INF-3203 A1 : Bitcoin Mining Competition

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Bitcoin is a decentralized digital currency that has revolutionized the way we think about money and financial transactions. One of the key features that sets Bitcoin apart from traditional currency is its use of a technology called blockchain, which allows for secure and transparent transactions without the need for a central authority. At the heart of the Bitcoin system is the concept of Proof of Work, a computational algorithm that ensures the security and integrity of the blockchain. In this process, miners compete to solve complex mathematical problems in order to add new blocks to the blockchain, and are rewarded with newly created bitcoins for their efforts. The use of Proof of Work has made Bitcoin one of the most secure and widely used digital currencies in the world, and has paved the way for a new era of decentralized finance and innovation.

Goal

This assignment entails the task of mining Bitcoin blocks in accordance with the guidelines of the Proof of Work protocol. To maintain the focus of this assignment, the use of a p2p network substrate has been excluded to avoid unnecessary issues. Instead, each candidate will act as a client, and a server will be at your disposal for block verification. The process of mining a block in the Bitcoin blockchain is associated with a reward in the form of Bitcoin. At the culmination of the competition, the participant with the highest number of successfully mined blocks will be recognized as the winner, but be careful of not melting your GPUs! For this task, you have to work in groups of 2-3 people.

Background

The following section contains pertinent information regarding blockchain and Proof of Work. If you are not familiar with such concepts, please read it thoroughly. A list recommended papers is listed below [1-6].

Blockchains

A blockchain is a distributed digital ledger of transactions that is maintained by a network of computers, rather than a central authority. It is a continuously growing list of blocks, each containing a timestamp and a cryptographic link to the previous block, forming a chain of blocks hence the name "blockchain". Once recorded, the data in any given block cannot be altered retroactively without the alteration of all subsequent blocks, which requires consensus of the network majority. Blockchains utilize different types of consensus mechanisms to reach agreement and validate transactions across the network. This makes blockchains resistant to modification and ensures the integrity of the data they contain.

The most well-known consensus mechanisms are Proof of Work [1] (Bitcoin), Proof of Stake [2-3] (Ethereum, Avalanche), BFT blockchains [5] (Algorand, Ripple Stellar), and Proof of Storage [6] (Filecoin). In a Proof of Work system, miners compete to solve complex mathematical problems to validate transactions and add new blocks to the blockchain. Proof of Stake, on the other hand, instead of miners involves validators being chosen based on their ownership of the native cryptocurrency of the blockchain. This reduces the energy consumption and hardware requirements compared to Proof of Work. In a Byzantine Fault Tolerant blockchain, nodes in the network must reach a consensus on the state of the blockchain even in the presence of faulty or malicious nodes. Such consensus algorithms typically involve a higher degree of redundancy and communication overhead compared to Proof of Work or Proof of Stake. Finally, Proof of Storage requires users to prove that they have stored data reliably and for a specific amount of time. Each consensus mechanism has its own strengths and weaknesses, and the choice of mechanism can significantly impact the security, efficiency, and scalability of the blockchain network. This assignment is predicated on the largest operational blockchain, namely Bitcoin, which relies on a consensus mechanism based on the Proof of Work algorithm.

Proof of Work

Proof of Work is the consensus mechanism used by Bitcoin. The basic idea behind Proof of Work is to require participants, called miners, to perform a computationally intensive task in order to create a new block of transactions on the blockchain. This task is designed to be difficult, requiring a significant amount of computational power and energy, in order to ensure that the miner has expended real resources and has a legitimate interest in maintaining the integrity of the network. Once a miner has completed the task, they broadcast the new block to the network, and other nodes on the network can verify the Proof of Work and add the block to their own copy of the blockchain. Miners are incentivized to participate in the process through a reward system, typically in the form of newly created cryptocurrency that is awarded to the miner who successfully creates a new block. To elaborate, a miner's task is to perform double hashing on the block header, consisting of the previous block hash, timestamp, and Merkle root, together with a nonce. This process continues until the hash falls below the specified target, which is also known as difficulty. The miner increments the nonce until a matching hash is discovered.

```
+-----------------+
|  Block Header   | <--- Previous Block Hash + Timestamp + Merkle Root
+-----------------+
        |
        |       +----------------+       +--------------+       +-----------
---------+
        + ------>|  Double Hash  |------>|  is valid?  |--YES->|  reward
6.25 BTC  |
        |       +----------------+       +--------------+       +-----------
---------+
        |                                        |
+-----------------+                              |
|     Nonce       |<------------ +1 ------------ NO
+-----------------+
```

Merkle Tree

The security of the Proof of Work lies in the fact that each new block's hash is computed using a cryptographic function that incorporates the root of a Merkle tree, which consists of all the transactions within the block.

