

Raftian: Pygame Meets Raft

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The problem of shared consensus in a distributed system is both older than a millennium and more relevant than ever: while in the Aegean island of Paxos the challenge was to keep track of the many laws passed in a parliament where legislators had better to do than attend sessions full-time, nowadays the ubiquity of web-based architectures and applications (from a simple cloud storage to the whole banking system) gives daily headaches to developers and system administrators alike. To reduce ibuprofen consumption in the IT sector, Ongaro and Ousterhout devised an easily understandable and implementable alternative to the Paxos algorithm, namely the Raft consensus algorithm, which we employ in this work to implement communication via XML-RPC between multiple Pygame applications, each running a game instance that aims to simulate a simplified version of a real-time strategy game.

CCS Concepts: • **Computer systems organization** → **Fault-tolerant network topologies**; • **Computing methodologies** → **Concurrent algorithms**; **Self-organization**; *Graphics input devices*.

Additional Key Words and Phrases: Python, Raft, Distribution, Consensus, Gaming, Multiplayer, Multithreading, RPC, Pygame

ACM Reference Format:

Marco Bellò and Tullio Vardanega. 2018. Raftian: Pygame Meets Raft. 1, 1 (August 2018), 15 pages. <https://doi.org/XXXXXXX.XXXXXXX>

1 INTRODUCTION

From sharing spreadsheets between a handful of laptops in a small basement office, through large-scale rendering on a supercomputer, to the entire global finance system, distributed computing has become an essential component of the modern world that we almost take for granted: nowadays, what most people need a computer for can be done in the browser thanks to services like email clients, cloud calendars, media streaming platforms and web-based office suites (like Google Docs) that expose word editors, spreadsheets managers, presentations programs and more, all while being constantly synchronized to the cloud, which not only ensures data persistence and availability, but also enables sharing and collaboration between users.

It does not end here: other examples of distributed applications include cloud storage services like Dropbox, Google Drive or OneDrive, streaming services like Netflix, YouTube or Spotify, distributed computing like blockchain technologies or AWS, online banking services (the banking system itself is distributed since way before), social networks, and even maritime and aircraft traffic control systems. Moreover, the rise of the gaming industry played a significant role in pushing forward distribution: in 2024 the gaming market revenue was estimated to be 187.7 billion U.S. dollars [2], making it a hefty slice of the pie that is the entertainment industry [13], with 111 billions generated by free-to-play games [3] (70 billions from social and casual games alone [8]), which interests us since their business model often relies on cosmetics, game passes and advertisements, forcing them to be constantly on-line.

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Let's now define what distribution *is*: a distributed system is a computer system whose inter-communicating components are located on different networked computers [1, 17], which coordinate their actions via message-passing to achieve a common goal. There are three significant challenges to overcome: maintaining components' concurrency¹, eliminating global-lock reliance and managing the independent failure of components, all while ensuring scalability (often the purpose is scaling itself) and transparency to the user, meaning interactions with any exposed interface must be done while being unaware of the complexity behind them.

Most importantly, shared consensus must be guaranteed: it does not require much thought to see that all servers in a cluster should agree on one or more shared values, lest becoming a collection of un-related components that have little to do with collaboration (thus distribution). In the most traditional single-value consensus protocols, such as Paxos [10], cooperating nodes agree on a single value (e.g., an integer), while multi-value alternatives like Raft [11] aim to agree on a series of values (i.e., a log) growing over time forming a sort-of cluster's history. It is worth noting that both goals are hindered by the intrinsically asynchronous nature of real-world communication, which make it impossible to achieve consensus via deterministic algorithms, as stated by Fischer, Lynch and Paterson in their FLP impossibility theorem [5]. Thankfully this can be circumvented by injecting some degree of randomness.

1.1 Project's Contributions

The concepts and examples we mentioned so far allow us to finally present the goal of this project: we will create a simplified clone of Travian², an old real-time³ player-versus-player⁴ strategy game⁵, where players build their own city and wage war on one another (less wrinkly readers may be more familiar with the modern counterpart Clash of Clans⁶), built with Pygame⁷, a Python library that creates and manages all necessary components to run a game such as game-engine, graphical user interface, sounds, player inputs and the like, where each player resides in a separate server (or node) that communicate with the others via an algorithm modelled after Raft's specifications.

