

1 **Data Mining: BeeViva Challenges**
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14 **1 RICE VARIETIES**
15

16 From sharing spreadsheets among a handful of laptops in a small basement office, through large-scale rendering on a
17 supercomputer, to the entire global finance system, distributed computing has become an essential component of the
18 modern world: nowadays, what most people need a computer for can be done in the browser thanks to services like
19 email clients, cloud calendars, media streaming platforms and web-based office suites (like Google Docs) that expose
20 word editors, spreadsheets managers, presentations programs and more, all while being constantly synchronized via
21 the cloud, which not only ensures data persistence and availability, but also enables sharing and collaboration between
22 users.
23

24 It does not end here: other examples of distributed applications include cloud storage services like Dropbox, Google
25 Drive or OneDrive, streaming services like Netflix, YouTube or Spotify, distributed computing like AWS, online banking
26 services (the banking system itself is distributed since way before), social networks, and even maritime and aircraft
27 traffic control systems. Moreover, the rise of the gaming industry played a significant role in pushing distribution
28 forward: in 2024 the gaming market revenue was estimated to be 187.7 billion U.S. dollars [4], making it a hefty slice
29 of the pie that is the entertainment industry [15], with 111 billions generated by free-to-play games [5] (70 billions
30 from social and casual games alone [10]), which interests us since their business model often relies on cosmetics, game
31 passes and advertisements, forcing them to be constantly on-line.
32

33 But enough with examples, let's now give some definitions: a distributed system is a computer system whose
34 inter-communicating components are located on different networked computers [1, 20], which coordinate their actions
35 via message-passing to achieve a common goal. On the other hand, distributed computing can be defined as the method
36 of making multiple machines work together transparently to solve a common problem, making them appear as a
37 powerful single unit that provides large-scale resources to deal with complex challenges [18]. There are three significant
38 obstacles to overcome: maintaining components' concurrency ¹, eliminating global-lock reliance and managing the
39 independent failure of components, all while ensuring scalability (often the purpose is scaling itself) and transparency
40 to the client (either a human user or another program), meaning interactions with any exposed interface should be
41 done while being unaware of the complexity behind them.
42

43
44 ¹Concurrency refers to the ability of a system to execute multiple tasks through simultaneous execution or time-sharing (context switching), sharing
45 resources and managing interactions. It improves responsiveness, throughput, and scalability [8, 14, 16, 19, 23].
46

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Moreover, consensus must be guaranteed: it does not require much thought to see that all replicated servers in a cluster should agree on one or more shared values, lest becoming a collection of unrelated components that have little to do with collaboration (thus distribution). In the most traditional single-value consensus protocols, such as Paxos [12], cooperating nodes agree on a single value (e.g., an integer), while multi-value alternatives like Raft [13] 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 makes it impossible to achieve consensus via deterministic algorithms, as stated by Fischer, Lynch and Paterson in their FLP impossibility theorem [7]. Thankfully this can be circumvented by injecting some degree of randomness [2].

1.1 Project's Contributions

The concepts and examples we mentioned so far allow us to finally present the goal of this project: we created 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>.

2 PYTHON

We are now going to discuss the technologies employed in the development of the project, as well as presenting our implementation of the Raft's algorithm.

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

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 progress 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. [17]

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

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

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) [6, 9], meaning abundant documentation and resources. Secondly it has a huge ecosystem of libraries that implement all the functionalities we need for this project, namely: *XML-RPC* for the remote procedure calls (RPCs), *threading* to handle local concurrency and *Pygame* to manage everything game-related.

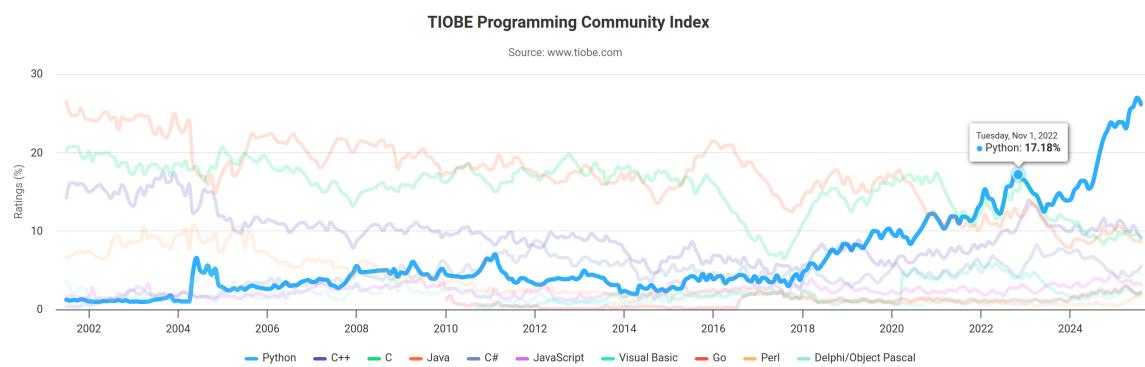


Fig. 1. TIOBE Programming Community Index, focus on Python statistics, 2025. (<https://www.tiobe.com/tiobe-index/>)

2.1 Remote Procedure Calls

In Raft's specifications it is stated that nodes communicate with each other via remote procedure calls [13], 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 *XML-RPC*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 it 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.

Listing 1. Client as server proxy

```
1 with xmlrpclib.ServerProxy('http://localhost:8000', allow_none=True) as client:
2     print(client.test_foo(42)) # print returned value
```

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).

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 2. Server

```

157
158 with SimpleXMLRPCServer (('localhost', 8000)) as server:
159     def test_foo(number):
160         return f'The number is {number}'
161
162     server.register_function(test_foo)
163     server.serve_forever() # keep server alive
164

```

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 has 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 are, by design of their own respective libraries, independent, blocking and perpetually executing loops.

Some Raft implementations we examined achieve concurrency through asynchronous programming¹¹, using libraries such as *asyncio*¹², thereby avoiding the need to manage common multithreading challenges like ensuring thread-safety by preventing race conditions or data corruption and other hazards such as lock-free reordering or incorrect granularity (see footnote for more¹³). That being said, while powerful and efficient, writing asynchronous code can be awkward and cumbersome, so we opted for a more traditional approach using multithreaded programming: in computer science, a thread of execution is the smallest sequence of programmed instructions that can be scheduled independently [11], and multiple threads may be executed concurrently sharing resources such as memory. This is directly counterpointed to multiprocessing, where each process has its own storage space, and moreover processes are typically made of threads. Processes and threads are profoundly different and do not serve the same purpose, but it is useful to cite both of them to provide the context needed to fully understand section 2.2.1.

