Design Exercise 2: Logical Clocks

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1 Project Overview

In this assignment, we developed a model of a small, asynchronous distributed system that runs on a single machine but simulates multiple machines operating at different speeds. Each virtual machine (VM) maintains a logical clock and processes events asynchronously.

1.1 System Specification

- Each VM operates at a randomly assigned tick rate (1-6 ticks per second, unless manually assigned).
- Each VM has a message queue for handling incoming messages asynchronously.
- Machines establish connections with all other VMs during initialization for message exchange.
- Each VM maintains a log file recording logical clock updates and system events.

1.2 Execution Model

At each clock cycle, a VM performs the following actions:

- If a message exists in the queue, it is processed:
  - Update the logical clock.
  - Log the event with system time, queue length, and updated clock value.
- If no message is present, generate a random number (1-10) and:
  - If 1: Send a message to one peer and update the clock.
  - If 2: Send a message to a different peer and update the clock.
  - If 3: Send a message to all peers and update the clock.
  - If 4-10: Perform an internal event and update the clock.

1.3 Analysis and Experiments

- Run the simulation at least five times for one minute each.
- Analyze logs to examine:
  - Logical clock increments and drift across VMs.
  - Impact of tick rate variations on clock values and message queues.
- Conduct additional tests with reduced clock variations and lower probabilities of internal events to observe differences.

1.4 Deliverables

- Submit the source code (or a link to the repository).
- Maintain a lab notebook documenting design choices and observations.
- Present findings and demonstrate the implementation on Demo Day 2.

2 February 28th: Project Approach

2.1 Design and Architecture

Our system follows a modular design, separating the core components of virtual machine logic, networking, and logging. Each virtual machine (VM) is implemented as an independent process, ensuring that each operates in its own address space.

2.2 Clock Management

Each VM is initialized with its own clock tick rate, randomly chosen between 1 and 6 ticks per second. The logical clock updates based on events, following standard message receipt rules where the logical clock is set to the maximum of its current value and the received clock value plus one.

2.3 Networking Setup

We use sockets to simulate a network, allowing machines to establish connections with every other machine during initialization. Non-blocking or asynchronous I/O ensures that message receipt is decoupled from the internal clock cycle, enabling efficient processing.

2.4 Event Loop for Each Machine

2.4.1 Message Handling

On each tick, a VM checks its message queue. If there is a message, it processes one message, updates its logical clock, and logs the event.

2.4.2 Random Event Generation

If there are no messages in the queue, the VM generates a random number between 1 and 10 to determine its next action:

- If the number is 1, 2, or 3, the VM sends a message to one or more other machines, updates its logical clock, and logs the event.
- Otherwise, the VM treats the tick as an internal event, updates the logical clock, and logs the event.

3 March 1: Structure and Implementation

The project follows a structured repository layout to facilitate maintainability and modularity. The directory structure is as follows:

```
distributed_system_project/
  README.md
  requirements.txt
  lab_notebook.md
  src/
      init.py
      main.py
      virtual_machine.py
      network.py
      logical_clock.py
      logger.py
  logs/
      (log files generated dynamically)
  tests/
  init.py
  test_virtual_machine.py
```

4 March 3: Simulations and Analysis

4.1 Simulation Workflow

During initialization, all VMs are created, assigned tick rates, and establish network connections. Once the simulation begins, each VM operates independently, processing events at its own speed. Messages arrive asynchronously and are processed at the local clock rate.

Events are logged with system time, logical clock values, and message queue lengths, allowing analysis of clock drift and queue behavior. The simulation can be run multiple times with configurable parameters such as tick rate variation and messaging probability to observe system behavior under different conditions.

4.2 Graphical Analysis

To facilitate data analysis, we introduced `analyze_logs.py`, which generates graphs from the log data. Users can execute:

```
python analyze_logs.py logs_archive_YYYYMMDD-HHMMSS.csv
```

to analyze clock drift, message queues, and event distributions over time. We also had to create `archive_logs.py` which turns all the individual `VM_I.log` into one big csv file, as well as clearing the logs by default at the start and end of experiment running to make sure there is no overhead from previous experiments.

5 March 4: Major System Changes

First, we observed we had accidentally incorrectly implemented the threshold logic, so we had to change that. Second, we standardized logging so that logs would always come immediately after a tick. Third, we realized that the send message log was incorrectly sending the new time rather than the time of the message's sender, so we had to update that increment.

We transitioned from a thread-based implementation to a fully multi-process design using the `multiprocessing` module with `subprocess.Popen` in `main.py` based on Professor Waldo's comments at the end of class. A new worker script, `run_vm.py`, was created to ensure each VM runs as a separate process, maintaining its own address space.

In `run_vm.py`, we introduced a real-time loop with dynamic sleep intervals based on `tick_rate`, allowing for non-linear drift. The original `virtual_machine.py` and `network.py` remained unchanged, as they already produced the expected drift behavior when executed in real time. The manager script now spawns processes with custom tick rates, such as 1, 10, and 100, to highlight significant differences in clock behavior.

To support this transition, we modified the peer communication system:

- **set_peers_from_config**: Now accepts a list of peer IDs, connects to them, and stores sockets in `self.peer_sockets`.
- **send_message_by_id**: Sends messages using stored peer sockets, ensuring messages are routed correctly.
- **run_tick**: Uses `send_message_by_id` for message passing, improving event handling.

These changes enhance the simulation by ensuring events now affect clock updates dynamically, making drift patterns more varied and realistic. Each VM maintains awareness of all peers and adjusts its behavior accordingly.

5.1 Code Structure and Log Management

5.1.1 Project Structure

- We reorganized the project into:

  - A manager (`main.py` in `src/`),
  - A worker (`run_vm.py`),
  - Core simulation code (`virtual_machine.py`, `network.py`, `logical_clock.py`).