This choice follows the authors' interest in exploring Raft capabilities and ease of implementation in a fun and novel way, using a language that while extremely popular is seldom used in such a fashion and, as far as we can tell, never with this mixture of libraries.

Both game and algorithm implementations have been reduced to a reasonably complex proof of concept to keep the project scope manageable: it is possible to instantiate games up to five players, each of which is restricted to the only action of attacking the others, while Raft's functionalities are limited to log replication and overwriting.

Experiments were conducted to evaluate both game responsiveness and the communication algorithm correctness.

All source code is visible at the following link: <https://github.com/mhetacc/RuntimesConcurrencyDistribution/blob/main/raftian/raftian.py>.

¹Concurrency refers to the ability of a system to execute multiple tasks through simultaneous execution or time-sharing (context switching), sharing resources and managing interactions. It improves responsiveness, throughput, and scalability [6, 12, 14, 16, 18].

²Travian: Legends is a persistent, browser-based, massively multiplayer, online real-time strategy game developed by the German software company Travian Games. It was originally written and released in June 2004 as "Travian" by Gerhard Müller. Set in classical antiquity, Travian: Legends is a predominantly militaristic real-time strategy game. Source: <https://www.travian.com/international>

³Real-time games progresses in a continuous time frame, allowing all players (human or computer-controlled) to play at the same time. By contrast, in turn-based games players wait for their turn to play.

⁴Player-versus-player (PvP) is a type of game where real human players compete against each other, opposed to player-versus-environment (PvE) games, where players face computer-controlled opponents.

⁵Strategy video game is a major video game genre that focuses on analyzing and strategizing over direct quick reaction in order to secure success. Although many types of video games can contain strategic elements, the strategy genre is most commonly defined by a primary focus on high-level strategy, logistics and resource management. [15]

⁶Clash of Clans: <https://supercell.com/en/games/clashofclans/>

⁷Pygame: <https://www.pygame.org/docs/>

2 PYTHON

We will now discuss the technologies employed in the development of the project (section 2) as well as presenting our implementation of the algorithm Raft.

Python is a high-level, dynamically typed and interpreted programming language that is often used for scripting, data analysis and developing small applications, making it a non-obvious choice for this project, which does not fall into any of these categories.

As a language, it has two main advantages compared to others: first of all it is undoubtedly the most popular and widely used in the world (figure 1) [4, 7] which translates to abundant documentation and resources, and secondly it has a huge ecosystem of libraries that implement all the functionalities we need for this project, namely: *xmlrpc* for the remote procedure calls (RPCs), *threading* to handle local concurrency and *Pygame* to manage everything game-related.



Fig. 1. TIOBE Programming Community Index, focus on Python statistics, 2025. (<https://www.tiobe.com/tiobe-index/>).

2.1 Remote Procedure Calls

In Raft's specifications it is stated that nodes communicate with each other via remote procedure calls [11], which in distributed computing is when a program causes a procedure (or subroutine) to execute in another address space (commonly on another computer on a shared network) calling it as if it were local (that is, the programmer writes the same code whether the subroutine is local or remote).

There are many libraries that implement this functionality, like gRPC (<https://grpc.io/>) which is a high performance open source RPC framework used by many big players, such as Netflix⁸ and Cockroach Labs⁹, available for many languages (Python included), but we opted for the standard library *xmlrpc*¹⁰ thanks to its promised simplicity and ease of use.

The library provides both server and client implementations, encapsulating the former in its own loop, while the latter can be fired as needed allowing a bit more flexibility in its usage.

In code 1, `client` is an instance of `ServerProxy`, which acts as the client-side interface for XML-RPC, allowing you to call the remote procedure `test_foo` as if it were a local function, even though it executes on a server in a different networked location.