In Python there are modules in the standard library for both of them, respectively *threading*¹⁴ and *multiprocessing*¹⁵. 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."¹⁶.

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

¹¹Two examples of Raft's implementations that leverage asynchronous programming are Raftos (<https://github.com/zhebrak/raftos/tree/master>) and Zatt (<https://github.com/simonacca/zatt/tree/master>)

¹²Asyncio is a library to write concurrent code using the *async/await* syntax: <https://docs.python.org/3/library/asyncio.html>

¹³Multithreading Hazards, Microsoft: <https://learn.microsoft.com/en-us/archive/msdn-magazine/2008/october/concurrency-hazards-solving-problems-in-your-multithreaded-code>

¹⁴The 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>

¹⁵The 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>

¹⁶Global Interpreter Lock: <https://docs.python.org/3/glossary.html#term-global-interpreter-lock>

209 leverage multiple cores. As previously stated, processes are much heavier than threads and thus more expensive to
 210 create, but do not incur the risks of shared memory.
 211

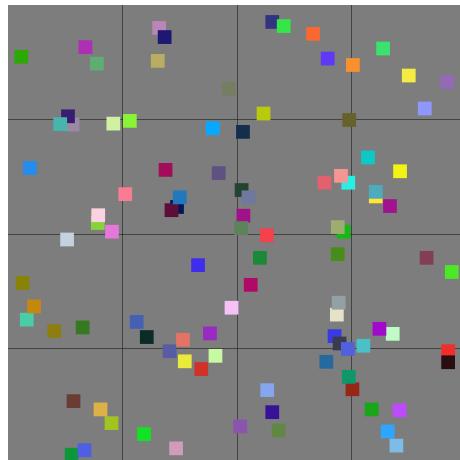
212 *2.2.1 Comparison.* To evaluate which of the two modules is more suited for our purposes, we devised a simple
 213 experiment: we created two game instances with one hundred and one thousands coloured dots respectively (figure 2),
 214 that move around by offsetting their position each frame of a random amount between minus five and plus five pixels
 215 (pseudocode 3).

216 Then we ran both of them in three scenarios: with the game instance alone (baselines), with a server alive in a thread
 217 and with a server alive in a process, and we measured the *frames per second* (FPS)¹⁷ in each case, since it is the most
 218 common metric to evaluate game performance. Higher FPS-count translates to a smoother and more responsive, i.e.,
 219 better, gaming experience.
 220

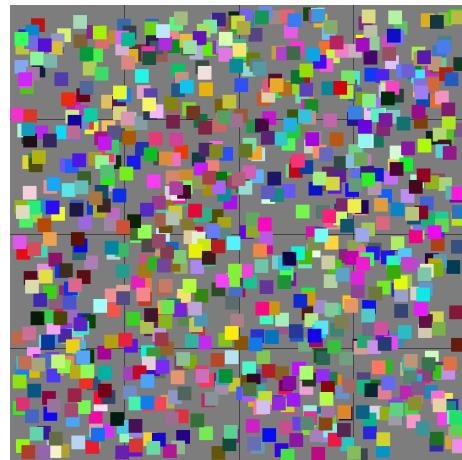
221 Listing 3. Pygame graphical dot offset
 222

```

223 # create random offsets for both x and y coordinates
224 xmov = random.randint(-5,5)
225 ymov = random.randint(-5,5)
226
227
228 # move the dot by a certain offset
229 dot.move_by(xmov, ymov)
230
  
```



231 (a) 100 dots game instance
 232



233 (b) 1000 dots game instance
 234

250 Fig. 2. Two game instances made with Pygame, with respectively 100 and 1000 dots that randomly move around
 251

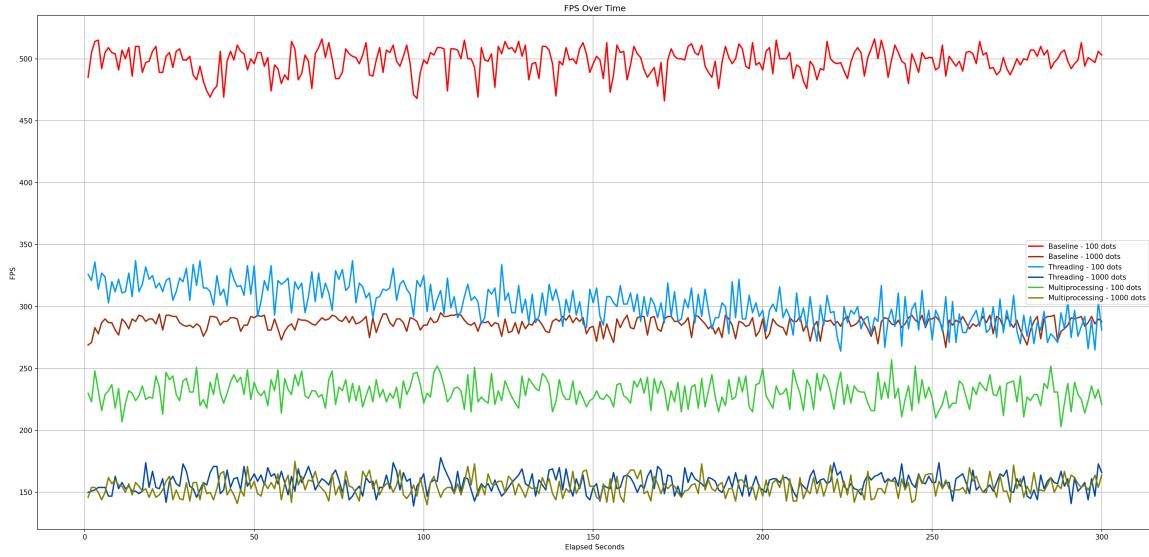
252 Results, shown in the graph at figure 3, tell us us that:

- 253 • Increasing the number of dots from 100 to 1000 halves the FPS count;
- 254 • Adding a server in a separate thread halves performance;

255 ¹⁷Frame rate, most commonly expressed in frames per second or FPS, is typically the frequency (rate) at which consecutive images (frames) are captured
 256 or displayed. This definition applies to film and video cameras, computer animation, and motion capture systems, while in the context of computer
 257 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

- 261 • Using *multiprocessing* yields worse performance than *threading* in the 100-dots scenario (about -30%), while
 262 performing similarly in the 1000-dots one.
 263

264 This leads us to conclude that, for our specific purposes, the *threading* module is the best choice, especially since
 265 the final game will be way less computationally expensive from a graphical standpoint, hence using a lighter weight
 266 alternative should be even more beneficial than tested.
 267



291
 292 Fig. 3. Performance evaluation graph: red hues for baselines, blue hues for threading and green hues for multiprocessing. Darker
 293 shades for 1000 dots and lighter shades for 100 dots game instances
 294
 295
 296
 297

298 All tests have been performed with the following machine:
 299

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

313 **2.3 Game Engines**

314 There are many ways to implement a graphical user interface: from clever shell tricks like htop¹⁸, to full-fledged game
 315 engines like Unity¹⁹ or Godot²⁰ that often come with their own editor and a *top-down* approach, meaning build the UI
 316 first and then go down to code as needed for scripting and refining.