6 Overall Design Choices

We made a few important design choices that we should isolate and highlight:

- We utilized the subprocess import from Python to ensure we are virtual machines in different address spaces and to resolve our error of putting everything in one thread
- We created the convention that we would always log immediately after a clock update (tick or message comparison time). This way, we're standardized in our logging
- We decided to use sockets and also had address reuse so ports are quickly freed up
- For timing, we went from dynamic tick rates via time.sleep to time.perf_counter to have more precise updates
- Logging utilized regex to peruse through the csv files we created, pulling the correct clock times

7 Testing

In this section, we outline the final set of experiments to evaluate different aspects of the simulation, focusing on the impact of tick rates and message exchange thresholds on clock drift and event distribution.

We ran each experiment 5 times, and we will display one set of results in this notebook and keep the rest in the repo. The 4 graphs per experiment we generated were:

- A graph of logical clock time vs true clock time
- A graph of clock drift relative to VM1, using interpolation
- A graph of the length of the message queue across time
- A graph of the various message types each machine had to deal with

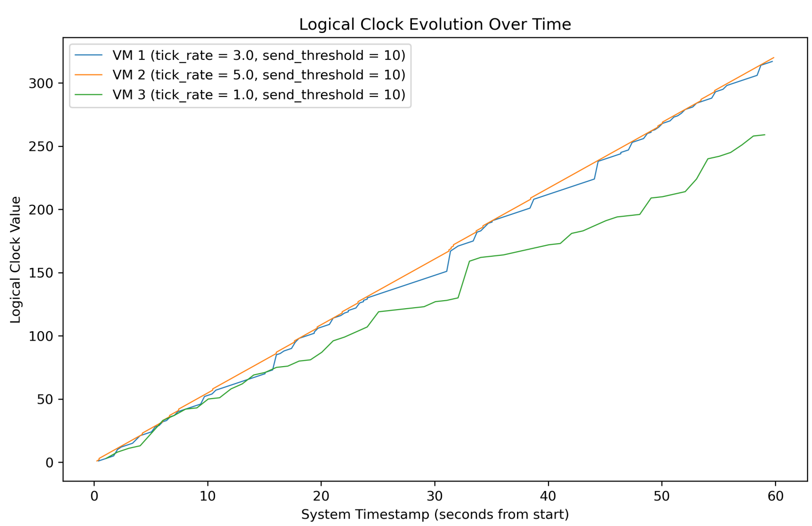
Our expected behavior should be that for each experiment, the fastest processes should be perfectly linear and the other slower processes should be trying to catch up but never surpass it (although there could be scenarios where it does actually catch up and equal the logical clock time of the fastest one). Something else to note is that we are using interpolation, meaning clock drift could be a decimal value. The reason for this is because the interpolation function estimates the clock value at any given (continuous) timestamp—even if the original clock updates are recorded as integers—so the difference between the actual integer value and the interpolated value can result in a fractional (decimal) number when we do the calculation of $VM_i - VM_1$.

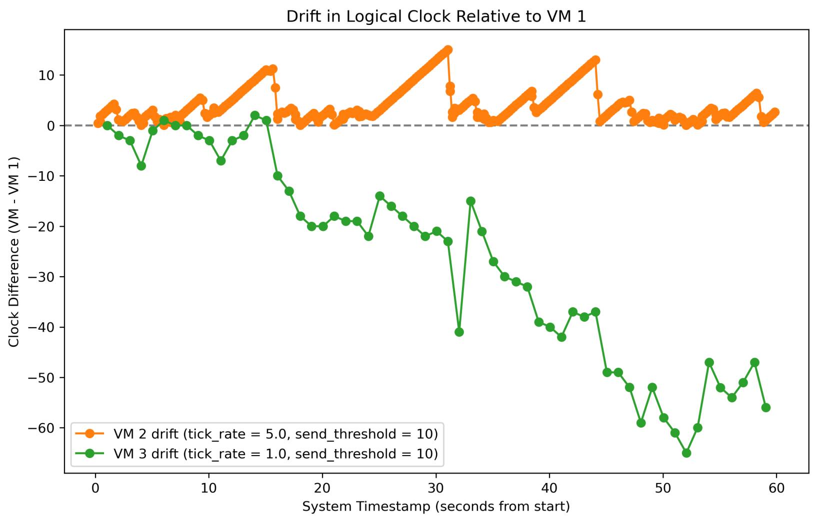
Some other expected behavior is that if the message queue ever builds up, slower processes should experience large clock drift. This is because their own internal clock is comparing the maximum of the sent message time (which was a long time ago per the idea of the queue getting built up), and the local time of the clock, which can't really update if it is stuck behind on all these messages. Eventually if the queue clears though, this would mean we should expect large jumps in logical clock time.

