related behavior, there is little consensus on the appropriate methods for addressing the problem. While blockchain activity may be audited by studying a public record of transaction history, current blockchain designs, pseudonymous accounts and uncertain network conditions generally offer block producers plausible deniability with regard to MEV activity.

Additionally, the behavior which allows for extraction of MEV depends on broader context such as the chain rules, DApps in use, and external market conditions. For example, lending protocols offer different forms of revenue [QZG⁺21] than decentralized exchanges [KDC23]. That said, a broad class of behaviors associated with MEV depends on the block proposer reacting to information regarding transactions pending inclusion.

Thus, a blockchain designer may seek to address these issues through cryptographic privacy. Although there are several means of achieving pre-settlement privacy, this paper looks in particular at the use of threshold encryption, which allows for encrypted transactions that can only be decrypted by a threshold of actors in a decryption committee. As many blockchains already make security assumptions that rely on the honest participation of a set of participants, threshold encryption and its security assumptions are seen to harmonize well with existing protocols. This has led to several system designs looking to implement threshold encryption schemes for mempool privacy [Ano23,Pro23b,Shu21,Sik19,ACG+18b]. However, as block production is a key component in blockchains and impacts not only the functioning of the underlying protocol, but also the manner in which the blockchain is used, further analysis is required. A start to this analysis is presented in this paper.

A class of users which clearly highlights the impact of changes to the protocol and the need for their thorough consideration are sophisticated traders. Since many of the most popular uses of blockchains today are financial in nature, these actors can inevitably be counted among participants. What is most interesting about sophisticated trading teams is their sensitivity to information and the lengths to which they will go to attain this information. In the recent past, some firms have paid to acquire satellite images of Walmart parking lots in order to count parked cars [HB22] while hundreds of millions of dollars were spent laying a cable between New York and Chicago for a 3ms reduction in roundtrip time between exchanges [BCS15]. In the blockchain sphere, there have been many instances in which competitive dynamics around order inclusion and access to information, broadly classed as MEV, have forced emergency updates to client software [Fou21,McK22,O'G21].

If such small advantages in access to information or ability to execute transactions can lead to such large investments or drastic measures, it is imperative to analyze pedantically the impact of changes in the informational and power structures in blockchains.

1.1 Contributions

The aim of this study is to stimulate further analysis of encrypted mempools, with an emphasis on the alterations different encryption schemes provoke in key informational and incentive structures in financial markets. The paper consists of an overview of problems which encrypted mempools may be used to address, an overview of encrypted mempools in different varieties with a focus on threshold encrypted mempools, and an overview of drawbacks and topics for further consideration. We additionally provide examples (mostly financial) highlighting some undesired or unexpected effects of encrypting mempools. These examples will serve as 'existence proof' that a nuanced discussion is necessary. With this research, we aspire to encourage the cryptography and finance communities to collaborate on discussions that encompass both cryptographic and market structure considerations.

Importantly, the paper does not seek to establish an optimal design as a notion of optimality can only be established relative to specific desiderata which vary depending on intended use-cases for blockchains, while many critiques outlined in this paper are broadly relevant.

1.2 Required Background

This paper seeks to make arguments that are generally applicable and seeks to remain agnostic to consensus protocols and DApps, except for the last section, which focuses specifically on Osmosis. However, arguing in generality is not always possible. Unless otherwise specified, blockchains being referred to are assumed to run in discrete time (i.e., block-based), use leader-based consensus and support general smart contracts. If necessary, Osmosis [KB23,Osm22] should serve as the canonical example. That said, designs that do not conform to this specification are not necessarily immune to the problems discussed in this paper.

Moreover, to ensure this research remains approachable for diverse audiences, we will refrain from using cryptographic formalism and financial jargon and only assume some familiarity with blockchain concepts such as smart contracts, mempools and automated market makers. Given the context-dependent nature of MEV, we invite the community to refine this study to their specific domain of interest.

1.3 Definitions

We now introduce some key terms that are used throughout this paper.

1.3.1 Settlement

Discourse in traditional finance often makes use of the concepts 'settlement' or 'settlement finality'.

Definition 1. "Settlement finality is a statutory, regulatory, and contractual construct which, generally, refers to the moment in time when one party is deemed to have discharged an obligation or to have transferred an asset or financial instrument to another party, and such discharge or transfer becomes unconditional and irrevocable despite the insolvency or entrance into bankruptcy of either party" [Lia17][fIS, Principle 8: Settlement finality].

Mapping settlement finality and other concepts from traditional finance to the blockchain sphere is a topic worth several papers and requires nuanced discussions about hard forks, technical and social consensus, and cryptographic signatures³.

When trading on blockchain protocols, e.g. Automated Market Makers (AMMs) [BCL21], "(blockchain) settlement is execution". In fact, on AMMs, the line between trade execution (i.e., the sequence of steps necessary to fulfil an order to buy or sell assets) and settlement can be blurred. Whether or not 'execution' and 'settlement' can clearly be differentiated in the trade lifecycle, depends on the specifics of the consensus algorithm. One may see trade execution as part of the block creation (i.e., a trade is executed when the pending transaction – 'trade order' – is included in the block), and trade settlement as the action to add the block containing the trade to the blockchain (i.e., a trade is settled when the block is added to the chain, and it is deemed infeasible to re-organize the chain of blocks). That being said, if a block doesn't get added to the chain, the trades it contains won't mutate the global state of the chain and will have to be re-executed against a newer version of the global state at a later stage as part of the creation of another block. Ultimately, the specifics of the blockchain determine the trade lifecycle, which dictates what type of manipulation can be carried out on the blockchain. For instance, if a blockchain is used as both a trade execution and settlement venue, manipulating the order of the flow of transactions to be included on the blockchain will lead to different trade execution flows, allowing, e.g., trade frontrunning. However, if the blockchain is only used as a settlement solution, e.g., [Wat19] with execution happening on an offchain venue like

This paper will brush over this nuance and use the term settlement loosely to refer to the point at which transactions are included in a valid block by a block producer and propagated to the network, ignoring the possibility of forks. In practice, different blockchains use different consensus algorithms, which means that different chains have different 'blockchain settlement finality'.

1.3.2 Efficiency

The notion of efficiency is broad, differs across contexts, and may be relative. As such, it is important to elucidate the meaning of 'efficiency' in the specific context of interest. To that end, we differentiate between 'technical efficiency' and 'economic efficiency', both of them denoting broad classes of 'efficiency' definitions.

'Technical efficiency' is used to encompass bandwidth complexity (i.e., number of bits exchanged on the network as part of a protocol execution), computational/algorithmic efficiency (i.e., amount of computational resources used by an algorithm) and other metrics associated with an underlying blockchain protocol.

'Economic efficiency' is used to refer to 'informational efficiency' [Nas], (i.e., the fact that security prices fully reflect all available information, which correlates with price discovery) or user welfare in equilibrium relative to the highest possible welfare outcome. The difference should be clear from context.

We defer the broader discussion on blockchain efficiency to Appendix A. For the purpose of this work, we highlight that both technical and economic efficiency are related. The better an information system performs, the more information it can process, and the closer assets can align with their 'true/information efficient' value. Similarly, socialized running costs, delays, and uncertainty arising from delays in using a system, negatively impact user welfare.

2 The Problem: Negative Externalities of MEV

Having introduced the notion of MEV broadly in the introduction, we now turn to a more detailed look at issues which blockchain designers may seek to address with encrypted mempools. The paper remains agnostic as to the severity or problematic nature of the issues listed, and seeks simply to illuminate some outcomes an opinionated blockchain designer or community may wish to eliminate.

Information Asymmetries As with traditional finance, every financial transaction in blockchain discloses information to the other participants in the market (Fig. 1). Importantly, the order in which trade information becomes available doesn't necessarily coincide with the sequence of trade executions, separating traditional and current blockchain systems. That is, information about a trader's transaction often becomes available to other market participants who are able to take action that changes the outcome of the original transaction as it has yet to settle. These conditions often disadvantage the original trader through added competition for arbitrage opportunities or adverse price movements [DGK⁺19].

It is useful to separate two dynamics which lead to such conditions. *Public mempools* mean that pending transactions are visible to any party participating as a node on the blockchain, while the *privileged role* of block producers may require that any transaction which is to be included in a block is known to the block producer before a commitment to the content of a block is made. The two dynamics are not mutually exclusive, but do require different considerations, as detailed below.

a CLOB [Wik23a], then the manipulation of blockchain transaction comes with different consequences. E.g., value might still be extracted by delaying settlement, i.e., delaying the inclusion of information on-chain, which may condition successful future state transitions on-chain for instance. In this case, delaying the exchange of securities/the discharge of 'on-chain obligations' can prevent (or delay) future trades from happening, which itself can be seen as a form of 'forward' manipulation of trade flows.

