CS 5433 Homework 2

Due 26 April 2018

In this homework, we will use the concepts we've explored in class to extend the previous assignment with networking, and explore topics in byzantine agreement and consensus.

Submit your work to CMS as a zip file similar to the one we provide, containing an additional **solutions.pdf** file for written answers. **You will work in ASSIGNED groups of 3-4 for this assignment; please see CMS for random group assignments, and do not discuss solution details outside of your assigned groups.** For all assignments, you make use of published materials, but must acknowledge all sources, in accordance with the Cornell Code of Academic Integrity. Additionally, you must ensure that you understand the material you are submitting; you must be able to explain your solutions to the course instructor or TA if requested.

As in the previous homework, we are offering three extra credit points for completing this homework early and reporting potential issues with it to course staff; we apprecite your patience on this new set of assignments as always.

This homework may be completed individually or as a group. All students have been assigned based on their preferences to one of these options, and group assignments are available here:
`https://docs.google.com/spreadsheets/d/1OC0_F8KYnWiycvZ2j09pZaVsNq6NRFS864uCsqKUsow/edit`

Disclaimer

In general, many of the technologies we are using this semester will be poorly (if at all) documented, will be constantly changing, and will often suffer from broken or dead code or packages. This is par for the course for cryptocurrency. **Please start the assignment early**. We do not guarantee responses from the TAs or instructors on errors in the assignment or such broken packages without at least 48 hours lead time.

This assignment also implements networking functionality, which is generally failure-prone. We will support such issues, and will only test your code across local connections with little to no latency.

Problem 0 - Setting Up

First, download the provided zip in CMS.

The grading and testing code will be written in Python 3.6. **Full setup instructions and documentation for the provided code is available by opening `docs/index.html` in any web browser.**

Your solutions can be written in any programming language; we strongly recommend Python for its ability to natively interface with the provided infrastructure. If you would prefer to use a different programming language, you can use subprocess.communicate or other Python methods to call out to external binary code, including interpreters for other languages (an example is provided here: `https://stackoverflow.com/a/16770371`).

If you do choose a different programming language, please note that support from course instructors for language-related bugs may be limited, and it is your responsibility to ensure interoperability of input and output functionality throughout your code. If using a language other than Python, you are also required to provide a SETUP file with a list of Ubuntu or Debian packages required for your solution. We will not deduct points for problems setting up your solution, but may contact you if such issues arise. You are responsible for remedying any problems in a timely way.

We encourage you to read and analyze the provided code that is not part of the assignment: please ask questions if anything is unclear to you!

Problem 1 - p2p Warm Up [15]

Last assignment, we created a mini toy cryptocurrency that included several features of a real cryptocurrency, including partial block and transaction validation rules, fork handling, proof of work and proof of authority mining, a block explorer, and more.

Several features we learned about in recent lectures are missing in this homework. We will first add a peer-to-peer network to our Cornellchain cryptocurrency, allowing several nodes to coexist across a network and synchronize their blockchains.

We have made several changes to the previous codebase in support of this we suggest you explore:

- The `run_webapp.py` script of previous homeworks has been replaced by `run_node.py`, a script that runs a self-contained node with a block explorer and connection to the peer-to-peer network. The operation of this script is explained in the web-based documentation under "Running Nodes". Configuration of available nodes on the peer-to-peer network is provided in `config.py`.

- The file `p2p/gossip.py` has been added, and the `p2p.interfaces` module has also been added to serialize and deserialize blocks and transactions as they are exchanged over the network. We recommend inspecting the interfaces, though their modification is not required for the assignment. All functions to handle incoming messages are provided (`gossip.handle_message`) , dispatching them to the appropriate submodule.

- The `generate_example_pow_chain.py` script from before will now also gossip blocks to any available nodes on the peer-to-peer network. Your code will have nodes re-gossip messages to any available nodes on *their* p2p network. Each message should only be forwarded once; code for this is provided in `handle_message` as part of re-gossip.

We recommend re-exploring the provided web documentation for a complete overview of the new modules added to this version. The blockchain module interfaces are unchanged from the previous assignment.

We now ask you to complete the following (with solutions to 2, 3 placed in a **solutions.pdf** to be submitted to CMS):

1. In `p2p/gossip.py`, complete the `gossip_message` function
   Provided tests: `tests.gossip`

2. First clear your databases for nodes 1-6 and the parent/master node (see the instructions on the web documentation under "Running Nodes"). Run 3-6 nodes in separate command line windows, and re-run the `generate_example_pow_chain.py` file. This file has been modified to broadcast its generated blockchain to all nodes in the gossip network. Open the block explorers of each of your node at the end of that script's execution; do they appear synchronized? Now, repeat the experiment, but this time stop one of the nodes around halfway through the execution, and restart it at the end. What do you observe, and does this suggest any additions required to our gossip protocol (if so, what changes, otherwise, why not)? You may consult the documentation of Bitcoin's gossip protocol, available at `https://en.bitcoin.it/wiki/Protocol_documentation`.