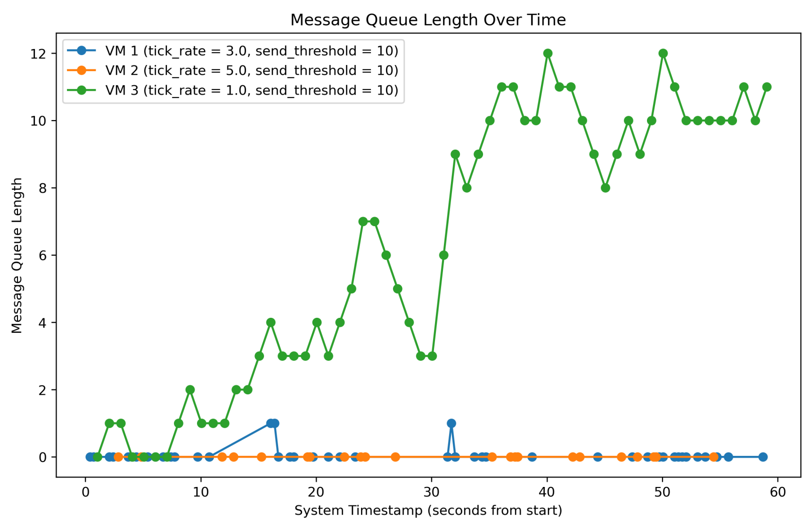
7.1 Default Experiment

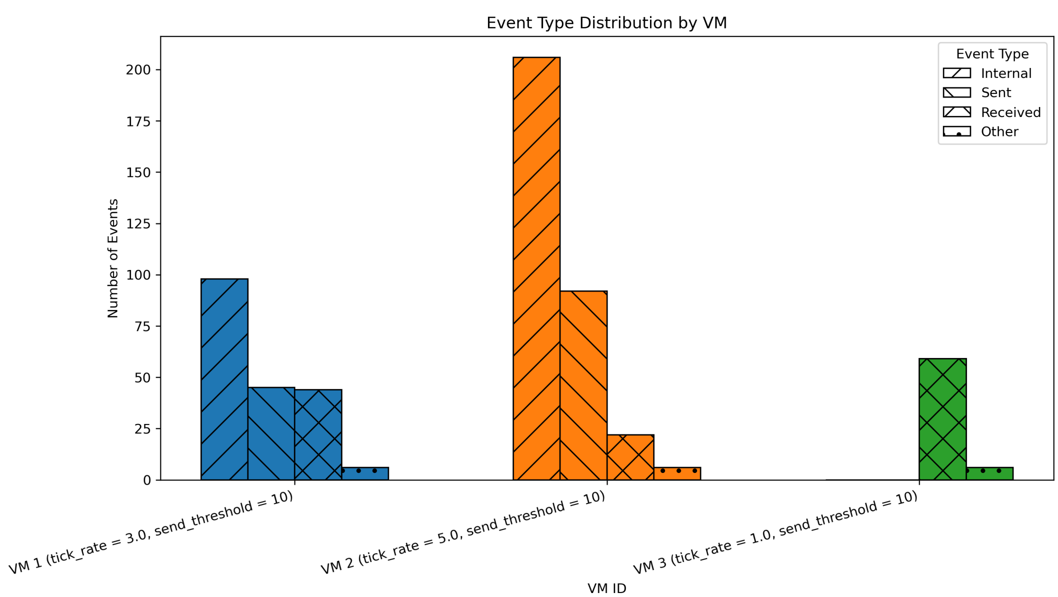
The baseline experiment serves as a control, where the system operates with its default parameters. This allows us to compare deviations in behavior when modifying specific aspects of the simulation. Here, we have 3 virtual machines running for 60 seconds, with random tick rates between 1 and 6 for each machine. We also have the default threshold at 10, meaning there is a 10% chance of sending messages to process 1, 10% chance of sending messages to process 2, and 10% chance of sending messages to both processes, and the remaining 70% chance being just to process an internal event.

To run this experiment, we simply used the command `python src/main.py`. We will display one set of graphs now, but the repo holds the other 4 test results from here:









Since this is our default experiment, we reference these results in later analysis as a baseline.

When plotting Logical Clock Value over System Timestamp, we observe near linear behavior for the three virtual machines, and the drift behavior in the second graph also matches what we expect from the build up in the queue.

We can see here that there are some key behaviors we've observed. First, since VM 2 is the fastest, it always drifts faster relative to VM 1. Meanwhile, since VM 3 is the slowest, it drifts slower relative to VM 1, which matches the clock drift. In addition, we see that the fastest clock in the first graph is always first (never passed) and is almost perfectly linear. We suspect it isn't perfectly linear due to the fact that our computers were naturally lagging, especially as other processes have to run on them, so there could be an instant where the fastest process doesn't have priority by the operating system.

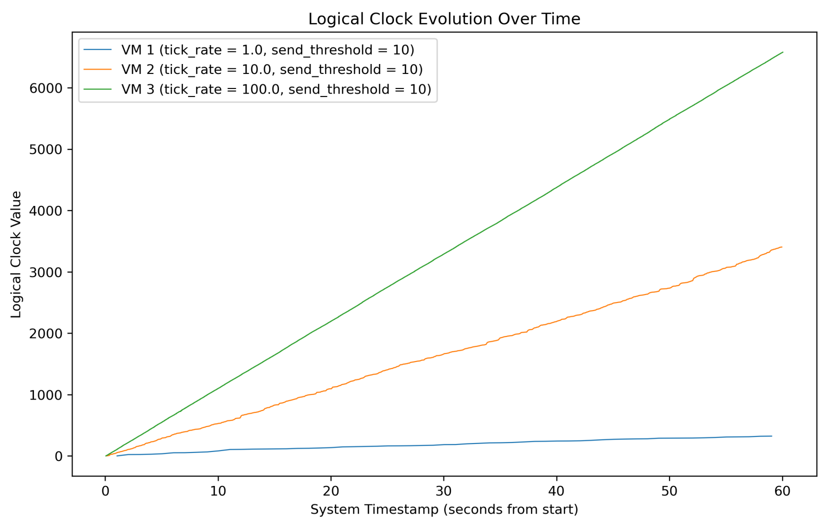
In addition, we can see that the slowest process has the largest queue, which makes sense, since faster processes have more chances to keep sending messages to slower processes while they're still in wait. Lastly, we can see that faster ticks obviously correlate to more events, and they have more chances to be internal events. However, slower processes are stuck more with received events since they have to deal with their message queue.

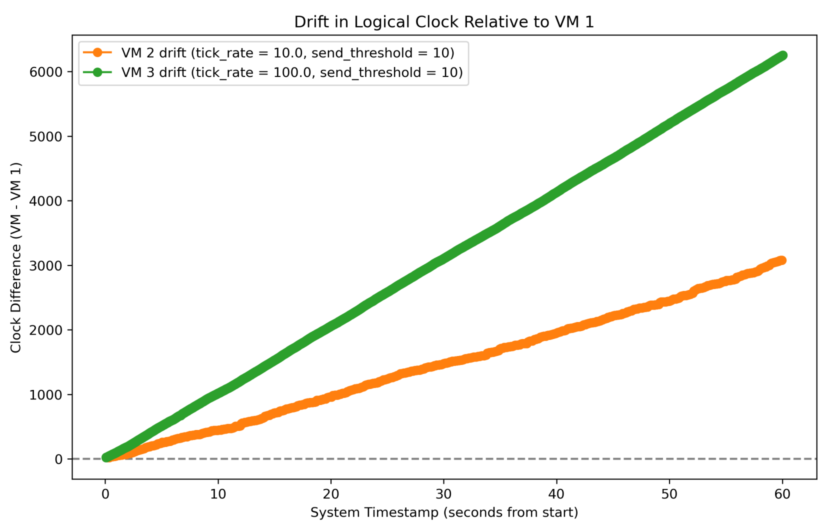
7.2 Varying Tick Rates by Orders of Magnitude