317 Unfortunately, our needs are quite opposite: what we want is a code-only, mono-language framework that while
 318 slowing down game development should simplify merging Raft with it. The choice thus boiled down to two alternatives:
 319 tkinter and Pygame.
 320

321 **2.3.1 Comparison.** Let's list strengths and weaknesses of the two.

322 • **tkinter:**

- 323 – Module of the standard library;
- 324 – Few lines of code to make simple UIs;
- 325 – Low flexibility;
- 326 – No game loop;
- 327 – Not a game engine;

328 • **Pygame:**

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

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

343 **3 RAFT**

344 It is not our intention to plagiarize Ongaro and Ousterhout's excellent work "*In Search of an Understandable Consensus*
 345 *Algorithm*" [13] by presenting the Raft algorithm's specifications. Instead, we are going to discuss how we molded it to
 346 our own use case.

347 The algorithm divides its nodes into three roles, namely *leader*, *follower* and *candidate*, and revolves around three
 348 core functionalities: leader election, log replication and cluster membership change. Log compaction is also mentioned,
 349 while a byzantine fault tolerant variant is never explored by the original authors. To grant consistency, Raft's design
 350 choice is to centralize all decisions on one node, the above mentioned leader, that synchronizes all cluster's nodes.

351 One last component, instrumental to the functioning of the algorithm, is the *term*: everything happens in a certain
 352 term, which divides time logically and increments every election. This is necessary to recognize out-of-date leaders: if
 353 some follower has a term greater than the leader's, said leader is outdated.

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

360
 361 ¹⁸Htop is a cross-platform text-mode interactive process viewer: <https://htop.dev/>

362 ¹⁹Unity is a cross-platform game engine developed by Unity Technologies: <https://unity.com/>

363 ²⁰Godot is a cross-platform open-source game engine: <https://godotengine.org/>

365 Lastly, to fire off non-blocking concurrent RPCs on the cluster, we leverage the *concurrent.futures* module using
 366 *ThreadPoolExecutor*. To avoid creating and destroying pools every time a server needs to communicate with the cluster,
 367 we embedded a finite amount of workers as class attributes (code 5).
 368

369

Listing 4. Class Raft definition

```
370
371 1 class Raft(SimpleXMLRPCServer):
372     2     def __init__(self,
373         3         addr: tuple[str, int],
374             4             allow_none: bool = True,
375                 5                 # ...
376                     6                     last_index_on_server: list[tuple[int, int]] | None = None
377                         7                         ):
378                             8 SimpleXMLRPCServer.__init__(self, addr=addr, allow_none=allow_none)
379
380
381
382
383
384
385
386
```

379

Listing 5. ThreadPoolExecutor created with as many workers as there are servers in the cluster

```
387
388 1 class Raft(SimpleXMLRPCServer):
389     2     def __init__(self,
390         3         # ...
391             4             )
392                 5                 # start executors pool
393                     6                     self.executor = concurrent.futures.ThreadPoolExecutor(max_workers=len(self.cluster))
394
395
396
397
398
399
400
401
402
403
404
405
406
407
```

3.1 Node Types

As previously stated, there are three node types: 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)

394

Listing 6. Node modes

```
395
396 1 class Raft(SimpleXMLRPCServer):
397     2     class Mode(Enum):
398         3         LEADER = 1
399             4             CANDIDATE = 2
400                 5                 FOLLOWER = 3
401
402     6
403     7     def __init__(self,
404         8         # ...
405             9             mode: Mode = Mode.FOLLOWER,
406                 10                )
407
408
409
410
411
412
413
414
415
416
```

406

Listing 7. Threadsafe looping timer

```
407
408 1 class LoopTimer(Timer):
409     2     def __init__(self, interval, function, args=None, kwawrgs=None):
410         3         Timer.__init__(self, interval, function, args, kwawrgs)
411             4             self.was_reset : bool = False
412                 5                 # ...
413
414     6
415     7 class Raft(SimpleXMLRPCServer):
416         8         def __init__(self,
417             9             # ...
```

```

417 10
418 11     )
419 12     # start timer
420 13     self.timer = LoopTimer(timeout, self.on_timeout)
421

```

3.1.1 *Leader Node*. The algorithm revolves around, and requires the existence of, one and only 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, periodically sends an empty remote procedure call called *heartbeat* (every 150-300ms).

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

To make sure the cluster never remains without a leader, every follower has an election timeout (between 150ms and 300ms) which resets every time an RPC from the leader is received. If it times out, the follower changes its state to *candidate*, increments 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, it is out of date and a new election is started.

3.1.3 *Candidate Node*. When a follower's election timeout times out, it becomes a candidate, increments its own term and starts an election. Votes for itself and then waits for one of two outcomes: wins, thus becoming a new leader, or loses (either another leader gets elected or the old one manifests 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 entries as *Data Classes*²¹ (decorators that simulate C's structures) as seen in code 8.

Listing 8. Dataclass Entry definition

```

452
453
454 @dataclass
455 class Entry:
456     term: int
457     index: int
458     command: str
459

```

3.3 Log Replication and Overwriting

All log propagation revolves around one remote procedure call named *append_entries_rpc*, which the leader calls on a list of server proxies that connect it to the followers. On their end, each follower calls the RPC on a proxy of the leader. It must be registered in the server to be callable, as seen in listing 9.

²¹Data 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>

indices						
Terms			Commands			
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

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

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

```

481 1 def handle_server():                                # enclose server in a callable function
482 2     with Raft(...) as server:                      # creates SimpleXMLRPCServer
483 3         def append_entries_rpc(entries, term, commit_index, all_log):
484 4             ...
485 5             server.register_function(append_entries_rpc)    # makes function callable on the other side
486 6             server.serve_forever()                          # keeps server alive
487

```

3.3.1 *Leader Propagates Entries.* The leader (each node as a matter of fact) periodically checks whether there are new commands to propagate (always stored in queue `pygame_commands`, more details in section 4), by overriding *SimpleXMLRPCServer*'s method `service_actions` (listing 10).