3. Notice that our node's list of peers is hard-coded in `config.py`. Does this suggest another missing component required to achieve a permissionless blockchain? Why not, or if so, what is the closest analogous message type in the Bitcoin p2p protocol documentation linked above?

Problem 2 - Adding Synchronous Rounds [20]

In our lectures on consensus, we often explored protocols in the *synchronous* model. The synchronous model assumes that the communication channel between participants (or network) has some bounded delay, Δ. Δ is known up-front and consistent among all participants in the protocol, and represents the maximum amount of time it may take a message to transmit across a network link.

A natural application of this model is to round-based protocols, in which nodes proceed in synchronized "rounds", talking and reacting to each others' messages while taking advantage of the assumption that no honest nodes will receive messages outside the intended round, if the messages were sent by an honest node. The protocols we discussed in class are generally round based. Consider the PKI model consensus protocol we discussed in class and in the notes (Figure 4.1 in the BA notes). We will now attempt to implement this protocol. We hardcode our PKI in `config.py` (PUBLIC_KEYS and SECRET_KEYS; since our nodes share config, we enforce in code that they only access the secret key of their own node ID; normally, the SECRET_KEYS vector would of course be limited to nodes a user controls).

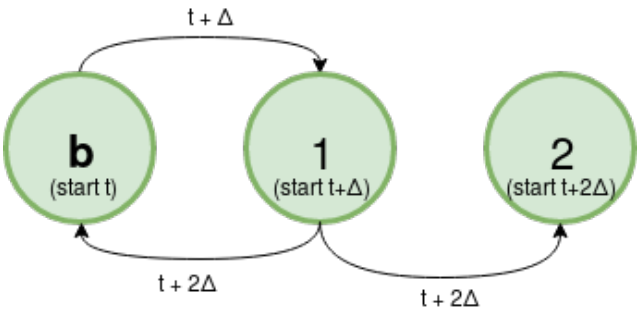
We must first implement the notion of synchronous rounds, assuming that our (actually asynchronous; the Internet provides no guarantees!) underlying network remains synchronous. Because we are doing all our testing locally on 127.0.0.1, this is a reasonable assumption, and messages are likely to be delivered quicker than our assumed Δ of two seconds.

We will also make an availability assumption, that is that all honest nodes will stay alive for the duration of the protocol; this is a relatively standard assumption, and can be removed through a "rejoin" protocol.

Lastly, we will make a clock synchrony assumption; this will allow us to start our series of rounds once and assume little divergence as a small number of rounds is completed, removing the need to re-synchronize each phase of each round, a slow process. This is also reasonable in our environment, as our nodes share the same local clock (you can run

these across computers too, and the small number of rounds we require likely means the assumption will hold).

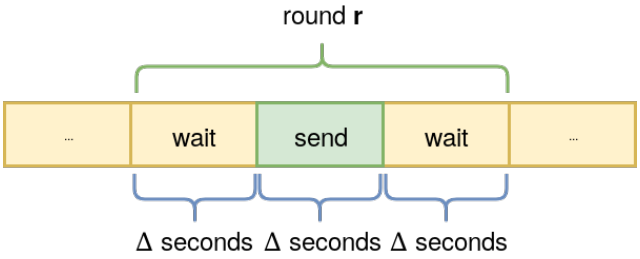
To start a synchronous round, any node can send a message `synchrony-start` to any other node. Honest nodes will gossip this message to the entire network. If any honest node gets a message at time `t`, all honest nodes will have the message by `t + Δ` (definition of synchrony). Therefore, honest nodes' internal clocks tracking their position in a round will always all differ by at most Δ. This is captured by the following diagram:



We can fairly simply deduct that any honest nodes' clocks will be at most Δ apart (+/- Δ) relative to each other.

Consider the scenario in the diagram, where a byzantine node b broadcasts a start message to only one of two honest nodes. This node then gossips the message to all other honest nodes. The last honest node to receives it differs from the Byzantine node's start time by $2 * \Delta$, but from the honest node's start time by only Δ. Nodes that receive start messages when their synchrony rounds are already in progress simply ignore these messages, meaning 2's later gossip of the message has no effect on any nodes.

Intuitively, from this synchronization protocol, we can simulate non-overlapping rounds using the following technique:



Our final protocol will send at the beginning of the send period. This is similar to the clock synchronization technique explored in class. Assuming perfectly synchronized clocks, all other nodes will see the message in the sending period by the synchrony assumption. Because honest clocks are not perfectly synchronized and can be +/- Δ apart (by the above intuition), we add a buffer on each side of the sending period where nodes can receive but not send messages. Nodes start round 0 immediately on receipt of a start message.