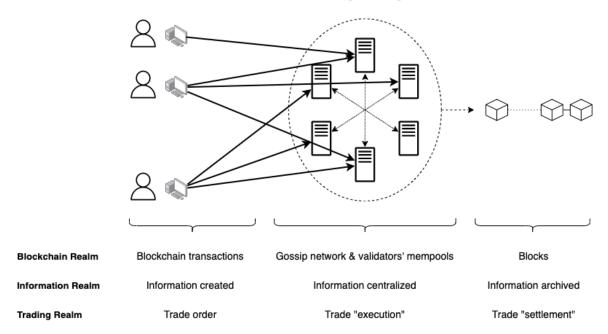


Fig. 1. A look at blockchain systems through different lenses

2.1 Fairness

A commonly cited goal of blockchain designers is fairness or neutrality. Aside from ideological orientation, blockchain designers have incentive to focus on perceptions of fairness, as users who view a system as unfair are likely to leave the system [LDG19]. Fairness is also a widely discussed in traditional financial markets [Liz,Pis] in which protections of unsophisticated 'retail' actors is often the stated goal.

Blockchain markets, however, differ from traditional markets both technically and in the various relationships and roles that comprise the system⁴. Notions of fairness also vary significantly across different contexts and stakeholders. Hence, some blockchain-specific definitions of fairness are necessary and have been proposed.

For example, Kelkar et al. [KZGJ20] introduce a definition of *receive-order fairness* which, informally paraphrased, states that if a sufficient fraction of nodes receive transaction x before transaction y, transaction x must be executed first. Another notion of fairness, *blind-order fairness*, is defined in [MS22] and informally describes situations in which the ordering of transactions is determined by a party that does not know the content of the transactions at the time of ordering.

While there is room to dispute individual notions of fairness — receive-order fairness favors agents with low-latency infrastructure and has been criticized as economically inefficient [AD23], and blind-order fairness favors users whose transactions are not sensitive to ordering and is subject to similar critiques on efficiency —, this paper does not take a normative stance and leaves selection of such criteria up to blockchain designers and communities.

The key point, is that many notions of fairness conflict with the power asymmetries embedded in the block producer role. As is discussed in Section 3, encrypted mempools can be a means of addressing these asymmetries and approximating properties such as blind-order fairness.

2.2 Externalities of Strategic Usage

Current blockchain implementations are resource constrained. As observed in [DGK⁺19], public mempools can lead to dynamics such as Priority Gas Auctions (PGAs) in which users pursuing

⁴ The lack of contractual obligation or promise of service delivery between blockchain users and validators differentiates blockchain from traditional financial settings in which activities like frontrunning are considered a violation of duty to *customers* [AM13].

the same profitable opportunity on the blockchain will strategically deviate from expected usage and rapidly update pending transactions in an attempt to outbid competition pursuing the same opportunity. As soon as one transaction and its corresponding payment to the block producer becomes public, competitors are able to submit competing transactions, often with payments incremented by the minimum amount. PGAs and similar dynamics⁵ can be costly for the network, congesting gossip layers and escalating fees as transaction-load increases.

2.3 Distortion of Protocol Incentives

Blockchain protocols incentivize behavior of stakeholders in the network through the use of varying incentive structures. The powerful and potentially highly profitable [Fla23] position in which block producers can find themselves forms part of this equation. Anticipation of additional profits from trading activity can have effects such as bringing in additional stake to a proof of stake network, increasing network security. These effects may be deemed especially desirable when variance in staking rewards correlates with other market factors that could otherwise reduce staking capital [Chi20]. At the same time, incentive structures could be skewed in undesirable ways such as concentrating rewards among a subset of block producers who are sophisticated traders — creating centralizing forces in the network, especially through mechanisms like staking pools — or incentivizing consensus-based misbehavior such as time-bandit attacks [DGK+19].

2.4 Censorship

As part of a goal of neutrality, guarantees against censorship are widely considered desirable. In other words, as long as a transaction is considered valid, is received by the block producer, and the network has capacity, a transaction should be included. Different exact definitions stipulate different time-related conditions for such properties.

If a block producer is able to identify essential information about transactions and has control over transaction inclusion, it can be trivial to selective deny execution of transactions for the period during which the block producer is elected. This may be politically motivated [WEY⁺23]. For example, the block producer resides in a country which has banned facilitation of transactions from a certain address or interacting with a certain contract. Censorship may also be economically motivated, either through bribery [PRF23] or to prevent activities such as price updates or posting of margin in order to take advantage of outdated prices or liquidations [QZG⁺21] in the future.

3 Encrypted Mempools

Using cryptography to carry out financial operation is not a new idea [CFN88,Ass,Syv,Wika,DC02]. Current blockchain designs draw heavily from a body of research in the field of digital cash, which sits at the intersection of different disciplines such as cryptography and consensus algorithms.

The main cryptographic primitives used in the design of blockchain systems are hash functions (integrity) and digital signature schemes (authentication). When it comes to mitigating the forms of MEV described in this paper, it seems natural to turn to our cryptographic arsenal to look for primitives to limit disclosure of information about pending transactions to block producers (or other network participants).

Encryption as a means to preventing unwanted disclosure of transaction data on blockchain systems has already been employed in Zcash [HBHW22,BCG+14] and other privacy-preserving

⁵ We note that the delay between sending orders and their execution can also be leveraged by traders to carry out 'spoofing' and mislead other market participants with false trading intentions. This practice is generally illegal in regulated markets, see [Wik23b] for more information.

protocols [RZ19,BAZB20,Wil18]. However, designing a privacy-preserving blockchain protocol is a different endeavor from mitigation of the information asymmetries in MEV. In the former, the goal is generally to keep the data secret to all parties that aren't involved in the transaction, unconditionally and forever. In the latter, the goal is to keep the transaction data secret until settlement, but not necessarily any longer than that. This is generally referred to as *mempool privacy*.

3.1 Mempool Privacy

Introducing a rigorous definition of privacy would require mathematical formalism. Fortunately, the ends of this paper can be served by a looser definition.

Definition 2. Informally, a blockchain design provides more mempool privacy than another design when it affords users greater ability to withhold information from block producers when submitting transactions.

Whereas blind-order fairness (defined in Section 2.1) specifically targets a state in which the block producer knows absolutely nothing about the content of transactions except for their validity and prior beliefs over the distribution of possible transactions, achieving mempool privacy can be seen as a broader goal of improving information asymmetries. In this conceptualization, adjusting a protocol to be blind-order fair would improve its mempool privacy. This broader definition, if used as full blind-order fairness, may not be feasible or desirable, as outlined below.

Realizing mempool privacy requires navigating several tradeoffs. From a purely economic perspective, changes in information revelation likely impact market dynamics, while technical implications like additional time required for the network to process blocks also have economic implications such as lengthened slot times or windows of uncertainty between transaction submission and revelation of the outcome. As such, there are several dimensions to mempool privacy which merit further exploration.

3.2 Privacy Considerations

Before considering the cryptographic primitives involved, private mempool designers must decide on the nature of the privacy which is to be enforced. Different use cases likely warrant very different designs.

- Message content: Messages generated by users and passed through the network contain different pieces of information, not all of which need be encrypted. For example, one may seek to keep only the data related to smart contract execution private (e.g., CALLDATA [Koc23]) while leaving other information like sending address, IP, or nonce visible. Such a scenario may limit forms of frontrunning, but account balances or positions may still expose some information about likely smart contract calls. Account-based censorship is also not addressed by such a scheme.
 - Consider on-chain margin trading. A block producer may be in a 'long' position and know that a certain trader, identifiable by their blockchain address, is 'short'. If the 'short' side of the market is squeezed (i.e., if the market moves against the trader and the shorted asset's price rises), the validator can deliberately censor all the positions of the shorts (traders) they are aware of. Such a strategy effectively locks the other side of the market, preventing margin calls from being met and forcing liquidations, leading to market movements favorable to the block producer. Depending on the DApp, the block producer may gain additional profit from liquidation fees or conducting the liquidations directly [Fin22].
 - Similar concerns are raised in [PRF23], which studies a setting in which transaction fees can be used as an indicator of transaction content.
- Denial-of-Service Resistance: As blockchains generally allow any actor to enter messages into the mempool, nodes which propagate these messages are susceptible to being overloaded with

very high message loads. Deduplication and cheap validity checks are common techniques to defend against such forms of attacks [Li22]. However, a naive cryptographic protocol can rule out verification of the validity of plaintext corresponding to propagated ciphertext. 'Valid' here depends on the specific implementation in mind, but for most protocols, payment of a fee is a minimal requirement for DoS resistance. An easy workaround is to make sender account information available so that fast verification of sufficient funds for fee payment can be verified, but this introduces some problems mentioned above. Another approach is to attach a cryptographic proof that a ciphertext corresponds to a valid transaction [HBHW22]. However, computing and verifying such proofs may introduce overhead with significant impact in latency-sensitive trading environments (see Appendix B for more information).