Then, it 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 clarify: if `lastLogEntry(index) = 7` and we have three new commands, their indices 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 propagations are successful on at least half of the cluster, 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, it 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.

Listing 10. Periodically checks whether there are new commands

```

514 1 def service_actions(self):                         # RUN method of the server, override
515 2     if time.time() - self.countdown >= .005:      # do actions every .005 seconds
516 3         global pygame_commands
517 4
518 5         if not pygame_commands.empty():            # propagate entries to cluster
519 6             self.propagate_entries()

```

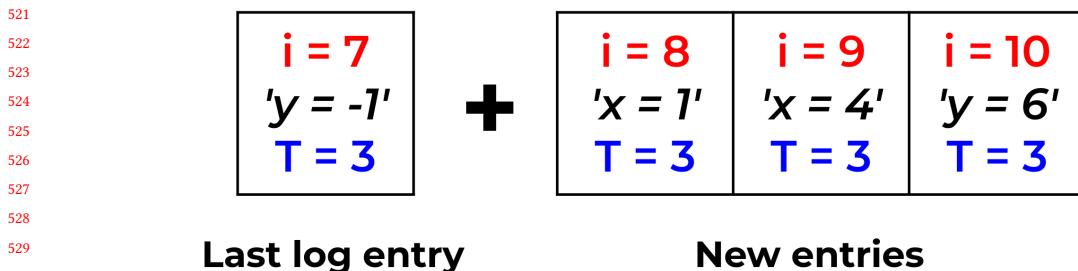


Fig. 5. New entries with the last log's entry pushed to the top of the list

Listing 11. Translates commands into new entries

```

536 1 def propagate_entries():
537 2 # ...
538 3     while not pygame_commands.empty():
539 4         command = pygame_commands.get()
540 5         log_index += 1                  # lastLogEntry(index) + 1
541 6         self.new_entries.append(Raft.Entry(      # append to support list 'new_entries'
542 7             term= self.term,
543 8             index= log_index ,
544 9             command=command
545 10        ))

```

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

```

546
547 1 def propagate_entries(self):
548 2     # ...
549 3     if self.log:                      # travel backwards through self.log for each reject
550 4         entries: list[Raft.Entry] = []
551 5         entries.append(self.log[-1])
552 6         entries.extend(self.new_entries)
553 7         log_iterator: int = -2          # log_iterator soft resets for each follower
554 8     else:
555 9         entries: list[Raft.Entry] = self.new_entries
556 10        log_iterator: int = -1
557
558 11    # ...
559 12    # inner function necessary for concurrent execution
560 13    def encapsulate_proxy(self, follower, entries, log_iterator):
561 14        # ...
562 15        with xmlrpc.client.ServerProxy(complete_url, allow_none=True) as proxy:
563 16            while not propagation_successful:
564 17                # send new entries (local for each follower)
565 18                # ...
566 19                result = proxy.append_entries_rpc(entries, self.term, self.commit_index, all_log)
567 20                if result[0] == False:
568 21                    # add another entry from self.log to new entries
569 22                    entries = [self.log[log_iterator]] + entries
570 23                    log_iterator -= 1
571 24                elif result[0] == True:
572 25                    propagation_successful = True

```

```

573 27
574 28     return propagation_successful # to propagate_entries, make propagation counter increase
575 29
576 30     results = []
577 31
578 32     # fires RPCs concurrently using ThreadPoolExecutor
579 33     future_result = {           # clever python syntax trick
580 34         self.executor.submit(
581 35             encapsulate_proxy,    # function
582 36             self,                 # function's parameter
583 37             follower,             # function's parameter
584 38             entries,              # function's parameter
585 39             log_iterator          # function's parameter
586 40             ): follower for follower in self.cluster}
587 41     for future in concurrent.futures.as_completed(future_result):
588 42         # results of RPCs
589 43         data = future.result()
590 44         results.append(data)
591 45
592 46     # finally counts if propagation was successful enough
593 47     if results.count(True) >= len(self.cluster) / 2:
594 48         self.log.extend(self.new_entries)           # add new entries to log
595 49         self.new_entries.clear()                  # clear new entries list
596 50         self.commit_index = self.log[-1].index    # ensure log gets eventually applied
597 51
598 52     else:
599 53         # new entries are not cleared, so they will be propagated again

```

3.3.2 *Follower Receives Entries*. When a follower receives an *append entries* request from the leader, first checks whether leader is up to date. If it's 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.

On the other hand, if 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 it's *True*, it 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 did not send all its log, so the follower searches through its own log for 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 entries that follow it and appends the new ones, otherwise ($\#(followerLog(someEntry) == leaderPrev)$) rejects the request. Since the leader, when faced with a reject, adds a new *prev* and keeps 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 clears its own log to overwrite it with the leader's

```

620
621
622 1 if all_log == True:
623 2     server.log.clear() # if leader sent all its log, clear and rewrite log (leader's log forcing)

```

```

625
626     if commit_index is not None:
627         server.commit_index = commit_index # update commit index
628
629     if entries is not None:      # not an heartbeat
630         if all_log == True:      # complete overwrite
631             server.log.clear()
632
633         if server.log: # if follower's log not empty search for an entry equal to leader's prev
634             entry_log_index: int | None = None           # save its log index (!= entry index)
635             for i, my_entry in enumerate(server.log):
636                 if (my_entry.index == entries[0].index
637                     and my_entry.term == entries[0].term):
638                     entry_log_index = i
639                     break # no need to search further
640
641             if entry_log_index is None:      # entry equal to leader's prev not found
642                 return(False, server.term)    # rejects
643
644             del server.log[(entry_log_index ):] # delete all log following leader prev
645
646         server.log.extend(entries) # append new entries
647

```

648 3.3.3 *Follower Sends Entries*. Since every server is a Raftian node with a game instance and thus player inputs, followers
649 have their own Pygame commands to propagate. Just like the leader, in their *service_actions* function they periodically
650 check whether there are new commands to propagate and call *propagate_entries* accordingly. Then, they translate all
651 Pygame commands into entries (same code as listing 11) and propagate them to the leader via *append_entries_rpc*.
652 Nothing else.

653 As previously stated, followers are *passive*, meaning they do not apply their own player inputs when they register
654 them, but only after the leader propagates them back to the whole cluster.