⁸Netflix Ribbon is an Inter Process Communication library built in software load balancers: <https://github.com/Netflix/ribbon>

⁹Cockroach Labs is the company behind CockroachDB, a highly resilient distributed database: <https://www.cockroachlabs.com/>

¹⁰XML-RPC is a Remote Procedure Call method that uses XML passed via HTTP as a transport: <https://docs.python.org/3/library/xmlrpc.html>

Listing 1. Client as server proxy

```

157 with xmlrpc.client.ServerProxy('http://localhost:8000', allow_none=True) as client:
158
159     print(client.test_foo(42)) # print returned value
160

```

The server must be instantiated and kept running by calling its event loop (e.g., using `serve_forever`), and all remote procedure calls must be registered using the `register_function` method of `SimpleXMLRPCServer` (code 2).

Listing 2. Server

```

167 with SimpleXMLRPCServer (('localhost', 8000)) as server:
168
169     def test_foo(number):
170         return f'The number is {number}'
171
172     server.register_function(test_foo)
173
174     server.serve_forever() # keep server alive
175

```

For this project, we extended *SimpleXMLRPCServer* to create a class that implements the Raft protocol (more details in section 3)

2.2 Concurrency

In this project the need for concurrent programming arises from two challenges: every server have an internal timer that fires at certain intervals, and every node has to run a game engine and the server itself at the same time, both of which can be simplified as two *"while true"* loops.

Most Raft implementations achieve concurrency with asynchronous programming, using libraries such as *asyncio*¹¹, which while powerful and efficient, makes writing code a bit awkward and cumbersome. We thus opted for a more traditional approach using multithreaded programming: in computer science, a thread of execution is the smallest sequence of programmed instruction that can be managed independently by the scheduler [9], and multiple threads may be executed concurrently sharing resources such as memory, which is directly counterpointed to multiprocessing where each process has its own storage space (moreover, processes are typically made of threads).

In Python there are modules in the standard library for both of them, respectively *threading*¹² and *multiprocessing*¹³. It is fundamental to note that the former does not provide real multi-threading since, due to the Global Interpreter Lock of CPython (the, for want of a better word, "official" Python implementation), only one thread can execute bytecode at once. To cite directly from the documentation: "[GIL is] The mechanism used by the CPython interpreter to assure that only one thread executes Python bytecode at a time. This simplifies the CPython implementation by making the object model (including critical built-in types such as dict) implicitly safe against concurrent access. Locking the entire interpreter makes it easier for the interpreter to be multi-threaded, at the expense of much of the parallelism afforded by multi-processor machines."¹⁴

¹¹asyncio is a library to write concurrent code using the `async/await` syntax: <https://docs.python.org/3/library/asyncio.html>

¹²The threading module provides a way to run multiple threads (smaller units of a process) concurrently within a single process: <https://docs.python.org/3/library/threading.html>

¹³The multiprocessing module is a package that supports spawning processes using an API similar to the threading module: <https://docs.python.org/3/library/multiprocessing.html>

¹⁴Global Interpreter Lock: <https://docs.python.org/3/glossary.html#term-global-interpreter-lock>

Thankfully, this does not apply with the *multiprocessing* module, which creates separate processes instead, offering both local and remote concurrency effectively side-stepping the Global Interpreter Lock, allowing programmers to fully leverage multiple cores. As previously stated, processes are much heavier than threads and thus more expensive to create, but do not incur the risks of shared memory.

2.2.1 Comparison. To evaluate which of the two modules is more suited for our purposes, we devised a simple experiment: we created two game instances with one hundred and one thousands coloured dots respectively (figure 2), that move around the screen offsetting their position each frame by a random amount between minus five and plus five pixels (pseudocode 3).

Then we ran both of them in various scenarios: with the game instance alone (baselines), with a server alive in a thread and with a server alive in a process, and we measured the *frames per second* (FPS)¹⁵ in each case, since it is the most common metric to evaluate game performance. Higher FPS-count translates to a smoother and more responsive, i.e., better, gaming experience.

