Security Review Report
NM-0417 Worldchain PBH Contracts

NETHERMIND
SECURITY

(April 1, 2025)

Contents

1 Executive Summary

This document outlines the security review conducted by Nethermind Security for the World Chain Priority Blockspace for Humans (PBH) smart contracts. PBH allows World ID users to execute transactions with top-of-block priority, providing a smoother and more seamless user experience. This functionality is powered by a custom block builder and EIP-4337-style smart contracts, which identify transactions containing valid World ID proofs. The priority blockspace is a fixed-size subset of the regular blockspace, with transactions in the priority blockspace being processed first, followed by regular transactions.

This audit engagement focuses only on the smart contract layer, which consists of three contracts:

1) A custom PBH entrypoint contract with World ID proof checking capabilities.
2) An EIP-4337 signature aggregator, which is tightly integrated with the PBH entrypoint.
3) A modified Safe Account EIP4337 module able to handle the unique PBH signature scheme.

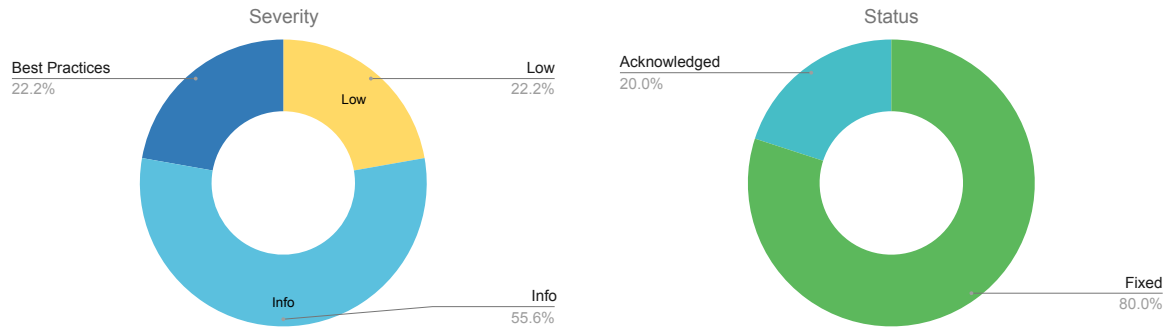
This document also covers a follow-up audit which introduced some changes to the smart contracts after public testing. During this follow-up engagement, no security issues were identified; however, we make a note about the nullifier hash timing changes which is highlighted in Section 7. These changes include:

1) Moving nullifier hash consumption to the end of block instead of immediately after validation.
2) Removing the multicall flow through the PBH entrypoint.
3) Increasing the number of PBH transactions that can be submitted within a month time-window.

The audited code comprises of 860 lines of code written in the Solidity language, and the audit was performed using (a) manual analysis of the codebase, (b) automated analysis tools, (c) simulation of the smart contract.

Along this document, we report five points of attention, where one is classified as `Medium`, one is classified as `Low`, and three are classified as `Informational` or `Best Practices`. The issues are summarized in Fig. 1.

This document is organized as follows. Section 2 presents the files in the scope. Section 3 summarizes the issues. Section 4 describes the system overview. Section 5 discusses the risk rating methodology. Section 6 details the issues. Section 7 details the issues. Section 8 discusses the documentation provided by the client for this audit. Section 9 and 10 details automated tooling used during the audit. Section 11 presents the compilation, tests, and automated tests. Section 12 concludes the document.



(a) distribution of issues according to the severity

(b) distribution of issues according to the status

Fig 1: (a) Distribution of issues: Critical (0), **High** (0), **Medium** (1), **Low** (1), **Undetermined** (0), **Informational** (0), **Best Practices** (3). **(b) Distribution of status: Fixed** (4), **Acknowledged** (1), **Mitigated** (0), **Unresolved** (0)

Summary of the Audit

Audit Type	Security Review
Draft Report	January 28, 2025
Final Report	February 11, 2025
Follow-up Report	April 1, 2025
Methods	Manual Review, Automated analysis
Repository	`worldcoin/world-chain`
Initial Commit Hash	`cc112c40157eca93e998649459340f4c5f3580c0`
Final Commit Hash	`64fa073799ffff9995bc6e415ef31c992113dff7`
Follow-up Commit Hash	`4be124c571b705a4b33a47c3e79b7e9d0baa9270`
Documentation Assessment	High
Test Suite Assessment	High

2 Audited Files

	Contract	LoC	Comments	Ratio	Blank	Total
1	contracts/src/PBH4337Module.sol	56	49	87.5%	24	129
2	contracts/src/PBHEntryPoint.sol	6	21	350.0%	4	31
3	contracts/src/PBHEntryPointImplV1.sol	152	97	63.8%	49	298
4	contracts/src/PBHSignatureAggregator.sol	54	43	79.6%	17	114
5	contracts/src/lib/PBHExternalNullifier.sol	32	39	121.9%	10	81
6	contracts/src/lib/SafeModuleSignatures.sol	43	21	48.8%	9	73
7	contracts/src/lib/ByteHasher.sol	6	5	83.3%	1	12
8	contracts/src/interfaces/IMulticall3.sol	50	1	2.0%	20	71
9	contracts/src/interfaces/IPBHEntryPoint.sol	33	6	18.2%	12	51
	Total	**432**	**282**	**65.3%**	**146**	**860**