We will now ask you to complete the following:

1. In `p2p/synchrony.py`, complete `receive_start_message()`. This function should initiate the synchrony round tracker by setting the start time and running the logger.
   Provided tests: `tests.synchrony_start`

2. In `p2p/synchrony.py`, complete `get_curr_round()`. Based on the start time and current time, this function should compute the return the current round number as an integer and a function of all the provided global constants.
   Provided tests: `tests.synchrony_rounds`

3. In `p2p/synchrony.py`, complete `should_send()` as per the timing rules above, returning True if an honest node would be broadcasting in this part of the round.
   Provided tests: `tests.synchrony_sends`

To test the complete protocol:

1. Run 2-6 nodes; node 1 should be among these nodes, unless you want to test what happens with a failed sender.

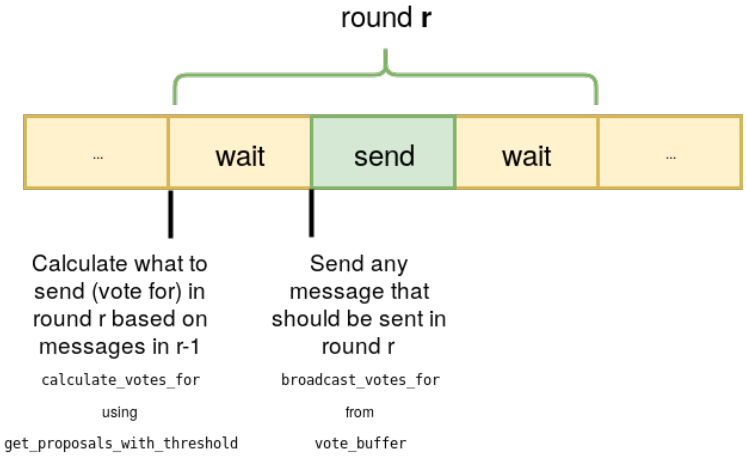
2. Once your nodes are running, run `start_synchrony.py` in the root directory.

Each node should produce logging output to the console tracking its current round / round state. These outputs should all be *synchronized* by our synchrony and clock synchrony assumptions above.

Problem 3 - Realizing BFT [25]

Having achieved synchronous rounds, we can now build a Byzantine fault-tolerant agreement protocol ("BA" protocol) for our nodes to come to consensus on a value. Notice that all such protocols we discuss have a sender and a message; for testing, we will have our nodes come to agreement on a random number proposed by the sender as the message, and choose Node 1 as an arbitrary sender.

Consider implementing the protocol in Figure 4.1 of the lecture notes. We will implement the protocol in two parts, as follows:



First, proposals that have reached the required signature threshold as described in the protocol (and are signed by the sender) are gathered, and "votes/signatures" for these proposals (consisting of a proposal,signature pair) are placed in the appropriate data structures. Then, a vote buffer is updated with any new votes that a node has not voted for, but should vote for in this round. Finally, at the start of the sending phase of the synchronous protocol we've built above, honest nodes broadcast all votes in their buffer to all other honest nodes, resetting their buffer.
(Note: Figure 4.1 describes coming to agreement on a bit, but coming to agreement on a message works identically).

We now ask you to complete the following (with solutions to 2, 3 placed in a **solutions.pdf** to be submitted to CMS):

1. In `byzantine_agreement/simple_ba.py`, complete `get_proposals_with_threshold(self, round)`. This function returns all proposals a node should vote for in round r given current data structures containing messages from round $r-1$.
   Provided tests: `tests.ba_proposals`

2. In `byzantine_agreement/simple_ba.py`, complete `calculate_votes_for(self, round)`. This function updates internal data structures with the results of the above (add to S_i in the pseudocode, and add to voting queue and other data structures in implementation).
   Provided tests: `tests.ba_votes`

3. In `byzantine_agreement/simple_ba.py`, complete `get_output(self)`. This function decides what to output if the protocol is completed.
   Provided tests: `tests.ba_output`

Congratulations, you now have a well-isolated, terminating/synchronous chunk of code that allows a leader to have all their peers come to consensus on a proposed value, satisying the properties we've studied of Byzantine agreement!

To test the complete protocol:

1. Run 2-6 nodes; node 1 should be among these nodes, unless you want to test what happens with a failed sender.

2. Once your nodes are running, run `start_ba.py` in the root directory. You can add Byzantine nodes to the protocol by modifying the BYZANTINE list in `config.py`; nodes with that ID will load code from `byzantine_agreement/byzantine_ba.py`. The current Byzantine behavior sends random data instead of signatures; we encourage you to experiment with arbitrary modifications to the superclass BA protocol's behavior to test your code's handling of Byzantine faults.