Listing 3. Pygame graphical dot

```
# create random offsets for both x and y coordinates
xmov = random.randint(-5,5)
ymov = random.randint(-5,5)

# move the dot by a certain offset
dot.move_by(xmov, ymov)
```

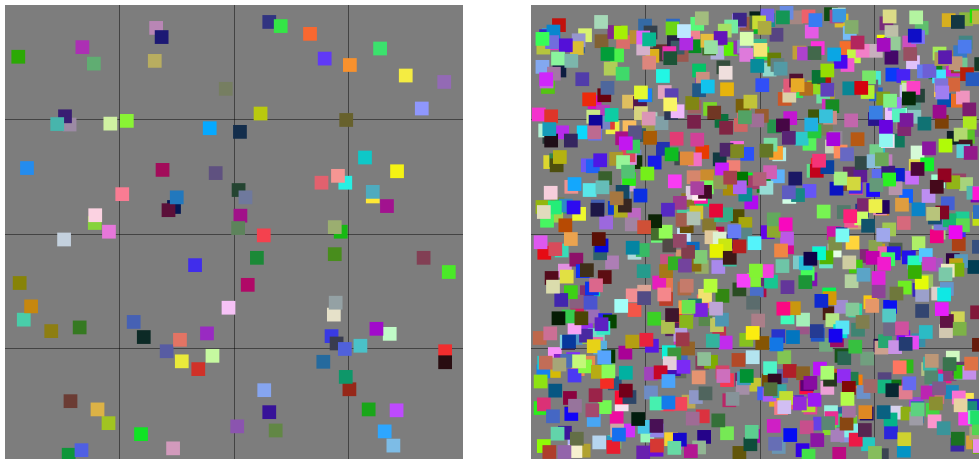


Fig. 2. Two game instances made with Pygame, with respectively 100 and 1000 dots that randomly move around.

Results, shown in the graph at figure 3 shows us that:

- Increasing the number of dots from 100 to 1000 halves the FPS count;

¹⁵Frame rate, most commonly expressed in frames per second or FPS, is typically the frequency (rate) at which consecutive images (frames) are captured or displayed. This definition applies to film and video cameras, computer animation, and motion capture systems, while in the context of computer graphics is the rate at which a system, particularly the graphic card, is able to generate frames. Source: https://en.wikipedia.org/wiki/Frame_rate

- Adding a server in a separate thread halves performances;
- Using *multiprocessing* yields worse performances than *threading* in the 100-dots scenario (about -30%) while performs similarly in the 1000-dots one.

This leads us to conclude that, for our specific purposes, the *threading* module is the best choice, especially since the final game will be way less computationally expensive from a graphical standpoint, hence using a lighter weight alternative should be even more beneficial than tested.

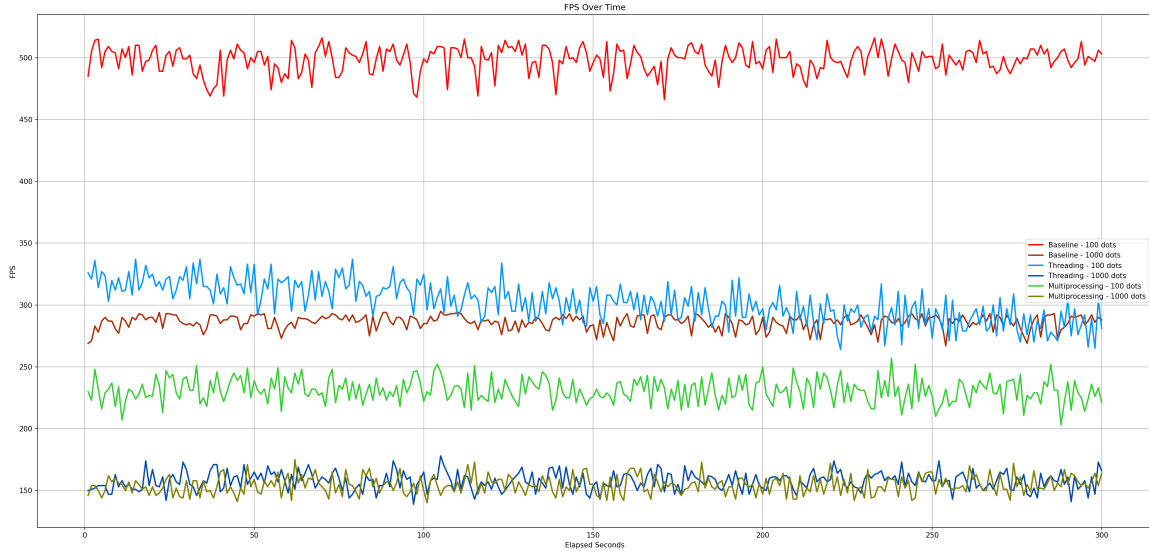


Fig. 3. Performance evaluation graph: red hues for baselines, blue hues for threading and green hues for multiprocessing. Darker shades for 1000 dots and lighter shades for 100 dots game instances.