3 Summary of Issues

	Finding	Severity	Update
1	Nullifier hashes may be consumed without a valid proof	Medium	Fixed
2	Missing length check for `pbhPayloads` and `userOps`	Low	Fixed
3	Unnecessary gas check in `pbhMulticall`	Best Practices	Fixed
4	`PBH4337Module` uses outdated `checkSignatures` function	Best Practices	Acknowledged
5	Natspec and comments	Best Practices	Fixed

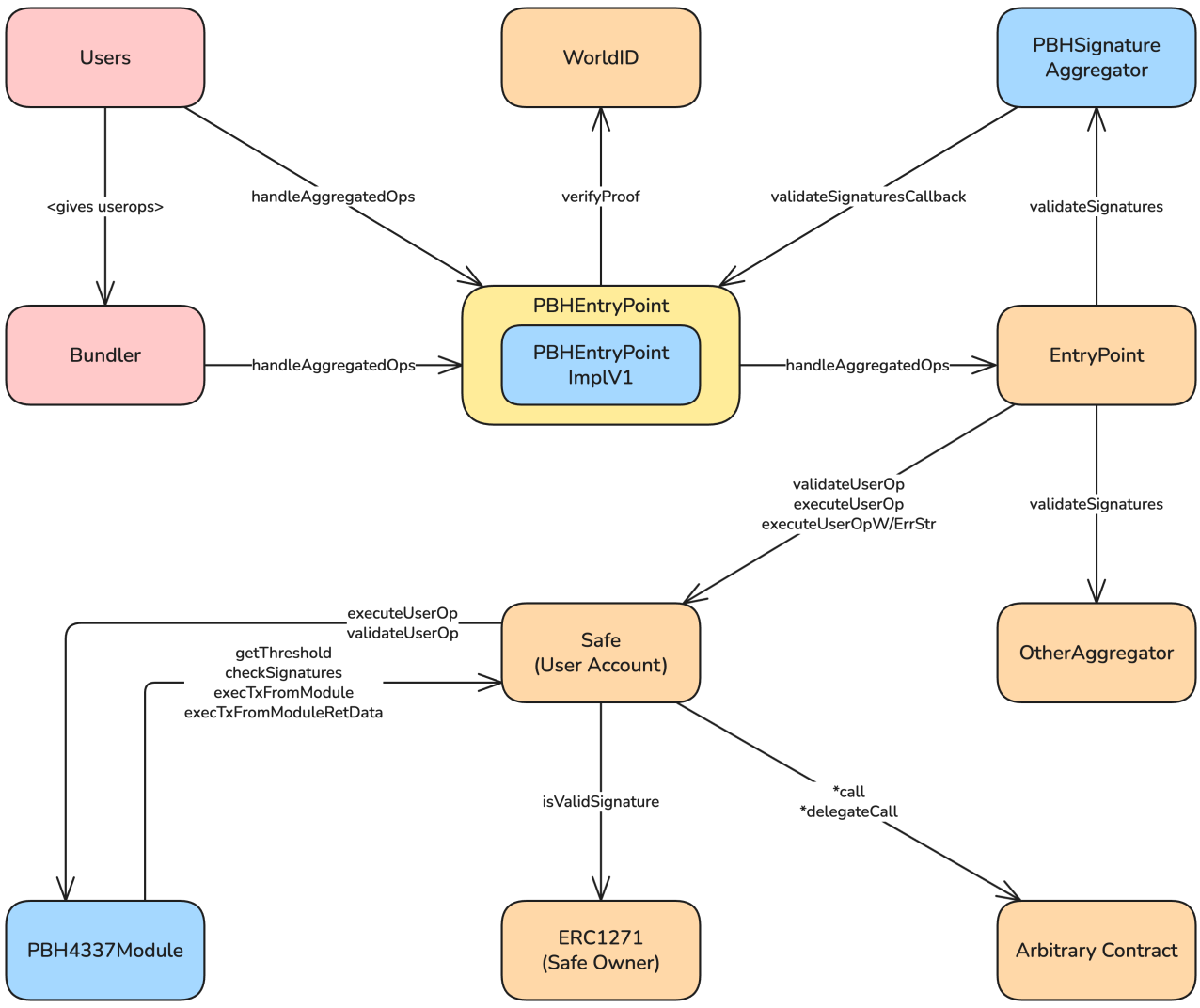
4 System Overview

The Worldcoin team introduced a custom block builder: `World Chain Builder`, which provides Priority Blockspace for Humans (PBH). With PBH a verified World ID user can benefit from top-of-block inclusion by providing a valid proof as part of their transaction. This mechanism ensures that certain transactions are prioritized for inclusion in the next block based on verified proof, offering a reliable way for users to access high-priority block space. The builder is designed to allocated a limited blockspace for PBH transactions per block, ensuring fair allocation between priority and non-priority transactions.