655 3.3.4 *Leader Receives Entries*. The leader does very little when receives entries from the followers: it just puts them
656 into its own *pygame_commands* queue. They will get processed and propagated eventually, as stated in section 3.3.1.
657

658 3.4 Apply Log to State

659 Let's first explain two key attributes: *commit index* and *last applied*. Both of these represent an index, but the former
660 is the highest-index entry successfully propagated in the cluster, while the latter is the highest-index entry already
661 applied to state.

662 Every node, whether leader or follower, applies entries to state in the same way: inside their function *service_actions*
663 they periodically check if there is a discrepancy between *commit index* and *last applied* attributes (i.e., *commit_index >*
664 *last_applied*). Then, starting from the last applied entry, they apply to state all successive entries up to and including
665 the one with the same index as *commit_index*, updating *last_applied* as they go. To clarify: servers apply all entries
666 between *log(entry.index == last_applied)* and *log(entry.index == commit_index)* as shown in figure 6.

667 To apply entries in our context means that they get appended to the queue *raft_orders*. The code can be seen at
668 listing 15 (for the complete source refer to the repository)

Fig. 6. All entries between *last_applied* and *commit_index* (included) get applied to stateListing 15. All nodes apply entries to state based on *commit_index*

```

691 def service_actions(self):
692     # ...
693     if self.commit_index is not None and self.commit_index > self.last_applied:
694         global raft_orders  # applying means appending entries to this queue
695
696     # ...
697
698     last_applied_log_position: int = -1
699     for i, my_entry in enumerate(self.log):
700         if (my_entry.index == self.last_applied):
701             last_applied_log_position = i
702             break # found log position of last applied entry
703
704     log_iterator = last_applied_log_position + 1    # improves code clarity
705
706     while self.last_applied != self.commit_index:
707         raft_orders.put(self.log[log_iterator])
708         self.last_applied = self.log[log_iterator].index
709         log_iterator = log_iterator + 1
710
711     # here self.last_applied == self.commit_index

```

3.5 Log Compaction

This functionality, as well as the following ones, have not been implemented due to time constraints. We decided to include them anyway since they were still the product of careful consideration and could prove useful in future implementations.

Log compaction, also called *snapshot*, is a way to clear servers' logs and save them in persistent memory, necessary in long-running or message-heavy applications. Every node autonomously decides when to do it.

The idea is as follows: inside their function *service_actions*, servers check whether their log is larger than a certain size (to be determined) and then call a *snapshot* method accordingly, which saves all entries in a JSON file progressively deleting them from the log, from the first one up to (but excluding) the *last applied*.

An alternative interpretation, closer to Ongaro and Ousterhout's idea, is saving the state of the cluster. When applied to our context, we can imagine a JSON file that describes all servers' state, by saving for each of them *id*, *url*, *port*, and *hp* values. *Index* and *term* of the last snapshotted entry should also be saved, as well as the current configuration (which will be mentioned in section 3.7). An example of the JSON structure can be seen at listing 16.

729 This method requires more pre-processing to generate the JSON, and more post-processing to later check log's
 730 correctness, but is also more compact, which helps when the leader calls *install snapshot*, a remote procedure call that
 731 can sometimes be needed to bring up to speed new or outdated servers by sending them the leader's snapshot.

733 It goes without saying, but whichever method is ultimately chosen, every new snapshot must comprise all information
 734 contained in the old ones.

736 Listing 16. The JSON for a snapshot that saves cluster's state would look something like this

```
737
738 {
739     servers:[
740         {
741             id : 1,
742             url : "localhost",
743             port : 8000,
744             hp : 70
745         },
746         {}, {}
747     ],
748     lastIndex : 11,
749     lastTerm : 3,
750     lastConfig : 8
751 }
```

752 3.6 Leader Election

753 As aforementioned, the leader is fundamental to grant consistency. To make the protocol fault tolerant, it can dynamically
 754 change over time via a distributed election: whenever a follower finds out that the leader is either outdated or missing
 755 (i.e., internal follower's timer times out before receiving any call from it), said follower starts an election. It changes its
 756 internal state to *candidate*, increases its own term by one, votes for itself, and then propagates to the whole cluster a
 757 specialized remote procedure call named *request_vote_rpc* (code, removed in the final version, at listing 17). Votes are
 758 given on a first-come-first-served basis, and to prevent split votes each server's election timeout is randomized between
 759 150ms and 300ms at the start of every election. This ensures that in most cases only one server will be candidate at a
 760 time.

761 At this point there are two possible outcomes: more than half of the cluster votes for the candidate (which we will
 762 call "A"), that therefore becomes leader and propagates a heartbeat to the whole cluster, or another candidate (which we
 763 will call "B") is more up-to-date (i.e., B's *term* is greater than A's or equal but with a greater *lastIndex*). In this last case,
 764 candidate A reverts back to follower and votes for B. The pseudocode for all the above can be seen at listing 18.

765 One last eventuality is that the old leader manifests itself. In this case, if the old one is equally or more up-to-date
 766 than the new one (both term and last index count), the latter reverts back to follower and the preceding monarch gets
 767 reinstated.

773 Listing 17. Pseudocode for *request_vote_rpc*

```
774
775 def request_vote_rpc(...):
776     # if candidate less up to date -> reject
777     if self.term > candidate_term:
778         return (self.term, False)
779
780     # if a candidate already exists
```

```

781   7     if self.voted_for is not None and not candidate_id:
782   8         return (self.term, False)
783   9
784  10     # vote for candidate
785  11     self.voted_for = candidate_id
786  12     return (self.term, True)
787  #...
788 14 server.register_function(request_vote_rpc)

```

789

790

791 Listing 18. Pseudocode for *to_candidate*, gets fired on *election timer* timeout

```

792 1 def to_candidate(self):
793 2     self.mode = Raft.Mode.CANDIDATE
794 3     self.term += 1
795 4     self.voted_for = self.id
796 5
797 6     self.timer.reset() # reset election timer
798 7
799 8     for server in self.cluster:
800 9         server.request_vote_rpc(...)
80110     count votes
80211
80312     if some_return.more_up_to_date:
80413         self.mode = Raft.Mode.FOLLOWER
80514     self.voted_for = some_return.id
80615
80716     if votes > len(self.cluster) / 2:
80817         self.to_leader() # handles mode change and heartbeat

```

809

810

3.7 What is Missing

There is one last functionality discussed by Ongaro and Ousterhout, which is gracefully managing changes in the cluster's members by leveraging a configuration attribute and keeping multiple configurations alive simultaneously for a certain period of time (figure 7). We never intended to include it due to time constraints, therefore there is nothing we can add beyond the original work.