All tests have been performed with the following machine:

- OS: Ubuntu 24.04.1 LTS x86_64;
- Kernel: 6.8.0-52-generic;
- Shell: bash 5.2.21;
- CPU: 13th Gen Intel i7-13620H;
- GPU: NVIDIA GeForce RTX 4050 Laptop GPU;
- Memory: 15610MiB;
- Python version: 3.12.3;
- Power Mode: Balanced;
- Power Supply: 100W via type C.






2.3 Game Engines

There are many ways to implement a graphical user interface: from clever shell tricks like `htop`¹⁶, to full fledged game engines like Unity¹⁷ or Godot¹⁸ that often come with their own editor and a *top-down* approach, meaning build the UI first and then go down to code as needed for scripting and refining.






Unfortunately our needs are quite opposite: what we want is a code-only, mono-language framework that while slowing down game development should simplify merging Raft with it. The choice thus boiled down to two alternatives: `tkinter` and `Pygame`.

2.3.1 Comparison. Let's list strengths and weaknesses of the two.

- **`tkinter`:**

-  Module of the standard library;
-  Few lines of code to make simple UIs;
-  Low flexibility;
-  No game loop;
-  Not a game engine;

- **`Pygame`:**

-  Extreme flexibility;
-  Direct access to game loop;
-  APIs to access many kinds of user inputs;
-  Verbose to obtain simple UIs;
-  Non-standard community-made framework.

We ultimately decided to opt for `Pygame` for four reasons: it is extremely flexible, exposes many useful functions (for example to catch different user inputs), gives direct access to the game loop and it is a novel and fun framework that has never, to the best of our knowledge, been used in such a fashion.

3 RAFT

It is not our intention to plagiarize Ongaro and Ousterhout's excellent work "In Search of an Understandable Consensus Algorithm" [11] by presenting the Raft algorithm's specifications. Instead, we will discuss how we interpreted and implemented it to mold it into our own use case

The algorithm uses three types of nodes, namely *leader*, *follower* and *candidate*, and revolves around three core functionalities: leader election, log replication and cluster membership change. Log compaction is also mentioned, while a byzantine fault tolerant variant is never explored by the original authors.

One last component, instrumental to the functioning of the algorithm, is the *term*: everything happens in a certain term, which divides time logically and increments every election.

Our Raft class directly extends `simpleXMLRPCServer` from XML-RPC module, as shown at code 4.

Lastly, to fire off non-blocking concurrent RPCs on the cluster, we leverage the `concurrent.futures` module using `ThreadPoolExecutor`. To avoid having to keep creating and destroying pools every time a server needs to communicate with the cluster, we embedded a finite amount of workers as class attributes (code 5).

¹⁶`htop` is a cross-platform text-mode interactive process viewer: <https://htop.dev/>

¹⁷Unity is a cross-platform game engine developed by Unity Technologies: <https://unity.com/>

¹⁸Godot is a cross-platform open-source game engine: <https://godotengine.org/>

Listing 4. Class Raft definition

```

class Raft(SimpleXMLRPCServer):
    def __init__(self,
                  addr: tuple[str, int],
                  allow_none: bool = True,
                  # ...
                  last_index_on_server: list[tuple[int, int]] | None = None
                  ):
        SimpleXMLRPCServer.__init__(self, addr=addr, allow_none=allow_none)

```

Listing 5. ThreadPoolExecutor workers

```

class Raft(SimpleXMLRPCServer):
    def __init__(self,
                  # ...
                  ):
        # start executors pool
        self.executor = concurrent.futures.ThreadPoolExecutor(max_workers=len(self.cluster))