Optionality: It may be the case that users of a blockchain have different preferences regarding the

forms of pre-settlement privacy which they would like applied to their transaction. This can be true even for the same use case under different market conditions. Consider sunshine and stealth trading in which traders may or may not want to expose their trade intentions before execution and/or settlement [SS09,AP91] or hidden and iceberg orders in which traders in traditional financial markets choose to expose only some information about a resting limit order [CMZ12]. Protocol designers may wish to provide optionality to cater to broad privacy preferences to serve user experience, market efficiency and to prevent users from pursuing similar outcomes through centralized out-of-protocol means. For example, a protocol which hides all transaction information of all transactions may see users, looking to advertise some aspect of their trade, providing plaintexts that correspond to public ciphertexts to a trusted third party. This party could then publicly attests to some properties of a pending 'encrypted' transaction. Such a trusted third

The simple examples of sunshine trading and iceberg orders are drawn from traditional trading environments in which the action space of users is narrow in comparison to the setting of smart-contract blockchains. It is unclear what the appropriate control over information revelation is in these novel settings, although the increased generality of users' action space would suggest more sophisticated controls are appropriate. In the limit of generality, one could imagine control over information revelation being provided in the form of a framework for proving arbitrary properties over pending transactions.

party would constitute an introduction of trust assumptions and information asymmetries, which

3.3 Encryption Methods

blockchain designers are trying to eliminate.

Beyond threshold encryption, which is the topic of the next section, the following encryption methods merit further investigation as primitives in implementations of encrypted mempools:

- Trusted Execution Environments (TEEs) [BKR22]: A trusted execution environment is a secure area within a device's processor that offers an isolated and protected space for running sensitive applications and managing critical data. TEE's provide robust security guarantees by ensuring confidentiality, integrity, and authenticity of the code and data they handle, even in the presence of potential threats from the main operating system or other software running on the device. The main approach for mempool encryption using TEEs that the authors are aware of is moving block production logic into a TEE [HP23]. Transactions can be decrypted using a decryption key that is stored in the enclave, before being executed and bundled into a block. A mechanism like a commit reveal scheme would have to be used to ensure that the decrypted block is only released when the block producer has limited means of influencing the settlement of transactions.

This solution is appealing for its pragmatism and ease of implementation. It doesn't require changes in the underlying blockchain protocol, does not compromise composability on smart-contract chains, and doesn't incur any settlement delay. However, the use of TEEs also comes with important drawbacks, such as the security model, which requires trust in entities like Intel, and

a lack of control by the blockchain community. If the TEE is breached e.g. [NBB20] protocol designers have no control over the rollout of a patch and have to wait for the hardware manufacturer to deploy a patch for their firmware. Such scenario could disable the MEV mitigation mechanism.

 Timelock encryption [Sek22] operates on the principle of having block producers commit to blocks before transactions are decrypted.

Timelock encryption-based methods are typically reliant on hardware assumptions and necessarily carry a certain degree of latency related to transaction settlement. While transaction settlement is effectively complete once the block is committed (assuming a system with 1-block finality, see Section 1.3.1), information about the outcome only becomes public after the plaintext becomes available. In some cases, the outcome of transaction execution will remain opaque even to the sender of the transaction until the block plaintext is uncovered.

Selecting an appropriate delay presents a unique challenge. The delay must be as short as possible to limit settlement latency. At the same time, the delay must be sufficiently long to prevent presettlement decryption or 'time bandit attacks' [Wik22]. This balance is crucial to the effective use of timelock encryption.

Interestingly, recent constructions of timelock encryption schemes propose to build on threshold cryptography [GMR23]. These new schemes may alleviate some existing challenges of timelock encryption and can offer unique tradeoffs relevant to the MEV mitigation effort of blockchain systems.

See also [Ste22] and [Cha23] for surveys on encrypted mempools.

3.4 Threshold Encrypted Mempools

(t,n)-threshold cryptography [BOY89,Des87,DF89,Des94] involves distributing confidential data (such as a secret key) and computations (like generating signatures or decrypting) among a committee of n participants to eliminate a single point of failure. This method aims to enable any group of more than a threshold, t, of committee members to collectively decrypt ciphertext while maintaining secrecy of the ciphertext pre-image even when an active adversary can compromise up to t-1 participants.

Threshold cryptosystems generally rely on a distributed key generation (DKG) protocol which enables a group of n parties to collaboratively generate a pair of public and private keys, following the distribution specified by the underlying cryptosystem [GJKR07].

The concept of threshold encryption is not tied to a specific implementation and this discussion remains agnostic to the underlying implementation, except that we do not consider homomorphic encryption schemes (i.e., we assume no meaningful computation can be carried out on ciphertexts; non-malleability).

Protocols Protocols such as [BO22] use threshold encryption to achieve mempool privacy by letting blockchain users encrypt their transactions to a (threshold) public key. The block producer then constructs a block consisting of encrypted transactions, which are decrypted by a committee no earlier than transaction settlement, after which decrypted transactions and the updated blockchain state are propagated and made public. Threshold-based schemes for mempool encryption are particularly well suited for blockchain protocols, which assume a threshold of active network participants for liveness guarantees. For instance, Practical Byzantine Fault Tolerant (PBFT)-based [CL99] consensus algorithms such as Tendermint [BKM18] are resilient up to $\frac{1}{3}$ of Byzantine participants [TPMG19].

By setting the decryption threshold to match the liveness assumptions of the underlying protocol ($\frac{2}{3}$ for Tendermint) and choosing the decryption committee to match the consensus participants, the introduction of threshold encrypted mempools does not require additional assumptions for liveness. Several designs leverage overlapping consensus and decryption committees [MS22,BO22,ACG+18a,Ano23]. More complex interactions between consensus protocols and threshold encryption schemes, such as

how the protocol deals with insufficiently many active participants, depend on individual protocol implementations.

Outside of liveness guarantees, threshold encrypted mempools likely require additional security assumptions on top of what the consensus protocol demands as highlighted in Section 4.1

Alternative designs choose decryption committees as separate from the nodes participating in the consensus protocol [Shu21]. In these settings, the threat of the committee failing to decrypt transactions on time likely changes the liveness guarantees of the underlying consensus protocol (more discussion in Appendix C).

The Case For Threshold Encrypted Mempools As illustrated by the examples listed above, threshold encryption offers a means to significantly adjust informational asymmetries. While threshold encryption alone is not sufficient to achieve the extreme of blind-order fairness (e.g., IP addresses and voluntary revelation of information), the primitive allows for obfuscation of information until settlement under certain security assumptions.

Using protocol-based solutions comes with the added benefit that the mitigation mechanism is fully under the governance of the system. In contrast to TEE's, using threshold encryption to design a protocol for mempool privacy allows for the MEV mitigation solution to be open source, leveraging protocol design skills of blockchain communities. As such, in the event of a vulnerability report, the community is able to issue a patch without requiring the involvement of a specific actor (e.g., a hardware manufacturer). Blockchain communities have already gone through several forks to patch vulnerabilities, e.g., [Sta22,CLW⁺17]. Leveraging the community's existing skill set and expertise to design an MEV mitigation solution allows for rapid response from a broad community, leading to a reduction in risk.

4 Limits of Threshold Encrypted Mempools

Having established some issues that arise from information asymmetries in blockchains and outlined ways in which threshold encryption may be employed to alleviate these issues, we now seek to point to a variety of additional considerations and limitations of such solutions. Every significant addition made to a blockchain protocol increases the attack surface and potential for error in written code, dependencies, and protocol design. While a specific design of a threshold encrypted mempool will be subject to the points raised below to varying degrees, this section seeks to broadly highlight areas in which careful consideration is required when evaluating a specific protocol design. That said, many critiques apply broadly to threshold encrypted mempools.

4.1 Collusion

In Section 3.4, a harmony between honesty assumptions in consensus protocols and threshold encrypted mempools is highlighted. However, this synthesis is restricted to liveness guarantees and threshold encryption likely imposes additional assumptions. Even if both the consensus algorithm and the threshold mempool decryption both rely on $\frac{2}{3}$ of honest voting power, there are important differences in the ease of collusion detection.

If more than $\frac{1}{3}$ of the nodes in a BFT-based system are malicious, the security and reliability of the consensus algorithm can no longer be guaranteed. Malicious nodes can collude to compromise the consensus mechanism, leading to issues such as double-spending, incorrect state transitions, or stalled progress in the network. Such attacks are generally observable and can lead to slashing penalties for misbehaving actors.