In the context of Proof of Work, a Merkle tree is a data structure used to efficiently summarize all the transactions (`t1, t2, t3, t4` in the graph below) included in a block. In Bitcoin, for example, every block contains a list of transactions, and in order to perform Proof of Work, miners must hash the block header along with a nonce value until a suitable hash is found. Instead of hashing every transaction in the block individually, which can be time-consuming and inefficient, a Merkle tree is used to aggregate all the transactions into a single hash.

```
            R=h(H1+H2)
           /          \
      H1=h(t1+t2)     H2=h(t3+t4)
      /        \      /        \
    h(t1)    h(t2)  h(t3)     h(t4)
```

A Merkle tree works by recursively hashing (`h` function in the graph above) pairs of transactions together until a single hash value is obtained, known as the Merkle root (`R` in the graph). The Merkle root is then included in the block header along with other information such as the timestamp, nonce, and previous block hash. By including the Merkle root in the block header, it is possible to prove that a particular transaction is included in the block without having to include the entire list of transactions. This is useful for verifying the validity of a block without having to download and process all the transactions included in it, which can save time and computing resources.

In summary, the Merkle tree is a key component of the Proof of Work consensus mechanism because it allows for efficient verification of the transactions included in a block, which in turn enables miners to perform Proof of Work more efficiently.

Getting Started

This section offers a comprehensive elucidation of the pre-code structure, the necessary prerequisites for executing it, and detailed instructions on how to run it. Additionally, it includes illustrative examples of runtime instances.

Prerequisites

While the code has been developed in `Python 3.7.9`, it is expected to be compatible with any subsequent versions without issues. The `requirements.txt` file contains a list of all the necessary packages and libraries required to execute the code. It is strongly recommended using a virtual environment when working with this project. To create a new virtual environment, you can run the following command:

```
python -m venv my_venv
```

After creating the virtual environment, activate it using:

```
source my_venv/bin/activate
```

Once you have activated the virtual environment, you can proceed to install the required packages by running:

```
pip install -r requirements.txt
```

Structure

The code functions as a simple Client/Server application, utilizing `Flask 2.2.2` as a lightweight web application framework for facilitating Client/Server communication, while `SQLite3` serves as a relational database management system that is employed for the purpose of storing user-related data. The client is able to establish a connection and communicate with the server by utilizing pre-defined API endpoints. This allows the user to perform local block mining, and subsequently submit the block to the server for verification. Additionally, the API endpoints provide functionality for retrieving information pertaining to the current status of the blockchain, user data, and visualization tools that enable the monitoring of the competition's progression.

Pre-code

Download the pre-code here and acquaint yourself with its structure. The scripts and folders are depicted below for your reference (#TODO are the scripts you can/should edit):

```
.
├── README.md
├── requirements.txt
├── src
│   ├── abstractions
│   │   ├── block.py
│   │   ├── transaction.py
│   │   └── user.py
│   ├── backbone
│   │   ├── consensus.py--#TODO
│   │   └── merkle.py-----#TODO
│   ├── main.py-----------#TODO
│   ├── server
│   │   └── __init__.py---#TODO
│   └── utils
│       ├── conversions.py
│       ├── cryptographic.py
│       ├── flask_utils.py
│       └── view.py
└── vis
    ├── blockchain
    │   └── blockchain.pkl
    └── users
        ├── user_pbk.pem
        ├── user_pvk.pem
        └── users.db
```

The `src` directory contains all the pre-existing code required for the project.

- The `abstractions` subdirectory contains data structures that represent blocks, transactions, and users. These scripts are not to be altered.
- The `backbone` subdirectory contains scripts related to consensus and the Merkle tree for transactions. It is the responsibility of the candidate to **implement the backbone** of the blockchain, which includes the Proof of Work and the Merkle tree.
- The `server` subdirectory only requires the importation of constants and Flask calls to the server.
- The `utils` subdirectory contains essential scripts that enable Client/Server communication, the visualization of users, blocks, and blockchains, and the cryptographic functions that the **candidate must utilize** to have their block verified.
- `main.py` is the script to run.