```

3.1 Node Types

There are three types of node, namely leader, follower and candidate (code 6). In this section we are going to show their characteristics and similarities. Note that all nodes have a timer: it is randomized for each of them and has been implemented by extending *threading.Timer*, thus making it thread-safe (code 7)

Listing 6. Node modes

```

class Raft(SimpleXMLRPCServer):
    class Mode(Enum):
        LEADER = 1
        CANDIDATE = 2
        FOLLOWER = 3

    def __init__(self,
                  # ...
                  mode: Mode = Mode.FOLLOWER,
                  )

```

Listing 7. Threadsafe looping timer

```

class LoopTimer(Timer):
    def __init__(self, interval, function, args=None, kwawrgs=None):
        Timer.__init__(self, interval, function, args, kwawrgs)

```

```

417         self.was_reset : bool = False
418         # ...
419
420     class Raft(SimpleXMLRPCServer):
421         def __init__(self,
422                     # ...
423                     )
424             # start timer
425             self.timer = LoopTimer(timeout, self.on_timeout)
426             self.timer.start()
427
428
429

```

3.1.1 *Leader Node*. The algorithm revolves around one leader node, whose job is to synchronize all servers' logs to ensure data consistency. It does so by replicating its own log on all followers (the non-leader nodes) by sending new or, if needed, old entries via remote procedure calls.

To make sure all nodes believe the leader's alive, it sends periodically (every 150-300ms) an empty remote procedure call called *heartbeat*

3.1.2 *Follower Node*. All nodes, except for the leader, are classified as followers. They are not allowed to replicate their own log, and when they receive any request they have to forward it to the leader.

To make sure the cluster never remains without a leader, every follower have an election timeout (between 150ms and 300ms) which resets every time an RPC from the leader gets received. When times out, the follower change its state to *candidate*, increment its current term and starts a leader election.

Followers become candidates in another scenario: whenever they receive an entry from the leader, they compare it with their own last log entry. If the leader's term is smaller the *append entry* is rejected and a new election is started.

3.1.3 *Candidate Node*. When a follower's election timeout times out, it becomes a candidate, increment its own term and starts an election. It votes for itself and then wait for either of two outcomes: wins, thus becoming a new leader, or loses (either another leader gets elected or the old one manifest itself) thus reverting back to being a follower.

3.2 Log

As stated, the leader's job is to accept requests (in our specific case they are player inputs) and then forward them to the followers. Let's talk about the structure of the log.

The log is basically a *list* (or an *array*) of entries, where *entry* is an element that encapsulates data (like an integer or a string), has an index (unique for each entry) and the term of its creation (figure 4). We defined entires as *Data Classes*¹⁹ (decorators that simulate C's structures) as can be seen in code 8.

Listing 8. Dataclass Entry definition

```

462 @dataclass
463 class Entry:
464     term: int
465

```

¹⁹Data Classes module provides a decorator and functions for automatically adding generated special methods to user-defined classes: <https://docs.python.org/3/library/dataclasses.html>

```

469     index: int
470     command: str
471
472
473
474

```

indices						
i = 8	i = 9	i = 10	i = 11	i = 12	i = 13	i = 14
'x = 1'	'x = 4'	'y = 6'	'x = 2'	'x = -3'	'x = 9'	'x = 0'
T = 3	T = 3	T = 3	T = 3	T = 3	T = 3	T = 3
Terms			Commands			

Fig. 4. Raf's log is fundamentally an array made of entries.

3.3 Log Replication and Overwriting

All log propagation revolves around one core remote procedure call named *append_entries_rpc*, which the leader calls on a list of server proxies that connects it to the followers, which in turn call on a proxy of the leader. It must be registered in the server to be callable, like can be seen at listing 9.

Listing 9. Register, thus making it callable, the remote procedure call *append_entries_rpc*

```

492 def handle_server():                                     # enclose server in a callable function
493     with Raft(...) as server:                             # creates SimpleXMLRPCServer
494         def append_entries_rpc(entries, term, commit_index, all_log):
495             # ...
496             server.register_function(append_entries_rpc) # makes function callable on the other side
497             server.serve_forever()                       # keeps server alive
498
499
500

```

3.3.1 Leader Propagates Entries. The leader (each server as a matter of fact) periodically checks whether there are new commands to propagate (always stored in queue *pygame_commands*), by overriding *SimpleXMLRPCServer*'s method *service_actions* (listing 10, more details in section ??).