Early decryption would expose users to frontrunning and targeted censorship as laid out in Section 2, without creating any obviously malicious activity on the blockchain gossip network or state.

Not only do members of the decryption committee have financial incentive to collude at the cost of users, it may be possible to do this in a plausibly deniable manner. Community members monitoring for misbehavior could attempt to detect patterns in blocks and correlate these with different block producers in order to attribute malicious behavior. However, due to pseudonymous accounting systems and network layers that provide few guarantees, individual instances of outcomes from misbehavior are likely to be explainable as coincidental outcomes of behavior without collusion. Such attribution techniques may also engender adversarial games in which honest block producers receive transactions which lead to blocks that statistically suggest manipulation and monitoring parties are caught in a perpetual cat-and-mouse game. That said, it is difficult to assess the efficacy and shortcomings of statistical monitoring without a specific implementation in mind.

In contrast to non-encrypted mempools, the information asymmetry that arises from colluding threshold committee members deviates from expectations of system stakeholders. Users may behave differently believing their transactions will be private before settlement and applications design may vary for the same reason. It may also be argued that providing a low-stakes motivation for collusion between validators can establish the social ties and standards that later enable other collusive behaviors.

A further concern is the fact that validators may sell their decryption shares or information from early decryption. In the extreme, this would lead to a market for early access to decryption shares. In fact, a malicious actor who is able to break privacy repeatably in a nominally private system may have a relatively greater advantage compared to honest participants than any individual in a public system.

Assessing the risk of collusion in decentralized systems. The weight of the concern around early decryption depends on the risk of collusion. As such, we include some motivating examples of collusion by financial actors. Seeing well known financial actors collude in regulated markets should act as a warning urging to design protocols resilient against collusion. If collusion has happened/happens on regulated markets, it seems natural to think that collusion has happened or will happen on new unregulated markets where the legal consequences of doing so are weaker or non-existent, and when the benefits of colluding may greatly outweigh the consequences of doing so.

- The Libor (London Interbank Offered Rate) scandal [Wikc]. The Libor is an average interest rate calculated through submissions by major banks across the world, representing the rate at which they are willing to lend to one another. Several large international banks, including Barclays, UBS, and Royal Bank of Scotland (RBS), were found to have manipulated the Libor rates to benefit their own trading positions, specifically in derivatives. Traders from these banks colluded to submit false rates that would affect the overall Libor calculation in their favor, thus maximizing their profits. This manipulation impacted various financial products, such as mortgages, student loans, and credit cards, which are tied to the Libor rate. The scandal resulted in billions of dollars in fines, damage to the reputation of the involved banks, and increased regulatory scrutiny of the financial industry. In response to the Libor scandal, regulators around the world have since developed and adopted alternative reference rates, like the Secured Overnight Financing Rate (SOFR) in the United States, to reduce the potential for manipulation and collusion.
- The Foreign Exchange (Forex) trading scandal [Wikb]. This scandal involved several major global banks, including Barclays, Citigroup, JPMorgan Chase, RBS, and UBS, who were found to have manipulated the foreign exchange market. Traders from these banks colluded in private chat rooms, using code names to identify clients and sharing confidential client information to coordinate their buying and selling activities. By manipulating the foreign exchange benchmark rates, such as the WM/Reuters fix, they were able to make illicit profits for their respective banks at the expense of clients and the wider market. The foreign exchange market is one of the largest and most liquid financial markets globally, with daily trading volumes of over \$5 trillion. The collusion by these banks distorted the market and eroded trust in the global financial system. Regulators across several countries launched investigations into the banks involved, ultimately levying billions of dollars

in fines for their manipulative practices. This scandal led to increased regulatory scrutiny and implementation of stricter compliance measures in the forex market to prevent similar misconduct in the future.

- The municipal bond bid-rigging in the US [O'T12]. This scandal involved several major banks and financial institutions, such as Bank of America, JPMorgan Chase, and UBS, as well as insurance companies and brokers. Municipal bonds are debt securities issued by state and local governments to finance public projects, such as infrastructure improvements and public services. When these bonds are issued, the proceeds are often invested in short-term instruments, like guaranteed investment contracts (GICs), until the funds are needed for the intended projects. The scandal revolved around the process of bidding for GICs, which was supposed to be competitive to ensure that issuers received the best possible returns on their investments. However, it was discovered that banks and financial institutions colluded with brokers to rig the bidding process. They submitted artificially low bids, ensuring that the banks would win the contracts, while providing issuers with below-market returns on their investments. The bid-rigging scheme allowed the banks and other involved parties to profit at the expense of municipalities and taxpayers. Regulators, such as the U.S. Department of Justice and the Securities and Exchange Commission (SEC), launched investigations into the matter, resulting in criminal charges, fines, and settlements totaling billions of dollars.
- and others, e.g., ISDAfix [Gar18,CFT18], the precious metals price-fixing scandal (mid-2010s) [oJ22,Reu15] etc.

4.2 Control Over Ordering

As time-sensitive information such as financial news, policy changes, or market updates continues to influence trader behavior [AMP13,BMK15], block producers are still able to leverage freedoms in determining transaction ordering to prioritize their transactions even with less (or without) information about pending transactions. For example, full control in transaction ordering would imply that the block producer always has first access to the stale prices from the previous block, capturing arbitrage profits or reacting first to market-moving news such as rate hikes.

Access to these prices, and preferential ordering in general, can also be sold in a market. A simple form of such a market would be an auction for rights to choose the top transaction in a block. While this is potentially more efficient than a random blind ordering, further analysis is required to explore the various tradeoffs of such an approach.

One proposed approach to limiting freedom over transaction ordering is to distribute control over ordering across a set of nodes [KDL⁺21]. While an analysis of the assumptions and tradeoffs of such an approach is merited, the problem is considered orthogonal to threshold encrypted mempools and is thus left for future work. While ordering and inclusion are the two main dimensions along which block producers can influence the content of blocks in current blockchain designs, the arguments above apply broad influence over block content that is afforded block producers.

4.3 Decryption Games & Information Asymmetry

Encrypting transaction data only hides the transaction information until the message is decrypted. Due to non-zero propagation delay, even honest committee members who first decrypt the encrypted payloads will know about the new state of the chain before other market participants. This early access to information can constitute a profitable head start in acting on new market information. We call this the 'decryption timing advantage', see Fig. 2.

Such an advantage is not unique to blockchain designs leveraging threshold encryption, and is a general consideration for latency sensitive information in distributed systems with rational actors [HY23]. With regard to threshold encrypted settings, it is worth pointing out that (1) this informational

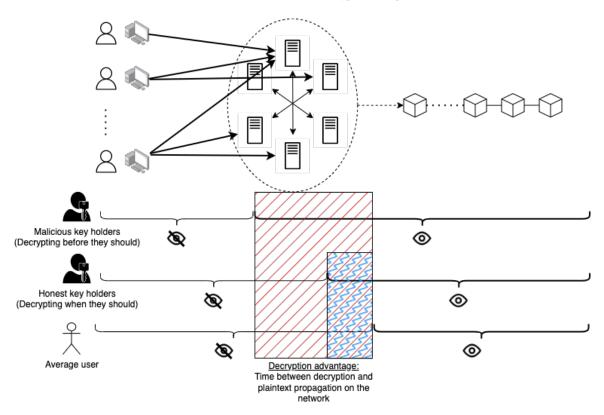


Fig. 2. A representation of the informational advantage keyholders have between transaction decryption and propagation of the plaintext(s).

asymmetry is not addressed by threshold encrypted mempools; (2) this asymmetry may be heightened in comparison to the unencrypted mempools wherein state updates can be estimated based on public pending transactions; and (3) an incentive to delay decryption may interfere with other components of the system.

Protocols such as [BO22] suggest that the elected block producer creates a block using encrypted transactions from the mempool. The encrypted block is shared in the network, and each node computes its decryption share for the transactions. Importantly, these decryption shares are coupled with votes to include the block — a key component of the consensus protocol. The transactions remain encrypted until at least $\frac{2n}{3}$ of the decryption shares are publicly broadcast during the voting phase, where n is the size of the committee set.

During this phase, when $\frac{2n}{3} - 1$ decryption shares have been published, any remaining validators that have not yet broadcast their decryption shares can locally decrypt the transactions in the block, without having to share their own decryption shares. This gives these validators an advantage in exploiting arbitrage and backrunning opportunities ahead of others.

This situation can be extended to groups of colluding nodes. For instance, consider a committee of 30 nodes where 20 nodes are needed for decryption. A set of 5 nodes are colluding, they could wait for 15 other nodes to publish their decryption shares. At this point, they can combine their 5 decryption shares, decrypt the transactions, and use the information ahead of the rest of the network, while delaying sharing of decryption shares as long as possible. Since the votes for blocks and propagation of decryption shares are a coupled activity, an incentive to delay the one affects the other, potentially impacting consensus stability.