Another concern, which was not considered in the Raft paper, is faults caused by bad actors that purposely send malicious information. This is a real problem for our use case, since players want to win and are therefore incentivized to act maliciously by cheating (a practice so widespread that has created its own multimillion-dollar market [3]).

The implementation of Byzantine fault tolerance was beyond the scope of this work. Therefore, we refer the reader to some example works for further details: "*A Raft Algorithm with Byzantine Fault-Tolerant Performance*" by Xir and Liu [22], and "*VSSB-Raft: A Secure and Efficient Zero Trust Consensus Algorithm for Blockchain*" by Tian et al. [21].

4 RAFTIAN NODE ARCHITECTURE

In the previous section (3), we explained in detail how nodes communicate with each other and handle their log. Now we will explain what actually happens inside a node, i.e., the architecture of a single node of the application, comprising of both a server and a game instance. Before showcasing it, we will briefly explain how Pygame works, thus taking the opportunity to present the user interface.

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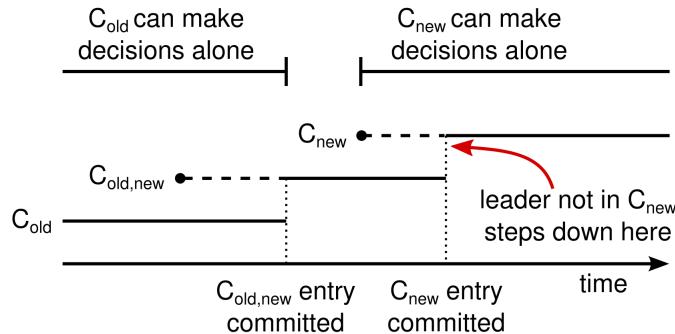


Fig. 7. Cluster goes through a hybrid configuration to pass from the old to the new one. Source: Raft paper [13]

4.1 Pygame

Pygame's approach is very straightforward: first comes the declaration and set up of all the graphical components, such as game window, fonts, colors, variables and constants. Every element gets positioned on the main window by coordinates (x,y) , where $(0,0)$ is the top left corner. Most items are made of two fundamental Pygame classes: *Rect*, which creates non-graphical objects that expose many useful methods, for example to position, move, and resize themselves, or to detect collisions and mouse clicks, and *Surface*, which is the most basic graphical component that has dimensions and can be drawn upon. Often we want to bind, thus constrain, surfaces with rects so that we use the latter for spatial operations. One last fundamental is the *blit* function, a method that draws one image onto another or, to be precise, that draws a source Surface onto the object Surface that calls it. We can give it an optional argument to specify a drawing destination, either with coordinates or a rect. To clarify: *baseSurface.blit(sourceSurface, destination)* draws *sourceSurface* onto *baseSurface* at the coordinates specified by *destination*. An example of all the above can be seen at listing 19.

Pygame, being low-level in nature, is very flexible and allows us to do pretty much whatever we want. For example, we defined our players as dataclasses that encapsulate both the players' data (like *id* or *health points*) and their Rect and Surface objects, as in listing 20.

Finally, Pygame gives us direct access to the game loop, which is implemented as nothing more than a *while loop*. In it, we can process player inputs and refresh the screen, dynamically changing what is displayed. In short, we manage everything that happens while the game is running. In listing 21 we can see two types of player input, one for quitting the game and a left-mouse click, the latter of which causes a refresh of the header. Specifically, if *Player 2* gets clicked, the header will display "*Player 2 pressed*", reverting back to its original state after a couple of seconds. The last command, *clock.tick(fps)*, allows us to limit the framerate, effectively slowing down or speeding up the game engine itself by constraining the amount of times per second the game loop repeats itself.

Listing 19. Pygame base components

```

1 pygame.init()                      # starts pygame
2 GREY = (125, 125, 125)              # define a color
3 DISPLAY = pygame.display.set_mode((1000, 1200)) # creates game window 1000x1200 pixels in resolution
4 clock = pygame.time.Clock()         # necessary to mange fps
5 font = pygame.font.Font(None, 60)    # creates default font
6 toptext = font.render("Top Text", False, BLACK) # header text

```

```

885 7 rect_header = pygame.Rect(0, 0, 1000, 100)      # creates rect for header
886 8 header = pygame.Surface((1000, 100))        # creates surface for header
887 9 header.fill(WHITE)                          # draw on surface
888 10
889 11 DISPLAY.blit(header, rect_header)          # draw on DISPLAY the header surface
890 12                                              # position is given by rect_header
891 13 #...
892 14 # draw text on coordinates
893 15 DISPLAY.blit(toptext, (rect_header.centerx - xoffset, rect_header.centery - yoffset))
894
895
896

```

Listing 20. Players defined as dataclasses that encapsulate Pygame elements

```

897 1 @dataclass
898 2 class Player:
899 3     id: int
900 4     hp: int
901 5     rc: pygame.Rect      # represents player position and size
902 6     ui: pygame.Surface    # exposes UI of the player e.g., colour
903
904 8 player1 = Player(
905 9     id=1,
906 10    hp=100,
907 11    rc=pygame.Rect(585, 685, 80, 80),   # x0, y0, width, height
908 12    ui=pygame.Surface((80,80))
909
910 14 player1.ui.fill(RED)                  # colour player red
911 15 DISPLAY.blit(player1.ui, player1.rc)    # draw on display via rect
912
913

```

Listing 21. All interactions and frame-by-frame rendering happen in the game loop

```

914 1 while True: # game loop
915 2     for event in pygame.event.get():      # process player inputs
916 3         if event.type == pygame.QUIT:
917 4             pygame.quit()
918
919 6         if event.type == pygame.MOUSEBUTTONDOWN and event.button == 1: # left mouse button click
920
921 8             pos = pygame.mouse.get_pos() # gets mouse position
922
923 10            if player1.rc.collidepoint(pos): # rect allows us to detect collisions
924 11                toptext = font.render(f"Player {player1.id} pressed", False, BLACK)
925
926 13                DISPLAY.blit(header, rect_header)    # erase previous text
927 14                DISPLAY.blit(toptext, (rect_header.centerx - xoffset, rect_header.centery - yoffset))
928
929 16                pygame.display.flip() # refresh on-screen display
930 17                clock.tick(60)       # limits framerate
931
932

```

4.2 Raftian User Interface

Figure 8 shows different phases of a normal Raftian's game session. Specifically, they demonstrate how the interface changes when the player repeatedly clicks on (thus *attack*) Player 3, the blue one on the top left (players are represented