Then, translates them into entries by giving each of them the current term and a log index that starts from *lastLogEntry(index) + 1* and increases by one for each entry. To give an example: if *lastLogEntry(index) = 7* and we have three new commands, their indexes will respectively be eight (8), nine (9) and ten (10). The translation can be seen at listing 11

At this point it propagates *new_entries* to the whole cluster, updating the commit index (necessary for applying log to state) as soon as at least half the propagations are successful, like so: *commitIndex = lastNewEntry(index)*.

What happens if the *append entries* gets rejected? The leader adds to *new_entries* its own last log entry: *new_entries = lastLogEntry + new_entries* (figure 5). Then repeats the propagation procedure, for each reject a new *last log entry* gets added, progressively traversing the log backwards. If, at a certain point, *new_entries == allLog + new_entries* (i.e., all leader's log gets propagated) the flag *all_log* is set to *True*.

Since every server may reject or accept different sets of entries, depending on their own local log, every propagation must be "local" for each follower.

The flow of execution for the log propagation is: *Raft: service_actions* → *Raft: propagate_entries* → *propagate_entries:encapsulates_proxy: append_entries_rpc*. The last one gets called as many times as needed on every single follower.

Of course, all propagation happens concurrently using a *ThreadPoolExecutor*, and the code for entries propagation (leader's side) can be seen at listing 12.

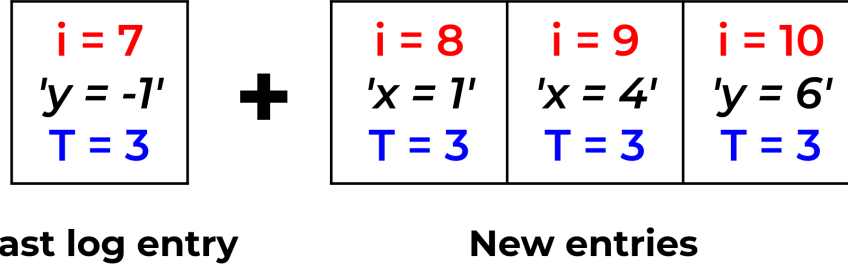


Fig. 5. New entries with the last log's entry added to the begging of the list.

Listing 10. Periodically checks whether there are new commands

```
def service_actions(self):
    # RUN method of the server, override
    if time.time() - self.countdown >= .005:
        # do actions every .005 seconds
        global pygame_commands

        if not pygame_commands.empty():
            # propagate entries to cluster
            self.propagate_entries()
```

Listing 11. Translates commands into new entries

```
def propagate_entries():
    # ...
    while not pygame_commands.empty():
        command = pygame_commands.get()
        log_index += 1
        # lastLogEntry(index) + 1
        self.new_entries.append(Raft.Entry(
            # append to support list 'new_entries'
            term=self.term,
            index=log_index,
            command=command
        ))
```

Listing 12. Leader propagation procedure, for complete code refer to project's repository

```
def propagate_entries(self):
    # ...
    if self.log:
        # travel backwards through self.log for each reject
```

```

573     entries: list[Raft.Entry] = []
574     entries.append(self.log[-1])
575     entries.extend(self.new_entries)
576     log_iterator: int = -2          # log_iterator soft resets for each follower
577 else:
578     entries: list[Raft.Entry] = self.new_entries
579     log_iterator: int = -1
580
581 # ...
582
583 # inner function necessary for concurrent execution
584 def encapsulate_proxy(self, follower, entries, log_iterator):
585     # ...
586     with xmlrpc.client.ServerProxy(complete_url, allow_none=True) as proxy:
587         while not propagation_successful:
588             # send new entries (local for each follower)
589             # ...
590             result = proxy.append_entries_rpc(entries, self.term, self.commit_index, all_log)
591             if result[0] == False:
592                 # add another entry from self.log to new entries
593                 entries = [self.log[log_iterator]] + entries
594                 log_iterator -= 1
595             elif result[0] == True:
596                 propagation_successful = True
597
598     return propagation_successful # to propagate_entries, make propagation counter increase
599 # encapsulate_proxy ends
600
601 results = []
602
603 # fires RPCs concurrently using ThreadPoolExecutor
604 future_result = {          # clever python syntax trick
605     self.executor.submit(
606         encapsulate_proxy, # function
607         self,              # function's parameter
608         follower,          # function's parameter
609         entries,           # function's parameter
610         log_iterator       # function's parameter
611     ): follower for follower in self.cluster}
612
613 for future in concurrent.futures.as_completed(future_result):
614     # results of RPCs