Generally, consensus protocols impose disincentives for late message propagation, but analysis of such safeguards have shown that there is often room and incentive for delays [SSST⁺23]. Further work in exploring the interactions between incentives to delay decryption and the enactment of specific consensus protocols is needed.

4.4 Cryptographic Assumptions

Extending a blockchain protocol with additional cryptographic primitives brings a set of cryptographic assumptions that may extend the assumptions currently made by the protocol. For instance, protocols like [BO22] rely on pairings. Pairings are widely used primitives, especially by modern proof systems e.g., [Gro16,GWC19] which are used by several DApps, e.g., [RZ19]. However, such primitives may be newly introduced to the underlying blockchain protocol when adding threshold encryption. Hence, using a pairing-based DKG to mitigate transaction-based MEV would bring along additional pairing-related cryptographic assumptions to the blockchain protocol in question (e.g., SXDH, CBDH [KU16]).

While relying on additional, well known cryptographic/hardness assumptions is not an issue per se, we find it important to explicitly mention that, even if a DKG's security seems to align with the consensus algorithm's security (via the ' $\frac{2}{3}$ threshold'), in practice, its security may rely on assumptions that are stronger (less desirable) than existing cryptographic assumptions.

So, introducing additional cryptographic primitives in the protocol brings along a set of additional assumptions. Likewise, most protocol designs implicitly assume a secure implementation/instantiation of the protocol. This is another big assumption that can get violated during the implementation phase.

4.5 Censorship

While targeted censorship of specific users or kinds of transactions as described in Section 2.4 can be curtailed by obfuscating this information, block producers may still be in a position to censor blindly, potentially creating externalities for non-targeted users. For instance, a block producer who wants to prevent an oracle update from being executed in the next block may choose to produce an empty block, censoring all pending transactions, if the protocol allows. More nuanced versions of such an attack may leverage whatever information is available to target only the relevant subset of transactions.

It is up to blockchain designers or communities to reconcile these consequences with their design goals. On one hand, broader censorship comes at a greater opportunity cost for block producers who forgo more fees and may be more easily detectable than targeted censorship. On the other hand, broad censorship is a problem in itself and may be exacerbated by disallowing targeted censorship.

4.6 Economic Efficiency

Depending on the information which is encrypted, some efficient economic outcomes may be precluded. Consider, as a stylized example, four user limit orders (two buy orders and two sell orders) submitted to an exchange like Uniswap [AZS⁺]. Ordering the trades buy, buy, sell, sell may cause the second and fourth trades to fail, while ordering buy, sell, buy, sell may allow all trades to execute. It is clear that the latter ordering is preferable, but a naïve implementation of encrypted mempools may make selecting the preferred ordering with high probability impossible without an intermediary.

This example points to a large and largely unexplored design space for ordering policies and counterparty matching in blockchain networks, with and without encrypted mempools.

4.7 Additional Transactions

A separate concern is effective usage of network resources. As most current blockchain protocols require duplicated execution of transactions for the verification of block validity, execution of transactions is expensive for the network. Additional cost is also incurred from the storage and propagation of pending transactions. Threshold encrypted mempools may entice additional transaction volume in several ways.

Priority gas auctions (PGA's) are an observed phenomenon [DGK⁺19] in which a profitable opportunity draws many transactions from actors (like arbitrageurs) who seek to capture the opportunity.

One of the externalities of PGA's is blocks congested by many transactions, most of which 'revert' (execution of the transaction fails), pursuing the same opportunity.

On Ethereum, where the phenomenon was first observed, the problem is currently mitigated by block producers simulating transactions before inclusion to prevent including transactions which will not successfully execute. This approach generally imposes high resource requirements, requires sophisticated anti-DoS systems and is coupled with other unique system features such as proposer-builder separation [Bar23], which are outside the scope of this paper.

While there may be other solutions to preventing PGA-driven congestion, threshold encryption rules out the approach described above and poses a risk of seriously degrading system performance if not addressed.

Speculative Transactions PGAs arise partly because, sophisticated users are willing to accept the costs of reverting transactions if the expected revenue is sufficiently high. We have noted a pattern in which opportunities like misaligned, or favorable prices are publicly exposed after block n is decrypted and the first opportunity to act on this information is in block n + 1, leading to dynamics like PGA's. Users may be able to access opportunities before their competition by speculatively acting before information about block n is released. This can be done by submitting transactions which either capitalize on an opportunity or revert for inclusion in block n itself. Such strategies are helped by smart contract paradigms, which allow execution of arbitrary arbitrage search strategies like graph search algorithms and limited by the cost (or hard limit) of such computation.

Such a speculative strategy provides the speculative user with both a chance to access an opportunity before their competitors and a chance to access opportunities which are not available in block n+1. To illustrate the latter point, simply consider a block that contains one large 'buy' and one large 'sell' order of the same size. From block to block, the price may not have moved significantly, but if a speculative user was able to insert a transaction in between the aforementioned transactions, an arbitrage opportunity may present itself.

Just like with PGAs, widespread speculative execution can congest the network or raise fees for other users and can potentially be avoided by market mechanisms which do not require all failed transactions to be processed by the network.

It is worth noting that transactions which touch on global state are generally speculative, even without encrypted mempools. Transactions like swaps must encode flexibility like slippage limits to account for other traders that access the same prices before them. The line between what is desirable or not is blurry and depends on desired system guarantees.

For a case study of similar dynamics, one can turn to Solana [Yak], a chain with low fees and latency. The chain reportedly sees traders commonly employ speculative strategies with very high reversion rates [Yak].

Volume spoofing As even small amounts of information can be valuable in a trading setting, one may see traders observing the number of pending transactions. As such, adversarial competitors may artificially inflate the number of pending transactions to generate false signals. For example, a single trade can be split over many transactions targeting the same block, placing additional load on peer-to-peer networks and consuming node storage.

4.8 Limited Network Size

Blockchain networks aim to decentralize authority and power. Often this entails encouraging a wide and diverse set of nodes to participate in network operations. The larger and more diverse the network, the more difficult it becomes for any single entity or small group of entities to gain a controlling influence over the network (e.g., $\frac{1}{2}$ Byzantine nodes). Hence, in an ideal situation, blockchain networks aim to have a large or uncapped set of nodes carrying out consensus.

In the context of threshold encryption, however, this ideal may be challenging to achieve. The process of key sharing, encryption, and decryption is resource-intensive, requiring substantial computational and bandwidth resources. This imposes a natural limit on the size of the decryption committee, meaning any design which couples participating in consensus and decrypting transactions limits network security in the same way.

This cap on the network size has implications for the decentralization of the network. A smaller set of nodes increases risk of collusion, lowers the cost of attack, and increases the impact of the failure of a large network participant. The value proposition of a blockchain as a decentralized network may consequently be diminished.

It's worth noting that while this presents an additional constraint for some blockchain networks, others already operate with a capped set of consensus participants. Networks operating under Tendermint consensus, for instance, typically work with a set of around 100 validators [Gho21,Mub21]. Proponents of such systems might argue that networks with larger numbers of nodes end up with control over nodes distributed largely among a few parties.

4.9 Additional Considerations

4.9.1 Speculative Execution For Risk Management

Not being able to audit the mempool can impede 'speculative execution' for risk management purposes. It may be valuable for DApps developers to inspect the mempool transactions related to their DApps to infer the future state of their contracts on chain and be ready to address any possible incoming issue (e.g., mass liquidation events).

For example, protocols for crypto derivatives can leverage open mempools for speculative execution to manage risk efficiently. In these scenarios, when a block contains transactions that move the market in a particular direction or oracle updates, supplementary transactions can be appended to liquidate positions that have reached their liquidation levels, ensuring tight liquidations (close to liquidation level), keeping leverage healthy within the protocol and limiting risks of default.

If transactions are encrypted in the mempool such speculative execution becomes more challenging as less information is available — both about whether a liquidation is taking place and about the state of liquidity on the chain for optimally unloading the collateral. Under extreme market circumstances, inefficient liquidation can cause the buildup of unhealthy leverage in the system which, in turn, can potentially lead to the socialization of losses by the protocol, affecting all market participants. Under less severe circumstances, inefficient liquidations are likely to be compensated for with higher fees.