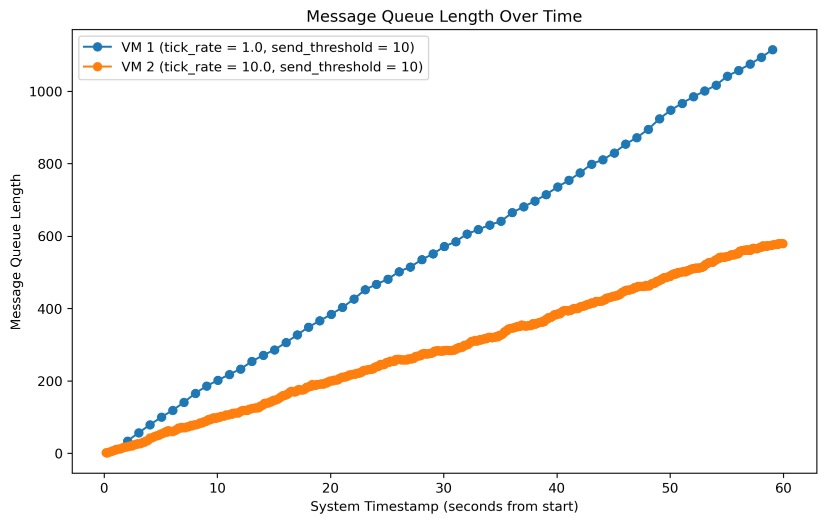
- **Purpose**:
  - Investigate how changing the tick rate (e.g., increasing or decreasing it by factors of 10) affects clock drift and synchronization behavior.
  - Understand whether more frequent or less frequent ticks impact message timing and processing.
- **Analysis Points**:
  - How tick rate changes influence clock updates.
  - The extent to which faster or slower ticks modify message processing rates.
  - Any emerging patterns in synchronization as tick rate varies.

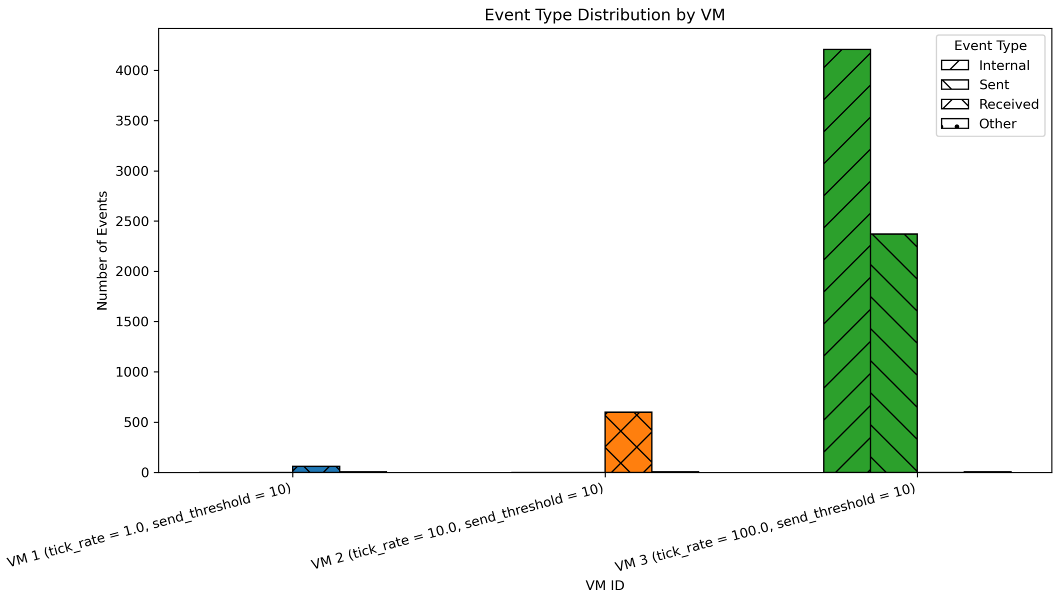
To run this experiment, we used the command `python src/main.py --tick_rates 1,10,100` which manually sets the tick rates to these values. Again, the other 4 test results are in the repo.

In theory, this setup should yield distinctly different logical clock behaviors: the VM with a tick rate of 100 is expected to increment its clock nearly linearly because it ticks very frequently, while the slower VMs (with tick rates of 1 and 10) will rely more on message receptions to update their clocks. As a result, the slower machines are likely to show more abrupt jumps in their logical clock values when they process incoming messages, and their overall clock progression will remain consistently behind that of the fastest VM. The drift plot should therefore display the largest deviation for the slowest VM, a moderate deviation for the medium-speed VM, and a nearly linear progression for the fastest VM. Also, we expect the message queue behavior to differ significantly among the VMs: the slowest VM (tick rate 1) is likely to build up a substantial queue since it processes events and messages infrequently, resulting in longer delays before clearing its queue; the medium-speed VM (tick rate 10) should exhibit moderate queue lengths; and the fastest VM (tick rate 100) will process messages rapidly, keeping its queue relatively short. Consequently, when graphing the message queue lengths, we should observe that the slowest machine's queue is much larger compared to the near-linear and minimal queue of the fastest machine.









An important general observation is that overall we see constant increases over time, which is what we hoped for. Moreover, we see that the VM3 drift has a greater slope than that of VM2, with greater oscillations in the message queue length over time, which is in alignment with what we expect. Clock drift should generally be constant since the orders of magnitude are so largely different that both of the slower processes will be stuck in the queue forever. We can see this with the queue graph too; both are basically never 0 and VM 3 is never in the message queue pipeline.