The PBH system consists of the following key components:

- **Bundlers:** Bundlers are off-chain entities responsible for collecting and submitting user operations (`userOps`) for PBH inclusion. A bundler groups multiple `userOps` together with an aggregator and submits the resulting bundles to the PBH EntryPoint.
- **PBH EntryPoint:** The `PBHEntryPointImplV1` contract is the core contract responsible for PBH validation. It exposes the primary entry points for submitting PBH transactions. The `PBHEntryPoint` is a proxy contract that points to the `PBHEntryPointImplV1` implementation, forwarding calls to the actual implementation.
- **Signature Aggregator:** The signature aggregator is a utility contract used by bundlers to group multiple `userOps`. It provides functions for signature validation, and is tightly integrated with the PBH entrypoint contract, using transient storage to verify that a set of `userOps` already have valid proofs associated with them.
- **PBH4337 Module:** The `PBH4337Module` extends the Safe 4337 module, enabling the acceptance of a threshold of ECDSA or ERC1271 signatures, with or without an attached proof.

The following diagram illustrates the system's main actors and components, along with their interactions:



Worldchain Contracts Overview

4.1 PBH EntryPoint

Users can submit PBH transactions using one of two available methods. A PBH transaction can either contain a single-user operation or a bundle of multiple-user operations.

- **handleAggregatedOps**: The user submits a PBH user operation, or a bundle of user operations, to the builder, which invokes the `handleAggregatedOps` function to submit the PBH transaction. The associated proof data is either verified on-chain, through the WorldID's `verifyProof` function, or by the block builder itself. Each set of user operations associated with the same aggregator is hashed and stored in transient storage for later signature validation. Once the verification is complete, the call is forwarded to the actual entry point of the Safe 4337 module, which processes the user operations, validating their signatures and executing them.

```
function handleAggregatedOps(
    IEntryPoint.UserOpsPerAggregator[] calldata opsPerAggregator,
    address payable beneficiary
) external virtual onlyProxy onlyInitialized nonReentrant
```

- **pbhMulticall**: Users are able to execute multicalls with top-of-block inclusion through the `pbhMulticall` function. This feature was in the original audit commit, however it was removed for the final and follow-up commit.

```
function pbhMulticall(
    IMulticall3.Call3[] calldata calls,
    PBHPayload calldata pbhPayload
) external virtual onlyProxy onlyInitialized nonReentrant returns (
    IMulticall3.Result[] memory returnData
)
```

4.2 PBH Signature Aggregator

The `PBHSignatureAggregator` contract is used as a utility by the bundler to aggregate UserOperation proofs onto the signature to be passed to the `handleAggregatedOps` function. This aggregation is implemented through the `aggregateSignatures` function, which consolidates the signatures from the user operations into a single aggregated signature.

```
function aggregateSignatures(
    PackedUserOperation[] calldata userOps
) external view returns (bytes memory aggregatedSignature)
```

The `PBHSignatureAggregator` contract also defines the `validateSignatures` function, which is invoked by the Safe 4337 EntryPoint contract to validate the signatures of the user operations. This function forwards the call to the `PBHEntryPoint`'s `validateSignaturesCallback` function. In this callback, the stored hashed user operations are compared with those provided. If they match, the signature is considered valid. This ensures that only correctly signed and verified operations are executed.

```
function validateSignatures(
    PackedUserOperation[] calldata userOps,
    bytes calldata
) external view
```

4.3 PBH4337 Module

The `PBH4337Module` extends the Safe 4337 module, allowing the handling of a set of signatures following the PBH signature schema. Eventually, it overrides the `_validateSignatures` function to allow the acceptance of a threshold of ECDSA signatures, with or without an attached proof.

5 Risk Rating Methodology

The risk rating methodology used by Nethermind Security follows the principles established by the OWASP Foundation. The severity of each finding is determined by two factors: **Likelihood** and **Impact**.

Likelihood measures how likely the finding is to be uncovered and exploited by an attacker. This factor will be one of the following values:

a) **High**: The issue is trivial to exploit and has no specific conditions that need to be met;

b) **Medium**: The issue is moderately complex and may have some conditions that need to be met;

c) **Low**: The issue is very complex and requires very specific conditions to be met.

When defining the likelihood of a finding, other factors are also considered. These can include but are not limited to motive, opportunity, exploit accessibility, ease of discovery, and ease of exploit.

Impact is a measure of the damage that may be caused if an attacker exploits the finding. This factor will be one of the following values:

a) **High**: The issue can cause significant damage, such as loss of funds or the protocol entering an unrecoverable state;

b) **Medium**: The issue can cause moderate damage, such as impacts that only affect a small group of users or only a particular part of the protocol;

c) **Low**: The issue can cause little to no damage, such as bugs that are easily recoverable or cause unexpected interactions that cause minor inconveniences.