```

```

625         data = future.result()
626         results.append(data)
627
628
629     # finally counts if propagation was successful enough
630     if results.count(True) >= len(self.cluster) / 2:
631         self.log.extend(self.new_entries)           # add new entries to log
632         self.new_entries.clear()                     # clear new entries list
633         self.commit_index = self.log[-1].index       # ensure log gets eventually applied
634     else:
635         # new entries are not cleared, so they will be propagated again
636
637

```

3.3.2 *Follower Recieves Entries.* When a follower receives an *append entries* request from the leader, first checks whether leader's term is up to date. If its not, i.e., $leaderTerm < followerTerm$, rejects by answering with the tuple $(False, followerTerm)$. In this context *answering* is done via the remote procedure call's return value.

If, on the other hand, the leader's term is equal or greater than its own (i.e., $leaderTerm \geq followerTerm$), the follower updates its commit index and, if $leaderEntries \neq \emptyset$, checks the *all_log* flag. If its *True*, clears all its own log to overwrite it with the leader's (fundamental to log forcing, listing 13). Otherwise ($all_log \neq True$) the leader's did not send all its log, so the follower search trough its own log an entry equal to the leader's previous one (i.e., the entry preceding the new ones). Let's make an example:

- Leader's log = [1, 2, 3, 4, 5];
- Leader's new entries = [6, 7];
- Thus leader's prev = [5].

If it finds an entry equal to leader's previous (i.e., $followerLog(someEntry) == leaderPrev$), deletes all log that follows it and append new entries, otherwise ($\neg(followerLog(someEntry) == leaderPrev)$) rejects the request. Since the leader, when faced with a reject, adds a new *prev* and keep repeating the send until it comprises all its log, at a certain point the follower will be forced to overwrite all its log, thus making it equal to the leader's. This overwriting is called *log forcing* and ensures that all logs are equal to the leader's. The code can be seen at listing 14 (for the complete one refer to the repository).

Listing 13. Follower clear its onwn log to overwrite it with the leader's

```

663 if all_log == True:
664     server.log.clear() # if leader sent all its log, clear and rewrite log (leader's log forcing)
665
666

```

Listing 14. Follower search in its own log for an entry equal to leader's prev

```

669 if commit_index is not None:
670     server.commit_index = commit_index # update commit index
671
672
673 if entries is not None: # not an heartbeat
674     if all_log == True: # complete overwrite
675         server.log.clear()
676

```

```

677
678     if server.log: # if follower's log not empty search for an entry equal to leader's prev
679         entry_log_index: int | None = None # save its log index (!= entry index)
680
681         for i, my_entry in enumerate(server.log):
682             if (my_entry.index == entries[0].index
683                 and my_entry.term == entries[0].term):
684                 entry_log_index = i
685                 break # no need to search further
686
687         # here entry_log_index == (position of entry equal to leader.prev) | None
688
689         if entry_log_index is None: # entry equal to leader's prev not found
690             return(False, server.term) # rejects
691
692
693         del server.log[(entry_log_index):] # delete all log following leader prev
694
695
696     server.log.extend(entries) # append new entries

```

3.3.3 *Follower Sends Entries.*

3.3.4 *Leader Recieves Entries.*

3.4 Apply Log to State

3.5 Log Compaction

3.6 Leader Election

3.7 Cluster Membership Change

3.8 Byzantine Raft

ACKNOWLEDGMENTS

To Robert, for the bagels and explaining CMYK and color spaces.

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A APPENDIX SECTION

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A.1 Appendix Subsection

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Received TODO; revised TOOD; accepted TODO