4.9.2 Market Impact and Price Volatility

The encryption of transaction data in the mempool also has significant implications for price discovery and other market dynamics. Traditionally, an open mempool can serve as an order buffer for DEXs, capturing trade intentions prior to their execution on chain. This visibility can help moderate price movements and enhance market stability. However, with transaction encryption, traders lose this visibility, potentially leading to greater price volatility and market swings as traders are unable to foresee and react to order flow changes. At the same time, privacy prevents dynamics such as those listed in Section 2 which may lead to more efficient execution for unsophisticated users, luring adoption and greater liquidity. Different forms of this debate extend to traditional finance, in which both 'dark' and 'lit' pools of liquidity exist.

While transaction encryption promises enhanced privacy, its potential to distort price information and introduce uncertainty requires further investigation. It may well introduce significant trade-offs between privacy and market efficiency, underscoring the need for comprehensive evaluation in implementing such mechanisms.

5 A Study Case: Osmosis

5.1 Osmosis Overview

Osmosis is an application-specific automated market maker blockchain specialized for decentralized exchange transactions rather than arbitrary state transitions, built on the Cosmos ecosystem [KB23,Shu22]. The Osmosis chain is also home to Mars Protocol [Pro23a], a collateralized lending platform.

Over time, the Osmosis community has explored multiple strategies to mitigate MEV risks, including threshold encryption of pending transactions to prevent information leakage [Ojh21b,Agg21,OACR21,Osm21]. Additional techniques have also been discussed as complements, such as joint block proposals [Ojh21a, Slide 58], transaction order randomization, and batch clearing of trades to reduce price impact [Pro22].

These design choices involve tradeoffs that warrant continued analysis and debate within the community prior to implementation. This section aims to highlight some key considerations around the current MEV mitigation agenda on Osmosis, especially considerations related to the implementation of threshold encryption on the network.

5.2 MEV Classification

To the best of our knowledge, the MEV mitigation agenda is not yet finalized on Osmosis, but existing proposals give good insights as to how the Osmosis community plans to handle MEV on the network. According to [AO22], the current approach to handle MEV on Osmosis consists of:

- 1. Preventing 'harmful MEV', which is defined as: at minimum including actions that are based upon knowledge of ready-to-execute transaction content, prior to its execution [AO22]. This includes behaviors like sandwiching, backrunning, censorship or delaying transactions, and
- 2. Capturing 'benign MEV' (i.e., MEV that is not 'harmful') which refers to extraction based solely on the existing state or public information, such as arbitrage and liquidation [AO22]. To do so, the Osmosis community proposes to capture 'benign MEV' via in-protocol mechanisms, to redistribute the proceeds to the community via a governance process.

This direction seems reasonable conceptually. However, developing a robust methodology to categorize MEV toxicity remains challenging due to the many subtleties involved. Perspectives on harm can vary significantly between agents within the network ecosystem. As users can freely move cryptoassets across blockchains, overly strict limitations deemed detrimental by key participants like liquidity providers could drive an exodus of capital and activity to other networks more aligned with their profit motives. Thus, a balanced perspective accounting for diverse viewpoints will likely be needed, even if it means tolerating some MEV behaviors deemed harmful by certain constituencies.

One constructive path forward would be establishing a community-governed framework to quantify and rate the impact of various activities, using historical on-chain data to parameterize 'harm' based on impacts to user welfare, system overhead, liquidity effects, etc. (e.g., using an open methodology such as [Blo20]).

Constructing a robust toxicity rating methodology seen as fair and accurate remains challenging. However, such a data-driven approach could provide a more objective basis to distinguish acceptable from harmful MEV on an ongoing basis. We believe engaging the full spectrum of network participants, especially validators critical to security and operations, will be vital in devising solutions seen as legitimate.

5.3 Slashing

Current proposals suggest using slashing penalties to disincentivize validators from behaviors such as 'running harmful MEV extraction software', 'outsourced block production software', or 'custom

transaction ordering software' [AO22]. However, enforcing slashing for the full spectrum of possibly 'harmful' behaviors faces inherent difficulties:

- Validators can disguise MEV activity across multiple accounts, or Sybils [Wik23c], to evade scrutiny. For instance, a validator may extract MEV via one account with no value at stake, while maintaining their validation role on another. Obscuring 'harmful MEV' activities using Sybils and benefiting from the information disclosure lag coming from the use of threshold encryption on the system could be used by malicious actors to, e.g., make it difficult for other network members to gather enough data to find statistical patterns in decrypted blocks, in order to avoid or delay detection of malicious validator behavior.
 - While social slashing [Wal22] (i.e., slashing by participant vote) may be possible in extreme cases, it involves a governance process, which may be hard to coordinate for frequent, harmful MEV-related activity that is hard to detect and quantify. Especially if not all voters have a technical financial background.
- Slashing is limited in its ability to disincentivize validators from MEV extraction. The potential
 profits likely exceed the cost of slashing penalties for a profitable attack. Slashing is bounded by
 the amount staked, whereas rewards for malicious strategies have no set upper bounds.
- Edge cases inevitably exist that are challenging to classify programmatically as permissible or malicious beyond doubt. Furthermore, the current definition of 'harmful MEV', defined as 'at minimum' can be seen as ambiguous and hard to enforce programmatically. For example, does threshold encrypted transaction spoofing in the Osmosis mempool qualify as 'harmful' under the current classification? The answer to this question looks unclear.

Moreover, activities that can be deemed harmful to the network may originate from any network user, not just validators. Non-validators have no staked assets at risk of slashing. For instance, a non-validator user may attempt to manipulate information related to Osmosis trading pools, by e.g., spoofing the mempool with 'dummy' encrypted transactions, or by voluntarily disclosing information about incoming trade intents (see, e.g., Section 3.2). Doing so with no 'value at stake' can allow influential traders to benefit from the market, without risking being penalized by the protocol⁶.

While such behavior may or may not be deemed 'harmful' under Osmosis' categorization framework (see Section 5.2), it is possible to foresee scenarios where behaviors that qualify as 'harmful' are possible, all while escaping slashing. Malicious wallet developers, for instance, could sandwich the trades of their users, allowing sandwiching activity to occur, even if the network uses threshold encryption. In this case, the wallet software would be able to access the transaction data before it gets sent on the network (i.e., before it reaches the mempool) or other information like IP addresses and the user interface used to generate the transaction [TWS23], and would allow non-validator wallet developers to carry out 'harmful' MEV while evading slashing penalties or causing misattribution of disallowed behaviour to certain validators.

5.4 Governance

The Osmosis improvement proposal [AO22] mentions that Osmosis should implement in-protocol systems to mitigate harmful MEV while transparently redistributing profits from non-harmful MEV to the community. Assuming consensus on classifying benign MEV, a question is how such captured profits should be redistributed.

The implemented *ProtoRev* Module Community Proposal [Plu21,Osm23a] added a module to Osmosis which automatically calculates and executes arbitrage after user AMM transactions, rebalancing Osmosis liquidity pools. To maintain technical efficiency, the module does not exhaustively

⁶ Repeated examples of market manipulation have been observed from firms (see Section 4.1) or individuals, e.g., [Bam23], which demonstrates the limits of 'reputation systems' to disincentivize such behavior

search for all possible arbitrage, but aims to capture the majority of opportunities. The proceeds of this arbitrage will form a new type of protocol revenue and will then be redistributed to the community.

ProtoRev offers interesting tradeoffs, as it makes full use of the particularities of Osmosis' bounded MEV domain and application-specific focus on decentralized exchange ⁷. This approach is pragmatic and creates an extra incentive to stake on the system (which improves the overall security of the network). Importantly, ProtoRev is compatible with the use of threshold encryption on Osmosis.

However, reliance on governance for redistribution raises concerns around converting MEV problems into 'governance problems'. In [Osm23b], the authors mention "Governance has full control over block-building and payment distribution. The chain can vote how MEV is distributed among network participants, with payments enforced in consensus". Here, 'the chain' refers to its stakeholders.

In particular, influential stakeholders who are able to sway governance decisions may vote to redirect 'benign MEV' profits primarily to themselves rather than the broader community, all while colluding to decrypt the mempool and benefit from privileged information. This 'privatization' of on-chain MEV proceeds could exacerbate centralization forces that MEV mitigation aims to alleviate. The community should deeply consider solutions like ProtoRev that address MEV via governance. While pragmatic in the near-term, heavy reliance on redistribution voting risks recreating similar issues to the MEV challenges such approaches intend to resolve.

5.5 Implementation of Threshold Encrypted Mempools

5.5.1 Design Considerations

To the best of our knowledge, Osmosis' current plans to implement threshold encryption are best characterized by the Ferveo protocol [BO22]. Ferveo proposes efficient distributed key generation and threshold public key encryption schemes to encrypt and decrypt transactions on BFT consensus blockchains, aiming to achieve mempool privacy.