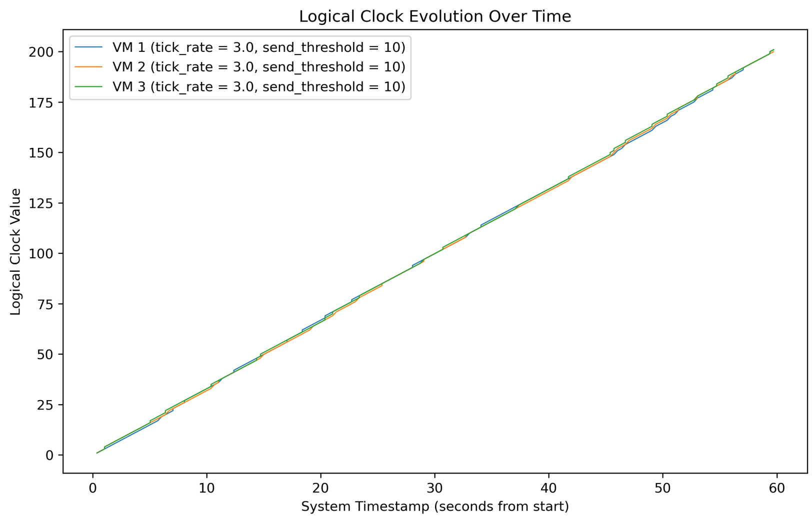
7.3 Uniform Tick Rates

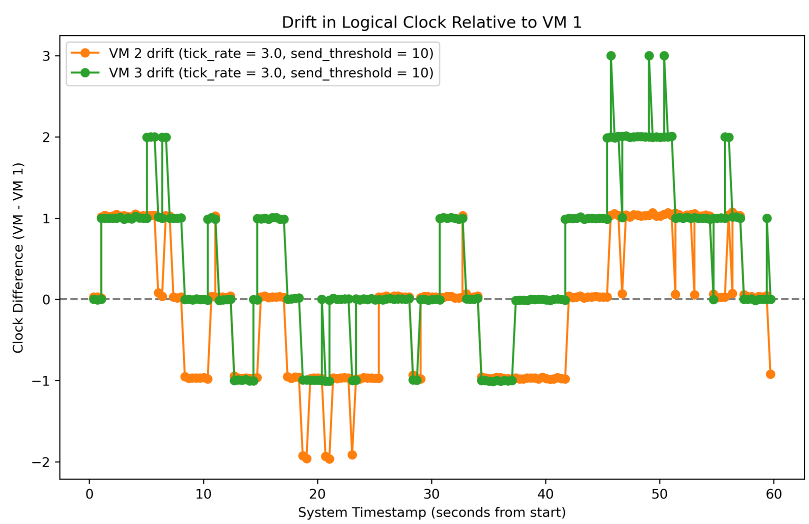
- **Purpose**:
  - Evaluate how enforcing a strict, uniform tick rate across all VMs impacts clock drift.
  - Determine whether a fixed tick interval leads to more predictable synchronization behavior.

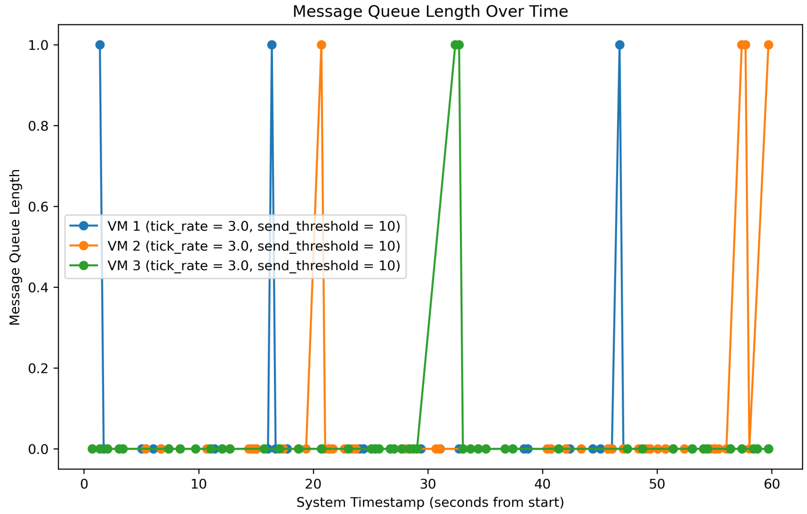
- **Analysis Points**:
  - Whether enforcing uniformity reduces randomness in drift.
  - Comparison of clock variations in this setting versus the default.

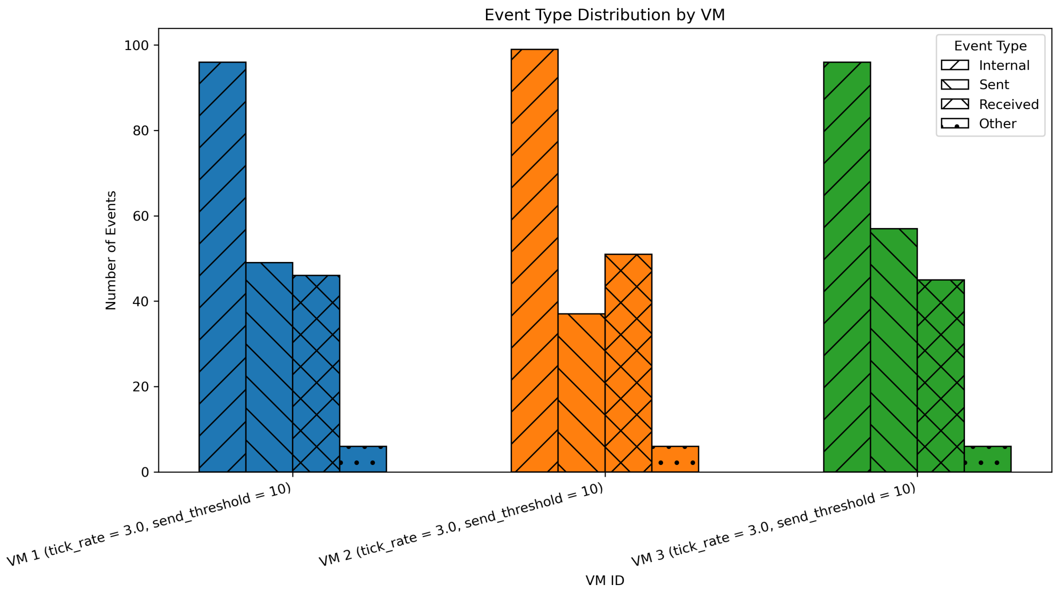
To run this experiment, we used the command `python src/main.py --tick_rates 3,3,3` which means all of the VM's have tick rates of 3. The other 4 trial results are in the repo.