When defining the impact of a finding, other factors are also considered. These can include but are not limited to Data/state integrity, loss of availability, financial loss, and reputation damage. After defining the likelihood and impact of an issue, the severity can be determined according to the table below.

		Severity Risk		
Impact	**High**	Medium	High	Critical
	Medium	Low	Medium	High
	Low	Info/Best Practices	Low	Medium
	Undetermined	Undetermined	Undetermined	Undetermined
		Low	**Medium**	**High**
		Likelihood		

To address issues that do not fit a High/Medium/Low severity, Nethermind Security also uses three more finding severities: **Informational**, **Best Practices**, and **Undetermined**.

a) **Informational** findings do not pose any risk to the application, but they carry some information that the audit team intends to pass to the client formally;

b) **Best Practice** findings are used when some piece of code does not conform with smart contract development best practices;

c) **Undetermined** findings are used when we cannot predict the impact or likelihood of the issue.

6 Issues

6.1 [Medium] Nullifier hashes may be consumed without a valid proof

File(s): PBHEntryPointImplV1.sol

Description: When attempting to execute a priority transaction through the PBH entrypoint, a user must provide a valid external nullifier and nullifier hash. These are combined with other data to verify a proof, ensuring that the user has a valid World ID. To prevent replay attacks, a storage mapping `nullifierHashes` tracks all previously used hashes. Upon successful execution of a PBH transaction, the nullifier hash will be marked as "used" and cannot be used again.

The entrypoint contract supports two PBH flows: `handleAggregatedOps` and `pbhMulticall`. Both functions verify the proof and mark the nullifier hash as used. If the entrypoint storage variable `worldId` is not set, then proofs are not verified onchain, and it becomes the builder's responsibility to validate them.

```
function verifyPbh(uint256 signalHash, PBHPayload memory pbhPayload) ... {
    // Check for nullifier hash reuse
    if (nullifierHashes[pbhPayload.nullifierHash]) {
        revert InvalidNullifier();
    }

    // Verify the external nullifier
    PBHExternalNullifier.verify(pbhPayload.pbhExternalNullifier, numPbhPerMonth);

    // Skip onchain verification if `worldId` is not set
    if (address(worldId) != address(0)) {
        worldId.verifyProof(
            ..., pbhPayload.nullifierHash, ...
        );
    }
}
```

When the `worldId` is not set, it may be possible for a user to call either of the two entrypoint functions with an invalid proof and still consume a nullifier hash. Depending on the builder implementation, there are two behaviors when an invalid proof is provided to the PBH entrypoint contract:

1. Allow the transaction to be included in the block but without priority
2. Reject the transaction, preventing it from being included in the block

If the builder follows the first behavior, users could call `handleAggregatedOps` or `pbhMulticall` with invalid proofs and still consume these nullifier hashes. During discussions related to this finding, the Worldcoin team raised the concern that an entity could become a bundler and get access to user PBH calls before they have been executed. This malicious entity could then attempt to mark a user's nullifier hashes as used before the user transaction executes, causing the user's call to revert since the nullifier hash is already used.

Recommendation(s): Ensure that the Worldchain block builder excludes transactions that include a call to the PBH entrypoint functions `handleAggregatedOps` and `pbhMulticall` if they do not meet the PBH conditions (invalid proof).

Status: Fixed

Update from the client: The World Chain block builder ensures that transactions can not call into the `PBHEntryPoint` unless it is specified as the transaction's `to` address. Additionally, in the follow-up commit a change has been applied to only allow authorized builder addresses to spend nullifier hashes.

6.2 [Low] Missing length check for `pbhPayloads` and `userOps`

File(s): PBHEntryPointImplV1.sol

Description: In the function `handleAggregatedOps`, there is a nested loop which iterates through the `userOps` for each aggregator. Each `userOp` should have a `pbhPayload` associated with it, which is used in `verifyPbh` to ensure that a valid proof has been provided. If any `userOp` has an invalid proof then the transaction will revert. The code is shown below:

```
function handleAggregatedOps(...) ... {
    for (uint256 i = 0; i < opsPerAggregator.length; ++i) {
        //...
        PBHPayload[] memory pbhPayloads = abi.decode(
            opsPerAggregator[i].signature,
            (PBHPayload[])
        );
        for (uint256 j = 0; j < pbhPayloads.length; ++j) {
            address sender = opsPerAggregator[i].userOps[j].sender;
            // Generate signal hash for verification
            uint256 signalHash = abi.encodePacked(...).hashToField();
            // Verify proof
            verifyPbh(signalHash, pbhPayloads[j]);
            // ...
        }
    }
    // ...
}
```

However, there are no checks to ensure that the length of `pbhPayloads` extracted from the aggregator signature is equal to the number of `userOps` in the aggregator's struct. The inner loop which does the proof verification will stop once it has reached the length of `pbhPayloads`. When `pbhPayloads` is less than `userOps` the loop will stop executing even though there are additional user operations which have not been verified. These skipped `userOps` will not be verified and their nullifier hash will not be consumed, but their call will still execute successfully.