The `vis` directory stores data that is useful for visualizing the project's execution at runtime.

- The `blockchain` subdirectory stores a pickle representation of the blockchain, which the candidate should become familiar with.
- The `users` subdirectory houses both the user database and the public/private key of a specific client.

Running the Code

It is imperative to configure and adjust several key features before executing the `main.py` script:

1. Students are expected to form groups consisting of 2-3 members and choose a **username**. It is requested that a list of usernames, along with the corresponding participating students, be sent to mohsin.khan@uit.no or dominik.thamm@uit.no as soon as possible. In order to avoid confusions, the username should be identical to the institutional username (e.g. abc123).
2. The aforementioned username should then be replaced in `src/server/__init__.py` within the `SELF` constant (e.g. `SELF = 'abc123'`).
3. The public and private keys must b e saved in the `vis/users/` directory.
4. Verify that the `ADDRESS` is set to `ete011@inf3203.cs.uit.no`.
5. You can run the script `main.py` by running it from the `src/` directory. You can start running the command `python main.py -h`, to check all available commands.

Get your Private/Public keys

In this particular blockchain implementation, verification is carried out utilizing the `rsa` framework. It is required that each transaction is signed using the sender's private key, and subsequently verified using the sender's public key by the recipient. The public/private key pair also plays a crucial role in signing the block that has been recently mined with the corresponding username. By doing so, once the block has been confirmed (after a period of 6 blocks), the reward will be granted to the user.

To get your public/private keys, you need to send your group username as specified earlier to mohsin.khan@uit.no or dominik.thamm@uit.no. Once the private and public keys have been acquired and saved in `vis/users/`, the candidate shall implement and read the server's reply to `GET_USERS` call so that `python main.py -i u` returns:

```
+---------------------------------------------------------------------------
-------------+
```

```
|                                     Users INFO
|
+----------+---------+---------------+--------------+------------------+--
------------+
| username | address | balance (BTC) | mined blocks | confirmed blocks |
reward (BTC) |
+----------+---------+---------------+--------------+------------------+--
------------+
|  enrico  | cf14e63 |     1000.0    |      2       |        0         |
0.0      |
|   aril   | e6586e7 |     1000.0    |      0       |        0         |
0.0      |
+----------+---------+---------------+--------------+------------------+--
------------+
```

The candidate is advised to familiarize themselves with the `sign` and `verification` implementations that are utilized from the `User` class.

API endpoints

The callable endpoints, which are located in the `src/server/__init__.py` file, are listed below. It is expected that the candidate will implement a POST request using `BLOCK_PROPOSAL` for mining, and will either generate their own transactions (it is worth noting that a user can only generate transactions with itself as sender) or request them from the server pool via the `REQUEST_TXS` endpoint. Additionally, they may employ GET requests such as `GET_USERS`, `GET_BLOCKCHAIN`, or `GET_DATABASE` endpoints in order to acquire network status, user data, and blockchain-related information. `REQUEST_DIFFICULTY` is already implemented.