The protocol design addresses some, but not all, considerations raised in Section 3.2:

- Message content & DoS: The protocol encrypts all transaction contents to all network participants until finalized in a block, except for public fees. This prevents spam by ensuring adversaries pay per transaction, and keeps blocks within gas limits. However, lacking full encryption reveals information and may enable selective censorship (see, Section 3.2), since public fees may indicate transaction intent. Fully encrypting transactions would likely create extensive ripple effects, necessitating significant protocol redesign. Given the current network state, these partial encryption tradeoffs seem inevitable.
- Optionality: Ferveo's design does not seem to enable optional disclosure of trade intent. Optionally disclosing (correct or misleading) trade information remains possible through revelation of plaintext corresponding to ciphertext, public unenforced claims about trade intents or the use of trusted third parties attesting to attributes of submitted encrypted transactions (as discussed in Section 3.2). However, users lack an avenue for making credible claims about trading intent without the use of centralized trusted parties. It remains unclear whether such out-of-protocol disclosure and actions resulting from this disclosure would qualify as a 'harmful' endeavor under Osmosis' MEV classification⁸. We refer readers to Section 3.2 for a more detailed discussion.

⁷ Implementing a module like ProtoRev to comprehensively capture benign MEV opportunities for the diverse array of arbitrary smart contracts on generalized platforms like Ethereum presents a significantly more complex problem. This stems from the virtually infinite extraction space created by generic smart contract composability and Ethereum's stated goal of remaining neutral between deployed DApps.

By disclosing one's (genuine or misleading) trade intentions one can induce market reactions and thus information streams in the mempool. In such case, inferring information about the state of the mempool may be possible – despite threshold encryption -, which may allow extracting value. If the trade intention is honest, an influential market participant can get the rest of the network to coordinate to provide him with high levels of liquidity or best execution (e.g., a 'whale' announcing a large sell on an AMM may induce LPs to provision liquidity to absorb the trade and minimize price impact, effectively allowing the 'whale' to get the 'network

Beyond securely implementing encrypted mempools while preserving efficiency, using Ferveo may impact validator incentives. Osmosis' plans empower validators with more responsibilities (see, e.g., [Con23b]) like generating decryption keys and decrypting encrypted transactions [BO22, Section 4]. This may lead validators to revise their commission structures to account for additional duties. Such changes could impact overall network incentives.

5.5.2 Limitations

Section 4 outlines several areas in which the implementation of threshold encrypted mempools may fall short of desired goals or have unintended consequences. In order to better understand the implications of such a scheme for Osmosis, we turn to these areas with the specifics of Osmosis in mind.

- Collusion: At present, just 7 validators, within the total pool of 150 active validators, cumulatively control over 34% of voting influence [Cos23]. This high centralization raises concerns regarding the potential impacts of introducing threshold encryption, which invites and is susceptible to inconspicuous collusion.
- Ordering & Information Asymmetry: Osmosis' current design, with or without encrypted mempools, does not limit control over ordering. Similarly, the impact of information asymmetry and risk of decryption games as described in Section 4 apply directly to Osmosis.
- Cryptographic Assumptions: Ferveo relies on cryptographic assumptions that, if added to Osmosis, would expand the set of assumptions of the network, rather than fully align with existing assumptions. In fact, to the best of our knowledge, the current implementation of Osmosis [Con23a] does not make use of cryptographic pairings, while Ferveo does. Furthermore, we believe that the willingness of the authors to use weighted decryption shares to align with the Tendermint's security assumptions paves the way for other misalignment, and collusion.
- Censorship: Although the concerns around broad censorship still apply to Osmosis, designs like [FR23] are created with Tendermint chains in mind and promise improved censorship resistance, albeit still subject to collusion concerns.
- Economic Inefficiency & Additional Transactions: The main idiosyncrasy of Osmosis with regard to efficient transaction ordering is ProtoRev. An analysis of the economic impact of protocolenforced arbitrage falls outside the scope of this paper. However, some superficial statements are worth making. Firstly, ProtoRev's rebalancing reduces the sensitivity of pool prices to volume traded, potentially reducing the impact of ordering on execution quality. The intuition behind this is that without rebalancing, a transaction may trade against only one pool, moving that price much further than the optimal routing would have done.
 - Secondly, due to ProtoRev's limitations, there is still incentive to speculatively submit arbitrage transactions. ProtoRev does not rebalance along all possible routes, nor does it take into account the price of assets on other domains like CEX's or other chains. As such, the concerns of blocks filled with failed transactions highlighted in Section 4.7 merit further investigation.
- Network Size: The proposed scheme should not impact the size of the validator set at the present moment, although the scheme might impact the feasibility of potential future changes, such as decreased block times or an expanded validator set.
- Risk Management and Market Impact: As Mars Protocol requires outside actors to liquidate bad debt and Osmosis is clearly intended as a home for trading, the considerations in Section 4.9 apply directly.

to work for them'). If the trade intention is dishonest (i.e., 'fake news'), the malicious market participant can manipulate the market, for e.g., get one side of the market to buy (resp. sell) at poor prices.

5.6 Summary

Based on the analysis carried in this paper, we conclude this section by providing some key suggestions as Osmosis considers implementing threshold encryption.

First, we encourage refining the classification of MEV on Osmosis. Defining 'harmful' MEV as 'a minimum' leaves ambiguity around behaviors not clearly 'harmful' or 'benign'. Clarifying these definitions would allow deciding on best measures to mitigate harmful MEV. It would also enable better assessing if/how threshold encryption aligns with the MEV mitigation agenda.

Second, we strongly encourage carefully evaluating collusion risks. The difficulty of detecting decryption collusion, coupled with the small number of influential validators on the network, warrants active discussion of threshold encryption's risks and benefits. This is especially important as Osmosis seeks to empower validators with more duties over time [Con23b]. Over-empowering validators may raise centralization pressures, incentivizing collusion for profits at later stages.

Third, when implementing threshold encryption, Byzantine scenarios around collusion, spoofing, etc. could be modeled on an incentivized testnet to empirically gather data. Teams of participants could voluntarily collude, manipulate information flows, and stress test the network in return for OSMO rewards. Likewise, validators could run specialized software to collect metrics, and malicious wallets could be implemented to model for some threats mentioned in this section. With client audits and testnet data, the community would be better equipped to decide if and how to deploy threshold encryption.

Finally, we encourage further exploration of modifications to the threshold encrypted mempool design that grant users greater control over the information which they choose to reveal.

In summary, implementing threshold encrypted mempools necessitates evaluating impacts on information flows, incentives, and harmful collusion potential. We believe this research can foster nuanced discussions within and beyond Osmosis, surfacing both drawbacks and advantages to enrich existing debates.

6 Conclusion

The merits of threshold encrypted mempools over public mempools remain unclear. While promising certain benefits like privacy, threshold encryption may introduce new inefficiencies, worsen power imbalances, and increase validator collusion risks. In particular, the temporary exclusive access to decrypted transactions creates an informational asymmetry that could enable validators to extract value through preferential transaction ordering. Additionally, the technical complexities of threshold encryption also risk unintended impacts on performance, overhead, transaction patterns, speculative trading, and governance incentives.

As such, we invite blockchain communities to carry out network-specific comprehensive evaluations on the benefits of threshold encryption, beyond the cryptographic and software implementation perspectives.

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A Blockchain efficiency

Blockchain technical efficiency. Many blockchain networks rely on gossip networks to propagate transactions to validator nodes. The bandwidth complexity of a gossip network is usually higher than that of a point-to-point communication channel because all nodes relay the same message to their neighbors until the whole network is covered, and this issue is exacerbated by MEV. In fact, each time an MEV searcher or validator steals a trade from a blockchain user (e.g., by replaying a transaction or front-running one, meaning the first transactions may not execute), bandwidth and computational resources used by the underlying blockchain gossip network may not lead to successful trade executions. These resources have thus been wasted. In other contexts, front/back-running leads to the creation of more transactions (by the bots sending front/back-running transactions) which increases block demand (raising the bar to include transactions in blocks and thus increasing transaction fees for users), consumes more computational and bandwidth resources, adds more data to the chain (increasing infrastructure requirements to run a validator node), etc.

Blockchain economic efficiency. Efficiency may be defined in absolute and in relative terms, the same way as a professional sprinter athlete may be fast on a 100m (in absolute terms, i.e., compared to a large population) but 'slow' on the same 100m compared to other sprinters in the race (e.g., if he/she arrives last in the world championship final race).