The expected results for uniform should be all the clocks running at relatively the same rate. Clock drift may occur slightly, but it should not have high variance. Message queues should be very small, and the distribution of events should be the same.









For our first graph, the three machines are all running at about the same rate, with drift for VM2 and 3 generally moving in the same direction with some variation in time and amplitude. Otherwise, the event type distributions are promising for all three. Although the drift sometimes oscillates, we chalk that up to interpolation or lag.

Something unique to the uniform tests is that because all of them are the same tick rate, this is the one instance where we should expect the virtual machines to constantly be oscillating between being too fast and too slow. However, the magnitude of this drift will never be too high, which is what we observe, being bounded by -2 and +3 seconds. This makes sense; since they're all the same rate, and sent message be updated at the same time, and it is probabilistically unlikely for other processes to clog up a specific process' queue.

When analyzing the queue length graph, we can also see that the queue never went above 1, which is a great sign. Lastly, but obviously, graph 4 is basically identical, which makes sense since all virtual machines have the same tick rate parameter, so they should be managing about the same events.

7.4 Increasing/Decreasing Threshold While Keeping Default Tick Rates

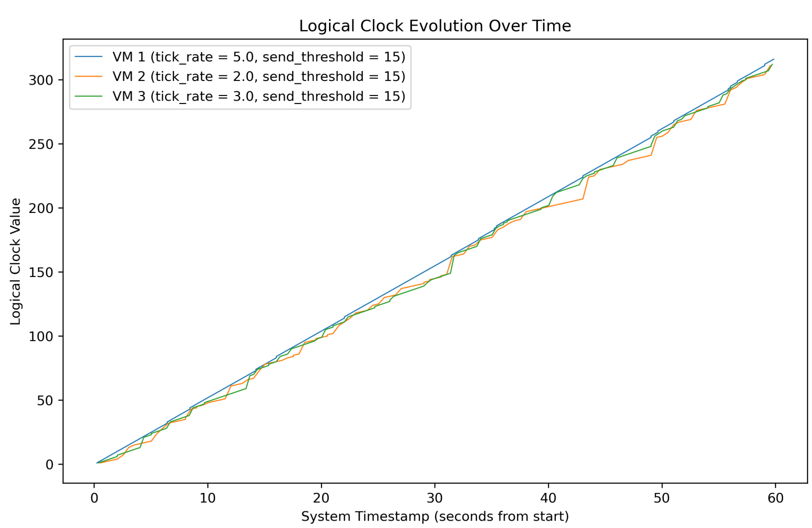
In these experiments, we keep the tick rate at its default value but vary the threshold determining whether a VM sends messages or performs internal events.

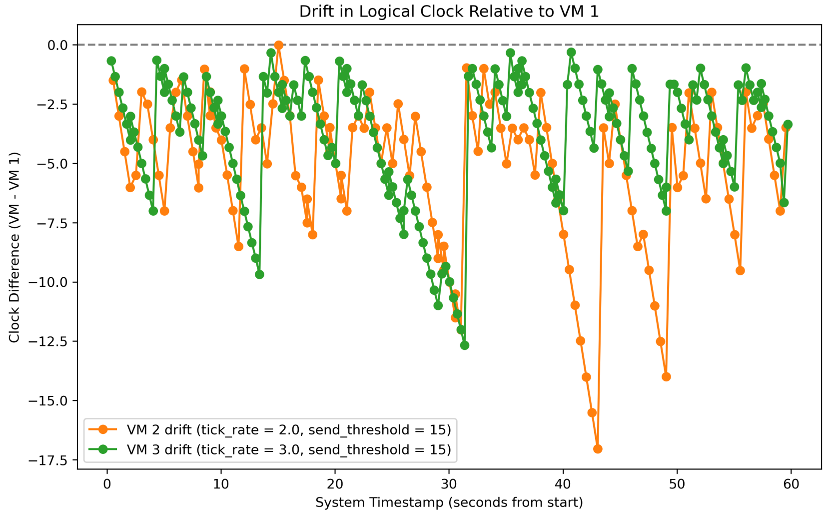
7.4.1 If We Increase the Threshold

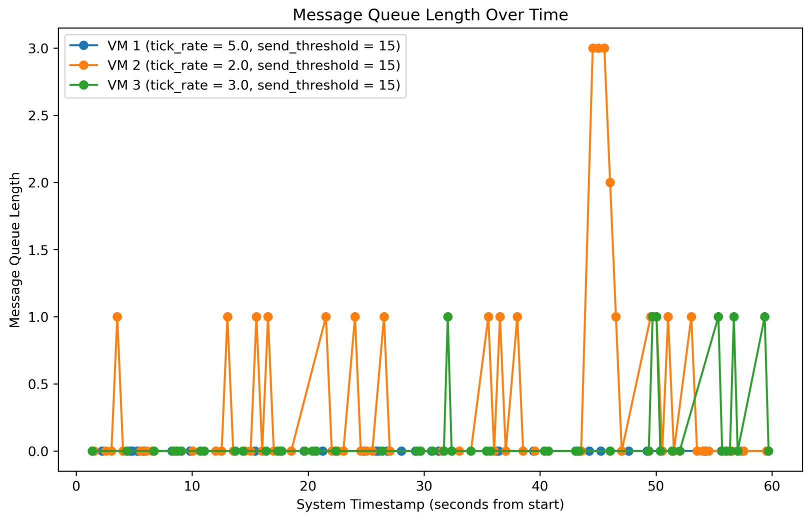
- **Purpose**:
  - Increase the probability that a VM sends messages instead of performing internal events.
  - Observe how increased message exchanges influence clock updates and drift.
- **Analysis Points**:
  - The size of clock jumps due to message receipts.
  - Changes in overall clock drift compared to the default experiment.
  - Any differences in message queue length or event type distribution.