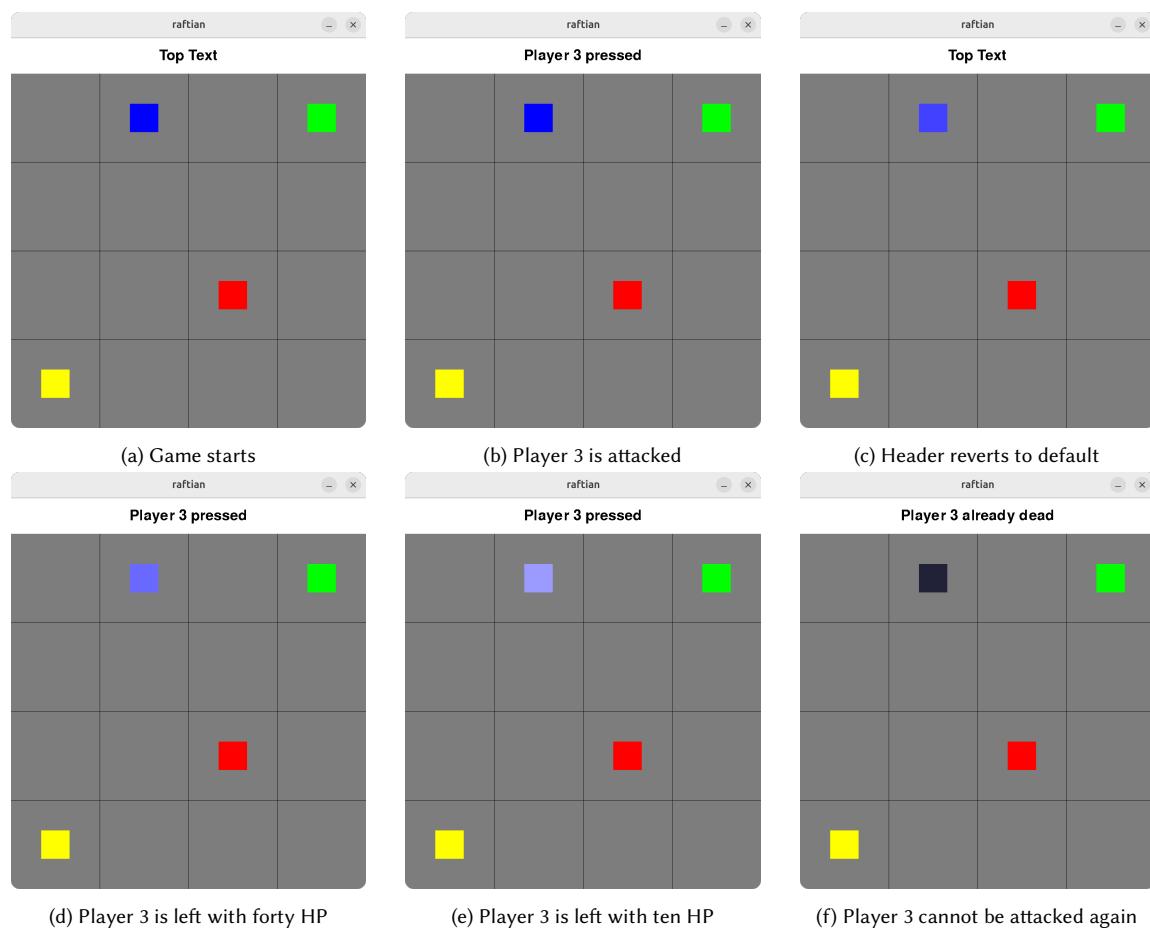
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937 as four coloured squares on the board). Players' colours become progressively desaturated as their health points decrease,
 938 by modifying their alpha channels as shown in listing 22. When a player is dead, its colour changes to a darker shade.
 939

940 In the header an attack message gets written, reverting back after half a second. Said message changes depending
 941 whether the player is still alive; if not, damage is ignored.

942 Listing 22. Whenever a player gets damaged, its colour gets desaturated

```
944 for player in players:
945     if player.id == order.command and player.hp > 0:
946         player.hp -= 30 # apply damage to player:
947
948     if player.hp < 90 and player.hp >= 60:
949         player.ui.set_alpha(190)
950         DISPLAY.blit(player_UI_cleaner, player.rc) # clean player UI
951         DISPLAY.blit(player.ui, player.rc) # redraw player UI
```



957 Fig. 8. Different phases of a normal Raftian's game session. Player 3 keeps getting damaged until it dies

4.3 Raftian Node Architecture

The architecture of a Raftian node can be seen at figure 9. Let's explain it: first of all, the game loop and the server are encapsulated in two functions to be handed over to two different threads, enabling concurrent execution (listing 23). Whenever a player clicks on (i.e., attacks) one of the four players, the game engine does not apply damage immediately. Instead, it generates a *command* which represent, if we want, the *intention* of attacking said player. This *command* is thus appended to a queue called *pygame_commands*, one of the two synchronized FIFO queues²² necessary to allow communication between server and Pygame's threads (listing 24). Both are instances of Python's standard library *queue* module²³, which implements thread-safe, multi-producer, multi-consumer queues.

At this point, Pygame does not concern itself anymore with said user input. The server, by itself, periodically checks the `pygame_commands` queue (as in listing 10) and, when not empty, removes elements from it (as in listing 11) and propagates them as entries to the leader (or to the whole cluster if said server is the leader, as in listing 12).

Then, the leader propagates the received commands to the whole cluster, which we will now call *orders*. Each server adds received orders to its own log, as explained in section 3.3, so that they can later be appended to the *raft_orders* queue when entries get applied to state (as in section 3.4). This way, the original user input gets propagated back to the server that generated it in the first place.

Finally, Pygame checks (periodically) the `raft_orders` queue for orders. When it finds them, it removes them from the queue and updates the user interface accordingly (an example can be seen at listing 25).

The whole idea is to keep server and game engine as separated as possible: the former reads commands, propagates them and writes received orders, the latter reads orders, updates the UI, and writes commands, following a unidirectional cyclic communication pattern.