This method of skipping proof verification can be done even when the `worldId` address is set and onchain proof verification is supposed to occur. Since this logic flow of skipping proof verification is unexpected, the builder implementation may not be written in such a way that can detect this, and may consider all `userOps` as PBH regardless. If this is the case, then any user may be able to append additional `userOps` without an associated proof and bypass the `numPbhPerMonth` limit.

Recommendation(s): Consider adding a check to `handleAggregatedOps` to ensure that the length of `pbhPayloads` is equal to `opsPerAggregator`.

Status: Fixed

Update from the client: Addressed in PR #140.

6.3 [Best Practices] Unnecessary gas check in `pbhMulticall`

File(s): PBHEntryPointImplV1.sol

Description: The function `pbhMulticall` verifies a user's `calls` and `pbhPayload` before making a call to `Multicall3.aggregate3`, which executes the users intended actions. After these calls are executed, the following gas check is done:

```
function pbhMulticall(...) ... returns (...) {
    // Verify calls and proof
    // ...
    returnData = IMulticall3(_multicall3).aggregate3{gas: pbhGasLimit}(calls);
    // ...

    // Check if pbh gas limit is exceeded
    if (gasleft() > pbhGasLimit) {
        revert GasLimitExceeded(gasleft());
    }
    // ...
}
```

The purpose of this check is to ensure that an excessive amount of gas hasn't been spent in the transaction, as it may affect other PBH users if excessive gas amounts reach the block limits. However, this check is ineffective as it's possible for gas to have been spent before the call to `pbhMulticall`. The check only ensures that there is some small amount of gas (`pbhGasLimit`) remaining after the call.

Recommendation(s): Consider removing the ineffective check, and explore options for a more complete gas spend check, potentially one that is integrated into the builder.

Status: Fixed

Update from the client: Addressed in PR #139.

6.4 [Best Practices] Opportunity to save gas in `checkSignatures` on next `Safe` release

File(s): `PBHEntryPointImplV1.sol`

Description: The `PBH4337Module` is an override of a forked `Safe4337Module` with a change to `_validateSignatures` which allows it to handle the unique PBH signature structure. Once the `userOp.signature` has been processed properly (prepended and appended data extracted) the module calls `checkSignatures` on the user's `Safe` smart contract account, as shown below:

```
function _validateSignatures(...) ... {
    // ...
    // Get threshold
    uint256 threshold = ISafe(payable(userOp.sender)).getThreshold();
    // ...
    // Extract signature
    if (isPBH && userOp.signature.length > expectedLength) {
        if (userOp.signature.length - expectedLength != ENCODED_PROOF_BYTES) {
            revert InvalidProofSize();
        }
        signatures = userOp.signature[TIMESTAMP_BYTES:expectedLength];
    }
    // ...
    try ISafe(payable(userOp.sender)).checkSignatures(keccak256(operationData), operationData, signatures) {}
    catch {
        validSignature = false;
    }
    // ...
}
```

In `Safe`'s latest code (ahead of the latest version `1.4.1-3`), there are two versions of this function, each accepting different arguments:

```
checkSignatures(bytes32,bytes,bytes)
checkSignatures(address,bytes32,bytes)
```

A comment in the `Safe` implementation states that the `(bytes32,bytes,bytes)` function will only exist for compatibility reasons, and that the newer `(address,bytes32,bytes)` should be used instead. When the next `Safe` version is released, using the newer function will reduce gas costs since the unhashed `operationData` won't have to be sent as part of the call, only the hashed data.

Recommendation(s): No action needs to be taken now, this finding only serves to highlight the opportunity to reduce gas costs during signature verification when a future `Safe` version is released.

Status: Acknowledged

Update from the client: Acknowledged.

6.5 [Best Practices] Natspec and comments

File(s): `/*`

Description: The following is a list of Natspec and comment corrections:

```
`PBHEntryPointImplV1.initialize` the args `multicall3` and `_pbhGasLimit` are missing natspec comments
`PBHEntryPointImplV1.initialize` @dev comment for `_worldId` has typo "addess" -> "address"
`PBHEntryPointImplV1.PBHEntryPointImplInitialized` event arg `pbhGasLimit` missing natspec comment
`PBHExternalNullifier.encode` the arg `version` is missing a natspec comment
```

Recommendation(s): Consider correcting the comments mentioned above.

Status: Fixed

Update from the client: Addressed in PR #142 and PR #153.