Let's take the example of a DApp designed to allow synthetic stocks trading or designed to trade tokens representations of fiat in a decentralized FX trading system, e.g., [Syn23]. If the throughput of the underlying blockchain protocol does not allow keeping up with trading on other systems, the price of synthetic stocks or fiat may constantly run out of sync with their 'true'/efficient price. While arbitrageurs may bring prices back in sync, this assumption only holds true if the cost of arbitraging (e.g., transaction fees etc.) is lower than the arbitrage opportunity. For instance, if demand for block space is significantly higher than the blockchain's throughput, and if the blockchain information processing capability is lower than the throughput of other systems on which similar assets are traded, transaction fees may surge significantly, making small arbitrage unprofitable. In this case, unmatched arbitrage opportunities can keep prices out of sync9.

In such cases, the use of different execution and trading venues, with different technical efficiency may make one side of the market worse off compared to their counterparts trading on other, faster venues ¹⁰.

⁹ When an asset is traded across multiple platforms operating at varying speeds, price asymmetry can occur due to, e.g., the differing rates of information processing. This situation presents a continuous stream of arbitrage opportunities. If arbitrageurs capitalize on these discrepancies, they help stabilize prices, which is beneficial.

However, if a blockchain has a limited capacity for processing transactions, it might end up accommodating predominantly arbitrage transactions from different DApps. This could disadvantage average traders due to the scarcity of available block space. Furthermore, without a transaction ordering policy, validators might prioritize transactions from average traders over arbitrageurs, causing the former to transact at less favorable prices.

Arbitrage may not always be profitable. If the price difference is too small relative to the combined trading fees on both ends, arbitrageurs could incur losses. Consequently, they might refrain from arbitrage activities. Additionally, the inherent risks associated with arbitrage, such as execution risk and counterparty risk, might deter potential arbitrageurs. For instance, price fluctuations may occur between the time of identifying the arbitrage opportunity and the execution of trades, leading to potential losses.

Thus, in situations where arbitrage is either cost-prohibitive or considered too risky, arbitrageurs are not incentivized to disseminate the missing information to the information-deficient system. If this system has active participants, they could be left trading at a price that doesn't account for all available information, rendering this specific market inefficient in the short term. The market will only regain efficiency when arbitrage becomes economically viable and the perceived risks manageable, prompting arbitrageurs to reintroduce the missing information.

It can be posited that an asset's true representation exists solely on its native platform (for instance, ETH on Ethereum), as the technical efficiency of the platform gives rise to a unique information structure for the asset. Consequently, any remaining price discrepancy across what appears to be the 'same asset' on different chains is attributable to the fact that these assets are fundamentally dissimilar. For instance, WETH is not equivalent to ETH. These assets are defined on distinct systems that have differing information structures (such as variable throughput across different chains) and unique risk profiles (for example, a Proof of Work asset bridged onto a Proof of Stake system). This could potentially justify a price gap that isn't immediately smoothed out by arbitrage activities. Again, it's a matter of truly understanding what one is trading.

All in all, technical efficiency can be (coupled with other things) an enabler for economically efficient markets, allowing to get closer to continuous time within the trading system. As such, we believe that it is important for protocol designers to understand the relationship between technical and economic efficiency. Understanding how specific design decisions may affect the economic efficiency of the system/DApps allows making appropriate tradeoffs and educated design decisions for blockchain protocol design or upgrades.

B Leakages and metadata

When designing privacy preserving protocols, the enemy is the metadata, and metadata come in all shapes or forms depending on the selected threat models: timing information (e.g., time it takes for a message to arrive at the destination on a network, under a specific topology, time it takes for an algorithm to execute, etc.), packet size, ways in which users interact with the protocol (their behavior can leak information about whether they received a message and/or the content of their messages) etc. It may be possible to address some of these leakages by taking them one by one, e.g., use Tor to prevent some classes of network attacks (though using Tor leaks as well, e.g., [Tai23]), or, use a mixnet [SSA+16]. It may also be possible to pad all packets to make them all the same size and thus indistinguishable. It may be possible to use zero-knowledge proofs to encrypt transaction fields like gasprice and prove statements about these to preserve the soundness of the protocol. It may be possible to carry out operations on ciphertexts using homomorphic encryption, etc.

That being said, the design of the final protocol will need to be studied to properly understand the remaining leakages, and using such a patchwork of cryptographic techniques comes with an overhead on computational and bandwidth complexity which may not be viable in practice.

Like all things in practice, tradeoffs need to be made. If all these leakages mitigations make the blockchain too slow or expensive to directly interact with and instead push users to roll-ups or centralized exchanges, it is worth asking whether this aligns with the desired outcome of decentralizing the financial infrastructure.

C Using a separate decryption committee

As suggested in [ZMB⁺23] it is possible to separate concerns between validators (producing blocks) and a secret management committee (SMC) that would reveal the plaintext of the encrypted transactions included in the block committed by the validator committee. As highlighted [ZMB⁺23], it is important to make sure that incentives are distinct between the two groups to avoid having validators colluding with SMC members. However, setting the appropriate collateral and parameters to cryptoeconomic protocols is not an easy feat. If the collateral needed to prevent Byzantine behavior is too high, the barrier of entry is high and access is only given to established, powerful market participants. If the value at stake is not high enough, collusion is not prevented. Moreover, while the in-protocol incentives may be distinct, MEV is a very lucrative business (with \$675 million extracted as of May 21st, 2023 [Fla23]). As such, off-chain incentives and money exchange can be set up to favor collusion between validators and SMC members. E.g., if validators redistribute 50% of their MEV proceeds to corrupt enough SMC members and gain privileged access to encrypted transaction, the penalties for colluding SMC members (provided collusion is detectable) must be very high, meaning the collateral requirements must be very high as well, causing possible issues with capital efficiency on the system (setting aside liquid staking for simplicity as it comes with a lot of potential for risk propagation within the system across L1 and L2s).

Moreover, having a distinct SMC requires more messages to be exchanged on the network. Multiplying actors and incentives also makes it harder to properly study the security of the network

under complex situations. What happens if transactions aren't decrypted on time because the Byzantine threshold is breached within the SMC? While this may not directly interfere with the liveness of the consensus, this would undoubtedly delay the disclosure of trade information on the system, which may equally impact the network. In fact, having a live consensus for a chain that fails to reveal transaction data could be as damaging as a network that is halted. Failing to decrypt transactions included in blocks would affect the economic efficiency of the system, with users mutating an unknown state, and thus trading on unknown prices on DEXs etc.

We leave this topic open for more discussion within the community.

D Order Flow Toxicity and Its Relationship with Miner Extractable Value

Order Flow Toxicity (OFT) refers to a condition in the financial markets where certain types of orders or trading behaviors adversely impact market liquidity, increase transaction costs, and threaten the overall market stability, see e.g., [ADMN⁺19,LLM16]. These 'toxic' orders are typically characterized by informed trading, where a subset of market participants utilizes superior information to gain an unfair advantage. This behavior can result in adverse selection for market makers, causing them to adjust their prices or withdraw from the market altogether to mitigate their risks.

D.1 Implications of OFT

The implications of OFT are profound for various stakeholders in a market:

- Market Makers: Market makers serve to provide liquidity to the market by consistently offering to buy and sell securities. However, they face the risk of adverse selection by informed traders. When exposed to toxic order flow, market makers may incur substantial losses, which could compel them to widen their bid-ask spreads or exit the market, leading to decreased market liquidity.
- Traders: For uninformed traders, OFT increases trading costs, particularly in the form of slippage
 the difference between the expected price of a trade and the actual executed price. Moreover, they risk trading against more informed parties, resulting in potential losses.
- Brokers: Brokers are responsible for executing trades on behalf of their clients. Under the notion
 of 'best execution,' they are required to execute trades in a way that is most advantageous to their
 clients. However, toxic order flow can impede brokers' ability to fulfill this obligation, potentially
 leading to regulatory scrutiny.

D.2 Best Execution and Reporting on Retail Execution Statistics

Regulations mandate brokers to strive for 'best execution' – obtaining the most favorable terms for their clients. This concept is defined broadly and involves several factors, including price, speed, likelihood of execution and settlement, size, nature of the order, and any other consideration relevant to order execution.

Furthermore, the US Securities and Exchange Commission (SEC) Rule 606 requires brokers to disclose information on their routing practices for non-directed orders in U.S. listed equities and options. The rule aims to promote transparency and ensure that brokers are acting in the best interest of their clients [SC23,Fin23,Sac23,Nom23].

D.3 OFT and MEV

In the context of DeFi, similar to OFT, MEV can lead to a harmful market environment. This is because informed users or miners can take advantage of transaction ordering to front-run or back-run

user transactions, leading to slippage or even failed transactions, potentially raising trading fees on the network etc. Blockchain's transparency can provide a potential solution to MEV, as it allows for better monitoring of transaction sequencing, and thus may allow for a better quantification of trade toxicity. This coupled with in-protocol punishments (e.g., slashing events when an actor sends trades that qualify as 'toxic' on the system), or new blockchain regulations could pave the way to mitigation strategies for MEV.