Listing 23. Start both Pygame and server's threads

```
1016
1017 1 def handle_pygame():
1018 2     pygame.init()
1019 3     #...
1020 4     While True:
1021 5         #...
1022 6 def handle_server():
1023 7     with Raft(...) as server:
1024 8         #...
1025 9         server.serve_forever()
1026
1027 11 server_thread = threading.Thread(target=handle_server)
1028 12 server_thread.start()
1029
1030 13 pygame_thread = threading.Thread(target=handle_pygame)
1031 14 pygame_thread.start()
```

Listing 24. Queues for commands and orders, they allow inter-thread communication

```
1032 1 # user inputs through Pygame which writes them here  
1033 2 # Raft reads them and propagates them to the cluster  
1034 3 pygame_commands = Queue()  
1035 4  
1036 5 # commands that have been applied to state are written here by Raft
```

²²FIFO, or First-In-First-Out, is a method for organizing the manipulation of a data structure, often data buffers, where the oldest data inserted is the first that gets processed, making it work in a sense like a pipeline

¹⁰³⁹ ²³Python's queue, a synchronized queue class: <https://docs.python.org/3/library/queue.html>

```

1041 6 # Pygame reads them and updates UI accordingly
1042 7 raft_orders = Queue()
1043
1044

```

Listing 25. Pygame periodically checks whether there are new orders and updates the UI accordingly

```

1046 1 while True: # Pygame's main loop
1047 2     ...
1048 3     while not raft_orders.empty():
1049 4         order: Raft.Entry = raft_orders.get()
1050 5
1051 6     for player in players:
1052 7         if player.id == order.command and player.hp > 0:
1053 8             player.hp -= 30 # apply damage to player:
1054 9             ...

```

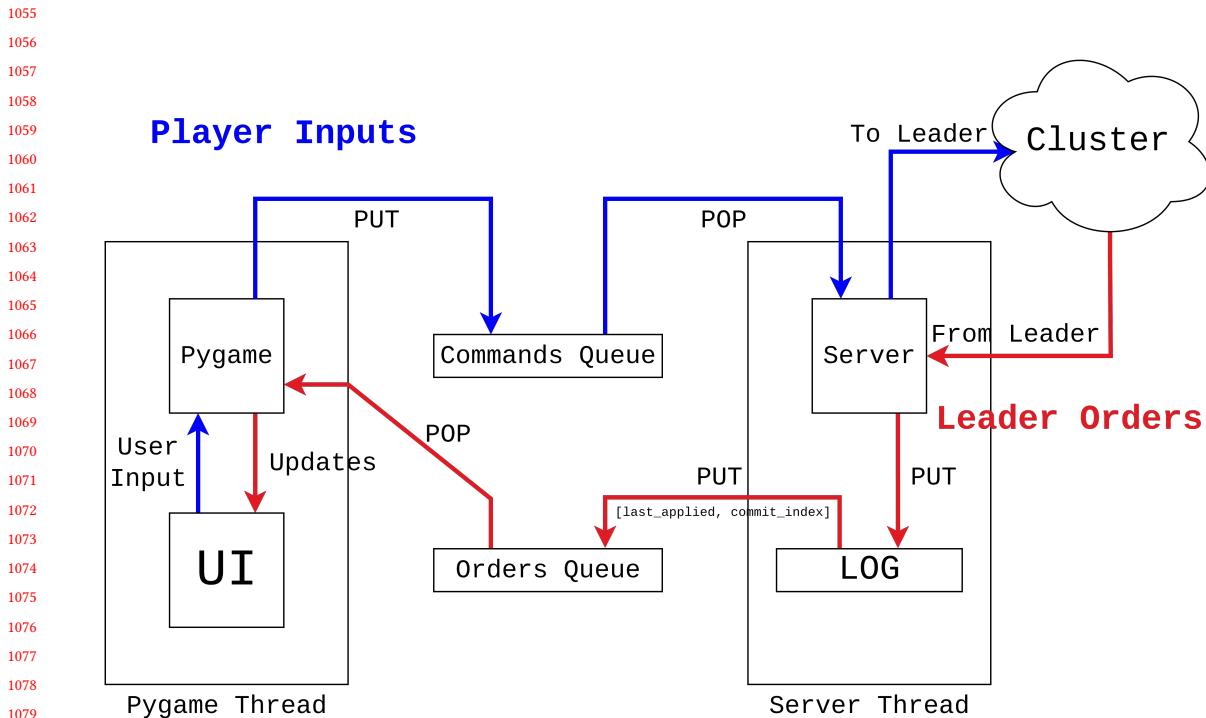


Fig. 9. Raftian node architecture

4.4 Evaluation and Results

While we did not have enough time to implement evaluation procedures for measuring things like response time or network latency, the game has been thoroughly tested. Responsiveness is good, with no noticeable input latency and a solid framerate way above sixty frames per second (which is still the preferred limit), and both log replication and overwriting functionalities have been confirmed working as intended. The proof of this fact can be observed in the logs at <https://github.com/mhetacc/RuntimesConcurrencyDistribution/tree/main/logs>, specifically by comparing logs

1093 among folders *bob1*, *bob2*, *bob3*, *bob4*, and *raftian*: all logs (meaning *Raft logs*) contain the same entries, in the same
 1094 order, between all players.
 1095

1096 5 REFLECTION

1098 Let's now discuss problems, potential future expansions and learning outcomes of this project.
 1099

1100 5.1 Self-Assessment

1102 Using *XML-RPC* and *threading* libraries proved to be sub-optimal: the former has a very contrived syntax and makes
 1103 writing procedure calls a bit unintuitive, since forces the programmer to think in the "opposite direction". When writing
 1104 a remote procedure call (i.e., those functions that get registered by *register_function()*) is important to keep in mind that
 1105 they are going to be used by the caller and not by sender (in whom code block they are written in).
 1106

1107 Code could be less coupled: both server and game loop reside in the same file, and a lot of components are either
 1108 internal classes or nested functions. Moreover, both command and order queues are global variables, which is generally
 1109 a practice to be avoided.
 1110

1111 On the other hand, code is well documented and as understandable as possible, even though following the flow of,
 1112 for example, an input propagation requires jumping through it many times.
 1113

1114 5.2 Future Works

1116 Apart from the two features already discussed (leader election and log compaction), future expansions could implement
 1117 cluster's membership change and a Byzantine fault-tolerant version of Raft. Adding new game functionalities, thus
 1118 command types, should be easy since they can be propagated by the existing infrastructure, and the same is true for
 1119 adding new players: provided that a new, bigger, user interface gets created, changing cluster's size should, in our
 1120 testing, work without any issues.
 1121

1123 5.3 Learning Outcomes

1125 We started this project by having very limited Python competencies, having never written concurrent programming,
 1126 never touched a game engine and never worked with network transmission protocols. All in all, we learned all of the
 1127 above, in some cases going so far as trying different alternative solutions (we implemented Raft nodes mockups with
 1128 threading, multiprocessing and asyncio libraries), making this project an invaluable learning experience.
 1129

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