7 Follow-up audit notes

7.1 Change in nullifier hash consumption timing

In the PBH entrypoint contract at the initial audit commit, the nullifier hash of a PBH payload would be immediately consumed after verification during `handleAggregatedOps` and `pbhMulticall`. A primary change in the follow-up audit commits was the timing of the nullifier hash consumption, where it is now marked as "used" in a final transaction at the end of the block instead of occurring within the PBH transaction itself immediately after verification.

```
// Initial audit nullifier hash management
function handleAggregatedOps(...) external ... {
    for (uint256 i = 0; i < opsPerAggregator.length; ++i) {
        // ...
        for (uint256 j = 0; j < pbhPayloads.length; ++j) {
            //...
            verifyPbh(signalHash, pbhPayloads[j]);
            // Marked as used immediately, same applies to `pbhMulticall`
            nullifierHashes[pbhPayloads[j].nullifierHash] = true;
        }
    }
}
```

This change in timing creates a small window between a PBH transaction and the end of the block where the PBH transaction has executed, but its nullifier hash hasn't been marked as used yet. This opens the potential for the PBH smart contracts to allow a nullifier hash to be used multiple times in a block, which could lead to PBH transaction inclusion limits being exceeded. The same nullifier hash would need to be used though, meaning the `userOps` must be identical between calls, including the Safe4337 nonce. This would require a malicious user to make changes to their Safe account in order to avoid a nonce reuse revert, which is feasible given that the owner controls their own account.

This concern was raised to Worldchain, and the Nethermind team was informed that a check in the out-of-scope builder infrastructure is in place to prevent nullifier hash reuse. If a duplicate nullifier hash is identified then the entire bundle will be removed from the mempool. Therefore, while it may appear that the smart contracts could possibly allow for nullifier hash reuse, the implementation of the block builder prevents this behavior.

8 Documentation Evaluation

Software documentation refers to the written or visual information describing software's functionality, architecture, design, and implementation. It provides a comprehensive overview of the software system and helps users, developers, and stakeholders understand how the software works, how to use it, and how to maintain it. Software documentation can take different forms, such as user manuals, system manuals, technical specifications, requirements documents, design documents, and code comments. Software documentation is critical in software development, enabling effective communication between developers, testers, users, and other stakeholders. It helps to ensure that everyone involved in the development process has a shared understanding of the software system and its functionality. Moreover, software documentation can improve software maintenance by providing a clear and complete understanding of the software system, making it easier for developers to maintain, modify, and update the software over time. Smart contracts can use various types of software documentation. Some of the most common types include:

- Technical whitepaper: A technical whitepaper is a comprehensive document describing the smart contract's design and technical details. It includes information about the purpose of the contract, its architecture, its components, and how they interact with each other;
- User manual: A user manual is a document that provides information about how to use the smart contract. It includes step-by-step instructions on how to perform various tasks and explains the different features and functionalities of the contract;
- Code documentation: Code documentation is a document that provides details about the code of the smart contract. It includes information about the functions, variables, and classes used in the code, as well as explanations of how they work;
- API documentation: API documentation is a document that provides information about the API (Application Programming Interface) of the smart contract. It includes details about the methods, parameters, and responses that can be used to interact with the contract;
- Testing documentation: Testing documentation is a document that provides information about how the smart contract was tested. It includes details about the test cases that were used, the results of the tests, and any issues that were identified during testing;
- Audit documentation: Audit documentation includes reports, notes, and other materials related to the security audit of the smart contract. This type of documentation is critical in ensuring that the smart contract is secure and free from vulnerabilities.

These types of documentation are essential for smart contract development and maintenance. They help ensure that the contract is properly designed, implemented, and tested, and they provide a reference for developers who need to modify or maintain the contract in the future.

Remarks about World Chain documentation

The documentation for the World Chain contracts is contained in two README files in the project's GitHub repository. The first README, located in the root directory, provides a high-level overview of PBH, covering both the smart contracts and block-building architecture. Within the `contracts` directory, there is a README specifically detailing the smart contracts. This document explains the dependencies of the contracts (EIP-4337, Safe Accounts) and provides an explanation of each contract. For the entrypoint contract, the two primary functions, `handleAggregatedOps` and `pbhMulticall`, are also covered.

The information is presented in a very concise and technical manner, with well-written explanations and references where necessary. It also features a section explaining development dependencies and instructions on how to build and test the code.

Code comments are also of high quality, with explanations for many functions describing the purpose, context, and situations where the function will be called. Other than functions, some comments exist in other areas of the code where extra information is necessary, allowing readers to understand the codebase at a faster pace.

9 Slither

All the relevant issues raised by Slither have been incorporated into the issues described in this report.

10 AuditAgent

All the relevant issues raised by the AuditAgent have been incorporated into this report. The AuditAgent is an AI-powered smart contract auditing tool that analyses code, detects vulnerabilities, and provides actionable fixes. It accelerates the security analysis process, complementing human expertise with advanced AI models to deliver efficient and comprehensive smart contract audits. Available at https://app.auditagent.nethermind.io.