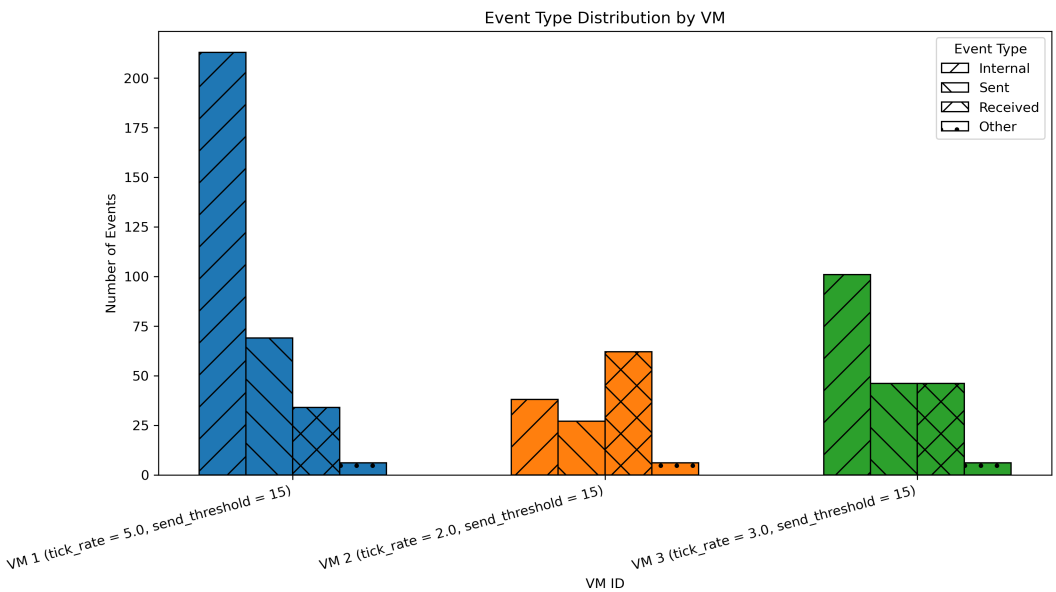
To run this experiment, we used the command `python src/main.py --send_threshold 15` which should mean that the probability of sending a message (regardless of how many processes to send to) should drop from 30% to 20%. We decided to keep smaller tick rates so we could compare to the main experiment. Again, other trials are in the repo.

For expected results, this should obviously mean that the probability of sending a message should decrease, so the average queue length should also decrease (since messages aren't being sent as often). However, this also means that when messages occur, they will be more outdated relative to every other clock, so we could potentially see choppy drifts with lower queues.









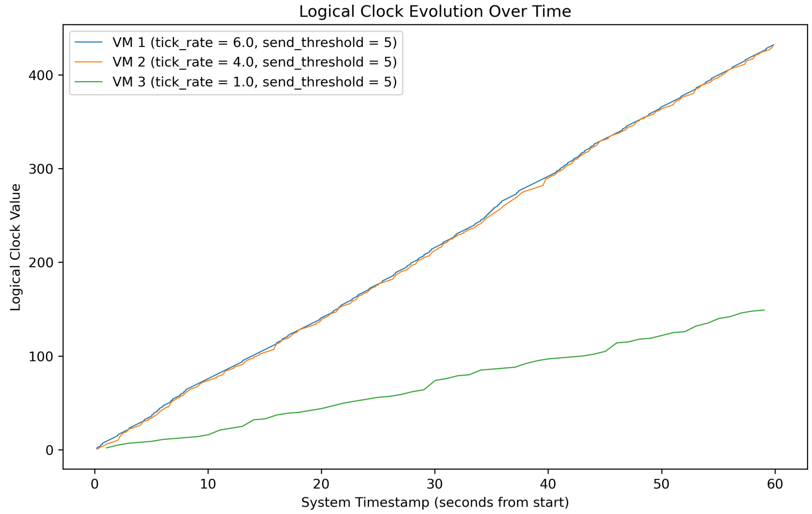
Once again, the three VMs evolve over logical clock value similarly, which is expected. The more dramatic spikes could be explained with our theorized hypothesis at the start. Of course, with a higher probability of an internal event, we're less likely to see a message queue. In addition, we can see that internal messages are increased in distribution, which is of course what we expect.