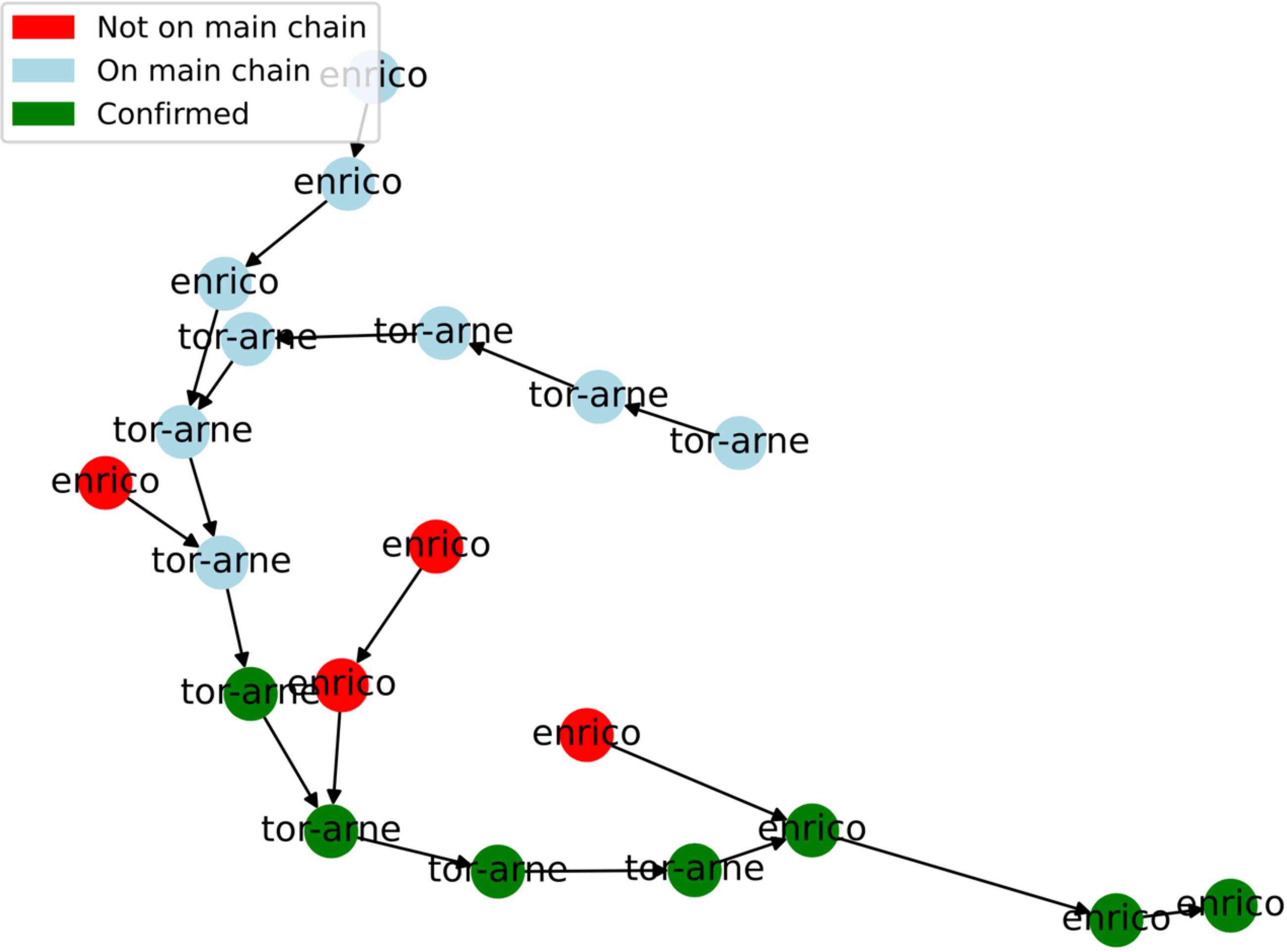
```
BLOCK_PROPOSAL = 'block_proposal'
GET_BLOCKCHAIN = 'get_blockchain'
GET_USERS = 'get_users'
REQUEST_TXS = 'request_txs'
GET_DATABASE = 'get_database'
REQUEST_DIFFICULTY = 'request_difficulty'
```

Various endpoints can be accessed via a simple command-line interface (CLI) menu, which is detailed below. Alternatively, by executing the command `main.py -h`, a list of different options will be presented. In order to avoid relative folder paths issues, execute the code from `src/` directory.

```
"""
Usage:
        -h                    : display usage information
        -i [b, u]             : display information for blocks or users
#TODO
        -t                    : request N transactions
#TODO
        -m                    : mine a block
#TODO
```

```
        -v b                 : visualize blockchain, saved to
vis/blockchain/blockchain.pdf
        -d                   : request DIFFICULTY level
"""
```

By executing the command `main.py -v b`, it is possible to retrieve the latest blockchain state in a graphical format. In case the visualization seems unclear, one can refresh it to obtain a better representation. This is an example of the generated pdf:



Object Serialization

Embedded within each class abstraction are methods for marshaling and unmarshaling, which facilitate the exportation of object instances in memory to other machines. These methods are implemented as `to_dict()` and `load_json()`. To initiate a server request, the `flask_call()` function can be utilized. The following are some examples:

```
# marshal
block_serialized = block.to_dict()
msg, data, code = flask_call('POST', BLOCK_PROPOSAL,
data=block_serialized)
# unmarshal
msg, block_serialized, code = flask_call('GET', BLOCK)  # Just an example,
not an actual call
block_deserialized = Block.load_json(json.dumps(block_serialized))
```

Your Tasks

In order to successfully complete this assignment, the candidate must complete both practical and theoretical tasks. If the minimum requirements are not met, the candidate must provide a comprehensive explanation. If the candidate encounters difficulties with coding, they should document their attempts and provide an explanation in their report.