Note that even this simple, non-consensus agreement protocol, which isn't enough to build a blockchain since it says nothing about how to choose a sender and how blocks correspond to rounds, is ***more robust*** *than the NEO network's consensus protocol, which was recently revealed could not tolerate the crash (nevermind full Byzantine) failure of even a single one of the nodes running such a consensus protocol to secure their blockchain:* `https://cryptovest.com/news/neos-consensus-glitch-what-really-happens-if-nodes-crash/`*. Ready for your own 4 billion dollar currency?*

Bonus, 5 pts: Consensus and agreement protocols are incredibly different to write in practice. Timing assumptions, security considerations of the implementation (e.g. unexpected runtime exceptions), and more can cause any consensus system to fail. Bitcoin notably (and virtually all cryptocurrencies) are prone to this; see `https://en.bitcoin.it/wiki/Value_overflow_incident`. It is highly likely that our (admittedly rushed) code contains such errors. For five points, violate any of the theoretical properties we've proved about our protocol in the notes without causing more than the expected number of Byzantine failures or violating the synchrony assumptions. Please contact Phil via e-mail if you are successful, as we're only awarding points to the first unique exploit of each bug (to prevent both bug sharing and any obvious issues we've missed in review from giving everyone credit). To sweeten the pot and play with incentives a bit, we will offer everyone in the class a point if five such unique bugs are discovered. (Note: this also means never use our cryptocurrency code in production; we've made a lot of security assumptions, and the code is written for pedagogical readability, not security. Consult real high-valued cryptocurrency codebases for example secure implementations; e.g. Bitcoin Core, Parity, and py-evm).

Problem 4 - BFT to Consensus [10]

THIS QUESTION IS OPTIONAL AND WORTH 3 POINTS OF EXTRA CREDIT FOR INDIVIDUALS COMPLETING THE ASSIGNMENT AND GROUPS WITH UNDER 3 MEMBERS.

Having completed our BFT protocol, we would now like to use this protocol to create a blockchain. Read the associated class notes on how to do this, then answer (informality is fine here, but be convincing):

Provide two appropriate functions for choosing the sender/leader of the above BA protocol that would achieve the properties we want from a blockchain / consensus protocol. What are the qualitative differences between these functions? You may use the function in the notes as one solution.

Add your solutions to **solutions.pdf**.

Some protocols, like Ethereum's "Casper the Friendly Finality Gadget", use a hybrid between traditional consensus protocols, Nakamoto consensus, and economic guarantees to achieve their desired properties. Ethereum's FFG uses a modified version of PBFT, a Byzantine-tolerant replication technique, to achieve finality. It works as follows: coinholders can put down deposits to "stake" instead of mine. They vote on blocks using a consensus protocol like we've been exploring. If they fail, honest nodes cooperate to provide the blockchain with proof, and faulty users lose their deposit. If they don't misbehave or fail, nodes get rewarded.

Problem 5 - Theory of Consensus [30]

Add your solutions to **solutions.pdf**.

1. **(Dolev-Strong)** Consider the Dolev-Strong BA protocol (which you implemented above) in Figure 4.1 of the lecture notes, and consider a setting with 4 players. Use

the abstract protocol provided in the notes for your solutions, not your above implementation. Recall that we have shown that this protocol is secure w.r.t. 2 faulty players as long as we run it up to round 3. What happens if we consider a variant of the Dolev-Strong protocol that stops after round 2.

(a) Show that this protocol still satisfies Validity.

(b) Show that this protocol does not satisfy Consistency w.r.t. 2 faulty players. (Hint: Consider a situation where the sender and one of the receivers is faulty.) Explain what prevents your attack if we run the protocol for one more round.

2. **(Future Self Consistency)** Use any BA protocol (for sending strings) to construct a consensus protocol which satisfies Consistency and Liveness, but *not* Future Self-Consistency. Intuitively explain why your protocol does not implement a "secure public ledger".

3. **(Permissionless BA)** Explain *informally* why we need to use proofs of work (and bound the fraction of adversarial computing power, as opposed to simply giving a bound on the fraction of adversarial players) to get a BA protocol in the permissionless setting. (We are not expecting a formal proof, just an intuition.)

Grading

As last time, passing all provided tests guarantees an 80% on questions with provided tests.

Evaluation

To help us tune future homeworks in the class, please answer the following in your **solutions.pdf**:

- Did you find the homework easy, appropriately difficult, or too difficult?
- How many hours total (excluding breaks :)) were spent on the completion of this assignment?
- Did you feel there was too much coding, the appropriate amount of coding, or not enough coding?

Any other feedback on the homework or class logistics are appreciated!