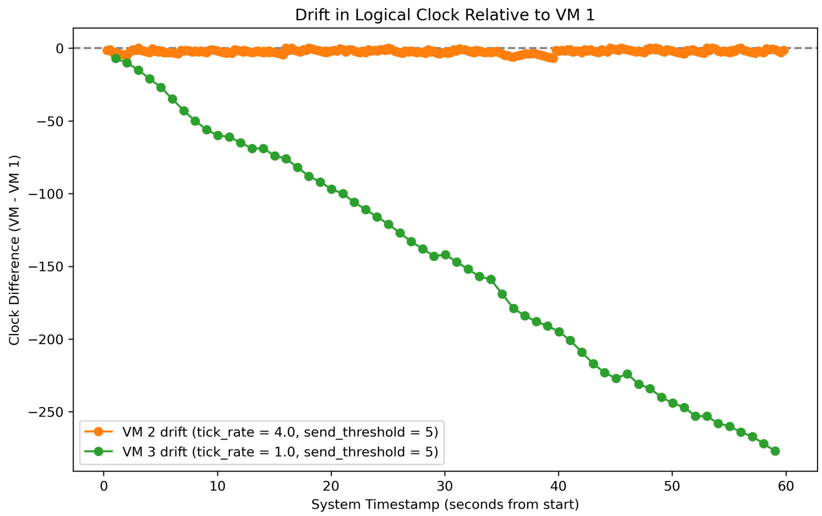
7.4.2 If We Decrease the Threshold

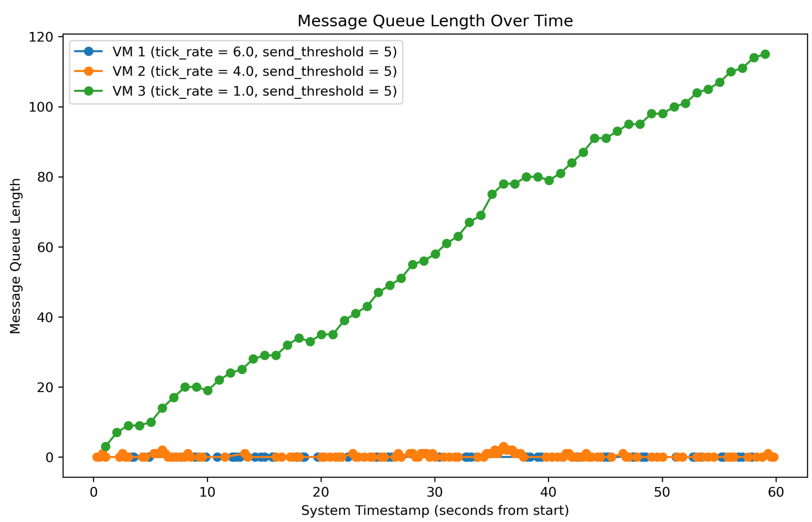
- **Purpose**:
  - Increase the relative frequency of internal events, thereby reducing the frequency of message exchanges.
  - Determine whether reducing messaging results in more uniform, predictable (more linear) drift.
- **Analysis Points**:
  - Differences in drift behavior when fewer messages are exchanged.
  - Comparison of clock increments (jumps due to message receipts versus steady internal increments).
  - Event type distribution, where we expect an increase in internal events.

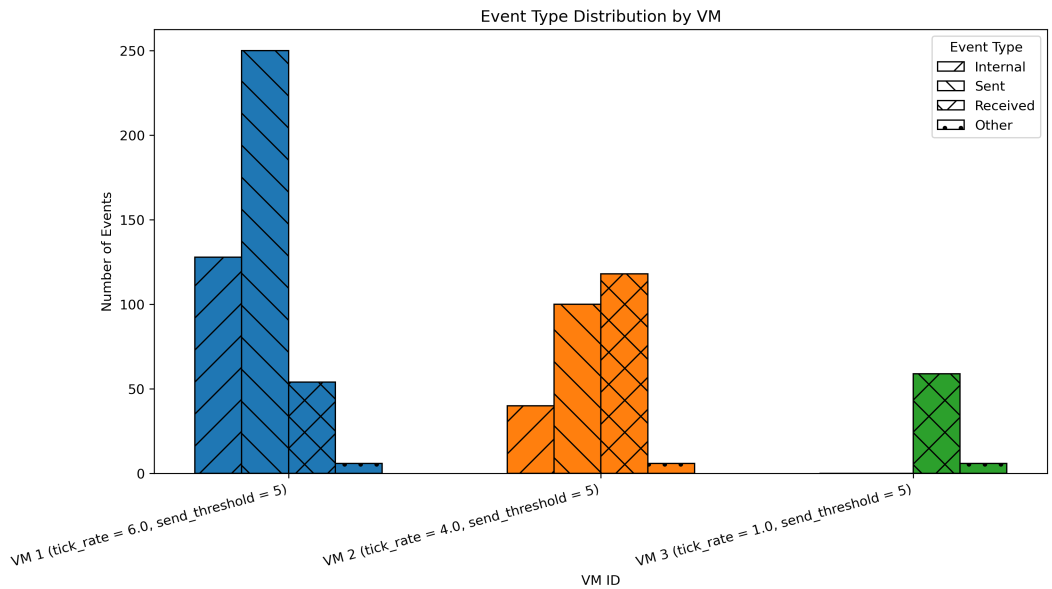
To run this experiment, we used the command `python src/main.py --send_threshold 5` which should mean that the probability of sending a message (regardless of how many processes to send to) should increase from 30% to 60%. We decided to keep smaller tick rates so we could compare to the default experiment. Again, other trials are in the repo.

For the experiment, the probability of sending a message increases from 30% to 60%. In theory, this means that VMs will send messages much more frequently. As a result, we would expect the average message queue length to increase since more messages are being generated and received. With more frequent messaging, the logical clocks will be stuck in their queues. If they get out, we might see big jumps in clock drift, but if they're constantly stuck in the queue, we won't actually see much drift. Consequently, the drift between VMs could become more smooth and exhibit less noticeable step changes, as the clocks frequently "catch up" to one another via these received messages less often.


Logical Clock Evolution Over Time
VM 1 (tick_rate = 6.0, send_threshold = 5)
VM 2 (tick_rate = 4.0, send_threshold = 5)
VM 3 (tick_rate = 1.0, send_threshold = 5)
Logical Clock Value
System Timestamp (seconds from start)


Drift in Logical Clock Relative to VM 1
VM 2 drift (tick_rate = 4.0, send_threshold = 5)
VM 3 drift (tick_rate = 1.0, send_threshold = 5)
Clock Difference (VM - VM 1)
System Timestamp (seconds from start)


Message Queue Length Over Time
VM 1 (tick_rate = 6.0, send_threshold = 5)
VM 2 (tick_rate = 4.0, send_threshold = 5)
VM 3 (tick_rate = 1.0, send_threshold = 5)
Message Queue Length
System Timestamp (seconds from start)



Something curious to consider is that VM 2 had very very little drift relative to VM 3. While VM 3 does have a much slower tick rate, comapred to the baseline experiments, we didn't see such drift, which is why it is cool to compare it to the default. We suspect as such that the message queues could get piled up, and we see this in our third graph, with VM 3 really outpacing the others with respect to the queue. Lastly, we can see that the probability for internal events has declined in the fourth graph.

8 Conclusion

Overall, it's important to note that there are inconsistencies and variations in some of our results that are beyond our control (e.g. running tests locally might have competing processes with what's happening in the background, etc), but our results generally match with what is expected (e.g. general linear behavior of logical clock evolution over time with the exception of some non-linear jumps, relative drift patterns, etc). Even though our results aren't hitting the theoretical optimal, we're pretty close, and given factors like hardware constraints, we feel good about our where our deliverable is at.