Code

Upon downloading the code from here, the candidate is required to perform the following tasks:

1. Send their username to mohsin.khan@uit.no or dominik.thamm@uit.no to obtain the public and private keys.
2. Familiarize themselves with the code and interact with the server by implementing and managing basic client-side responses with API calls of `GET_BLOCKCHAIN` and `GET_USERS`. Commands `python main.py -i [b, u]`;
3. Learn about Proof of Work and Merkle trees (useful for the report) so to handle and understand the `REQUEST_TXS` calls for mining new blocks. Command `python main.py -t`;
4. Implement **Merkle tree** structure in `src/backbone/merkle.py`;
5. Implement the consensus mechanism **Proof of Work** in `src/backbone/consensus.py`. Command `python main.py -m`;
6. Propose a criterion or algorithm for the selection of parent and mining of blocks that minimizes the likelihood of orphaning or inclusion in the less successful branch of the blockchain.

Note that the `hash_function()` is used for verification server-side in the Merkle tree, while `double_hash()` is used for Proof of Work. Both functions can be found in `src/utils/cryptographic.py`, and the order for double hashing a block header is the following:

1. previous block hash
2. time
3. Merkle root
4. nonce

The starting **difficulty is set at 6**.

Report

The report must present a comprehensive description of the approach employed by the candidate to solve the given problem. It should include a detailed explanation of their Proof of Work algorithm, demonstrating their understanding of how this consensus mechanism operates. If the candidate encountered any issues in their attempts to mine a block, these should be documented thoroughly in the report. For the report, the candidate should use the IEEE conference template, and the report must not be less than 5 pages long. The report should cover the following topics:

1. Introduction to **public** and **private** blockchains, highlighting the main differences, advantages, and disadvantages of each.
2. A detailed explanation of the concept of mining in Proof of Work blockchain networks, including how miners compete to add new blocks to the blockchain and the role that difficulty plays in this process.

From this, the candidate should discuss their approach to solving the Code task of this assignment.
3. A comparative analysis of the main strengths and weaknesses of the Proof of Work consensus mechanism. The candidate should also compare and contrast this mechanism with other consensus mechanisms, such as Proof of Stake [2-4], Byzantine FT [5], or Proof of Storage [6].
4. An analysis of the environmental impact of Proof of Work blockchain networks. The candidate should identify the key criticisms of Proof of Work from an environmental perspective and discuss potential solutions to address these concerns.
5. A discussion of the potential security threats to Proof of Work blockchain networks. The candidate should highlight the most significant security risks and provide recommendations for mitigating them.
6. A consideration of the scalability limitations of Proof of Work blockchain networks. The candidate should identify the key factors that affect scalability and explore potential solutions to address these limitations.

Wishing you the best of luck! If you have any inquiries, please feel free to contact us via email at mohsin.khan@uit.no or dominik.thamm@uit.no or visit me at my office in A214.

References

[1] Satoshi Nakamoto. Bitcoin: A Peer-to-Peer Electronic Cash System, 2008. Available here

[2] Vitalik Buterin. "A next-generation smart contract and decentralized application platform." white paper 3.37 (2014): 2-1. Available here

[3] Emin Gün Sirer, Kevin Sekniqi, and others, "Avalanche: A Novel Metastable Consensus Protocol Family for Cryptocurrencies", 2018. Available here

[4] Aggelos Kiayias, Alexander Russell, Bernardo David, and Roman Oliynykov, Ouroboros: A Provably Secure Proof-of-Stake Blockchain Protocol", 2017. Available here

[5] Yossi Gilad, Rotem Hemo, Silvio Micali, Georgios Vlachos, and Nickolai Zeldovich. 2017. Algorand: Scaling Byzantine Agreements for Cryptocurrencies. In Proceedings of the 26th Symposium on Operating Systems Principles (SOSP '17). Association for Computing Machinery, New York, NY, USA, 51–68. Available here

[6] Benet, J. (2017). Filecoin: A Decentralized Storage Network. Available here

Authors

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