11 Test Suite Evaluation

The test suite for the PBH contracts is extensive, covering public functions of the contracts as well as internal functions, as in the case of `PBH4337Module`, where a function override occurs. The fuzzing features of Foundry are used throughout the test suite to ensure that functions behave correctly with a wide range of inputs. For the `PBHEntryPoint` logic, testing extends not only to expected function behavior but also to initialization and proxy-related behaviors, such as blocking access to direct interactions with the implementation contract.

```
Ran 6 tests for test/PBHEntryPointImplV1Proxy.t.sol:PBHEntryPointImplV1ProxyTest
[PASS] test_handleAggregatedOps_RevertIf_NotProxy
[PASS] test_pbhMulticall_RevertIf_Uninitialized
[PASS] test_setNumPbhPerMonth_RevertIf_Uninitialized
[PASS] test_setWorldId_RevertIf_Uninitialized
[PASS] test_validateSignaturesCallback_RevertIf_NotProxy
[PASS] test_verifyPbh_RevertIf_NotProxy

Ran 3 tests for test/PBH4337Module.t.sol:PBHSafe4337ModuleTest
[PASS] testInvalidSignature
[PASS] testValidSignature_WithProof
[PASS] testValidSignature_WithoutProof

Ran 10 tests for test/PBHEntryPointImplV1Init.t.sol:PBHEntryPointImplV1InitTest
[PASS] test_handleAggregatedOps_RevertIf_Uninitialized
[PASS] test_initialize
[PASS] test_initialize_RevertIf_AddressZero
[PASS] test_initialize_RevertIf_AlreadyInitialized
[PASS] test_initialize_RevertIf_InvalidNumPbhPerMonth
[PASS] test_pbhMulticall_RevertIf_Uninitialized
[PASS] test_setNumPbhPerMonth_RevertIf_Uninitialized
[PASS] test_setWorldId_RevertIf_Uninitialized
[PASS] test_validateSignaturesCallback_RevertIf_Uninitialized
[PASS] test_verifyPbh_RevertIf_Uninitialized

Ran 9 tests for test/PBHExternalNullifier.t.sol:PBHExternalNullifierTest
[PASS] testFuzz_decode
[PASS] testFuzz_encode
[PASS] testFuzz_encode_RevertIf_InvalidMonth
[PASS] testFuzz_verify
[PASS] testFuzz_verify_RevertIf_InvalidExternalNullifierMonth
[PASS] testFuzz_verify_RevertIf_InvalidExternalNullifierVersion
[PASS] testFuzz_verify_RevertIf_InvalidExternalNullifierYear
[PASS] testFuzz_verify_RevertIf_InvalidNullifierLeadingZeros
[PASS] testFuzz_verify_RevertIf_InvalidPbhNonce

Ran 14 tests for test/PBHEntryPointImplV1.t.sol:PBHEntryPointImplV1Test
[PASS] test_handleAggregatedOps
[PASS] test_handleAggregatedOps_EIP1271
[PASS] test_handleAggregatedOps_RevertIf_Reentrancy
[PASS] test_pbhMulticall
[PASS] test_pbhMulticall_RevertIf_GasLimitExceeded
[PASS] test_pbhMulticall_RevertIf_Reentrancy
[PASS] test_setNumPbhPerMonth
[PASS] test_setNumPbhPerMonth_RevertIf_InvalidNumPbhPerMonth
[PASS] test_setNumPbhPerMonth_RevertIf_NotOwner
[PASS] test_setWorldId
[PASS] test_setWorldId_RevertIf_NotOwner
[PASS] test_validateSignaturesCallback_RevertIf_IncorrectHashedOps
[PASS] test_verifyPbh
[PASS] test_verifyPbh_RevertIf_InvalidNullifier

Ran 6 tests for test/PBHSignatureAggregator.t.sol:PBHSignatureAggregatorTest
[PASS] testFuzz_AggregateSignatures)
[PASS] testFuzz_AggregateSignatures_EIP1271Signature)
[PASS] testFuzz_AggregateSignatures_VariableThreshold)
[PASS] testFuzz_ExtractProof,uint8)
[PASS] testFuzz_ValidateUserOpSignature,uint8)
[PASS] test_AggregateSignatures_RevertIf_InvalidSignatureLength
```

12 About Nethermind

Nethermind is a Blockchain Research and Software Engineering company. Our work touches every part of the web3 ecosystem - from layer 1 and layer 2 engineering, cryptography research, and security to application-layer protocol development. We offer strategic support to our institutional and enterprise partners across the blockchain, digital assets, and DeFi sectors, guiding them through all stages of the research and development procehttps://www.overleaf.com/project/65c0e737f41a29601bda5c48ss, from initial concepts to successful implementation.

We offer security audits of projects built on EVM-compatible chains and Starknet. We are active builders of the Starknet ecosystem, delivering a node implementation, a block explorer, a Solidity-to-Cairo transpiler, and formal verification tooling. Nethermind also provides strategic support to our institutional and enterprise partners in blockchain, digital assets, and decentralized finance (DeFi). In the next paragraphs, we introduce the company in more detail.

Blockchain Security: At Nethermind, we believe security is vital to the health and longevity of the entire Web3 ecosystem. We provide security services related to Smart Contract Audits, Formal Verification, and Real-Time Monitoring. Our Security Team comprises blockchain security experts in each field, often collaborating to produce comprehensive and robust security solutions. The team has a strong academic background, can apply state-of-the-art techniques, and is experienced in analyzing cutting-edge Solidity and Cairo smart contracts, such as ArgentX and StarkGate (the bridge connecting Ethereum and StarkNet). Most team members hold a Ph.D. degree and actively participate in the research community, accounting for 240+ articles published and 1,450+ citations in Google Scholar. The security team adopts customer-oriented and interactive processes where clients are involved in all stages of the work.

Blockchain Core Development: Our core engineering team, consisting of over 20 developers, maintains, improves, and upgrades our flagship product - the Nethermind Ethereum Execution Client. The client has been successfully operating for several years, supporting both the Ethereum Mainnet and its testnets, and now accounts for nearly a quarter of all synced Mainnet nodes. Our unwavering commitment to Ethereum's growth and stability extends to sidechains and layer 2 solutions. Notably, we were the sole execution layer client to facilitate Gnosis Chain's Merge, transitioning from Aura to Proof of Stake (PoS), and we are actively developing a full-node client to bolster Starknet's decentralization efforts. Our core team equips partners with tools for seamless node set-up, using generated docker-compose scripts tailored to their chosen execution client and preferred configurations for various network types.

DevOps and Infrastructure Management: Our infrastructure team ensures our partners' systems operate securely, reliably, and efficiently. We provide infrastructure design, deployment, monitoring, maintenance, and troubleshooting support, allowing you to focus on your core business operations. Boasting extensive expertise in Blockchain as a Service, private blockchain implementations, and node management, our infrastructure and DevOps engineers are proficient with major cloud solution providers and can host applications in-house or on clients' premises. Our global in-house SRE teams offer 24/7 monitoring and alerts for both infrastructure and application levels. We manage over 5,000 public and private validators and maintain nodes on major public blockchains such as Polygon, Gnosis, Solana, Cosmos, Near, Avalanche, Polkadot, Aptos, and StarkWare L2. Sedge is an open-source tool developed by our infrastructure experts, designed to simplify the complex process of setting up a proof-of-stake (PoS) network or chain validator. Sedge generates docker-compose scripts for the entire validator set-up based on the chosen client, making the process easier and quicker while following best practices to avoid downtime and being slashed.

Cryptography Research: At Nethermind, our Cryptography Research team is dedicated to continuous internal research while fostering close collaboration with external partners. The team has expertise across a wide range of domains, including cryptography protocols, consensus design, decentralized identity, verifiable credentials, Sybil resistance, oracles, and credentials, distributed validator technology (DVT), and Zero-knowledge proofs. This diverse skill set, combined with strong collaboration between our engineering teams, enables us to deliver cutting-edge solutions to our partners and clients.

Smart Contract Development & DeFi Research: Our smart contract development and DeFi research team comprises 40+ world-class engineers who collaborate closely with partners to identify needs and work on value-adding projects. The team specializes in Solidity and Cairo development, architecture design, and DeFi solutions, including DEXs, AMMs, structured products, derivatives, and money market protocols, as well as ERC20, 721, and 1155 token design. Our research and data analytics focuses on three key areas: technical due diligence, market research, and DeFi research. Utilizing a data-driven approach, we offer in-depth insights and outlooks on various industry themes.

Our suite of L2 tooling: Warp is Starknet's approach to EVM compatibility. It allows developers to take their Solidity smart contracts and transpile them to Cairo, Starknet's smart contract language. In the short time since its inception, the project has accomplished many achievements, including successfully transpiling Uniswap v3 onto Starknet using Warp.

- **Voyager** is a user-friendly Starknet block explorer that offers comprehensive insights into the Starknet network. With its intuitive interface and powerful features, Voyager allows users to easily search for and examine transactions, addresses, and contract details. As an essential tool for navigating the Starknet ecosystem, Voyager is the go-to solution for users seeking in-depth information and analysis;
- **Horus** is an open-source formal verification tool for StarkNet smart contracts. It simplifies the process of formally verifying Starknet smart contracts, allowing developers to express various assertions about the behavior of their code using a simple assertion language;
- **Juno** is a full-node client implementation for Starknet, drawing on the expertise gained from developing the Nethermind Client. Written in Golang and open-sourced from the outset, Juno verifies the validity of the data received from Starknet by comparing it to proofs retrieved from Ethereum, thus maintaining the integrity and security of the entire ecosystem.

Learn more about us at nethermind.io.

General Advisory to Clients

As auditors, we recommend that any changes or updates made to the audited codebase undergo a re-audit or security review to address potential vulnerabilities or risks introduced by the modifications. By conducting a re-audit or security review of the modified codebase, you can significantly enhance the overall security of your system and reduce the likelihood of exploitation. However, we do not possess the authority or right to impose obligations or restrictions on our clients regarding codebase updates, modifications, or subsequent audits. Accordingly, the decision to seek a re-audit or security review lies solely with you.

Disclaimer