Department of Electrical and Computer Engineering
University of Victoria
SENG 462 — Distributed Systems and the Internet

Project Report

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Architecture and project plan	_____	/5
Security	_____	/5
Test plan	_____	/5
Fault tolerance	_____	/5
Performance analysis	_____	/5
Capacity planning	_____	/5
Total	_____	**/30**

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Overview

The goal of the project was to build a distributed day trading system, with a focus on performance. The client original stated the following actions as business requirements:

- View their account
- Add money to their account
- Get a stock Quote
- Buy a number of shares in a stock
- Sell a number of shares in a stock they own
- Set an automated sell point for a stock
- Set a automated but point for a stock
- Review their complete list of transactions
- Cancel a specified transaction prior to its being committed
- Commit a transaction

Additionally, the overall architectural goals of the system were:

- Minimum transaction processing times.
- Full support for required features.
- Reliability and maintainability of the system.
- High availability and fault recoverability (i.e. proper use of fault tolerance)
- Minimal costs (development, hardware, maintenance, etc.)
- Clean design that is easily understandable and maintainable.
- Appropriate security
- A clean web-client interface.

These requirements form the basis for the distributed daytrading system commissioned by DayTrading Inc.

Chapter 1

Architecture

1.1 Technology

1.1.1 Golang

Golang was selected originally because it gives a lot of tools to maximize scalability, but is also very easy to learn and use efficiently. Golangs idioms are relatively easy to learn and the architectural decisions Rob Pike made when bringing the language to fruition heavily favor the task at hand.

Golang has extremely lightweight threading. It is possible to spawn thousands of threads in a golang instance without bogging down a system. New threads are made for goroutines, http request, etc, and are managed by the golang thread scheduler, not the OS. This allows for a lot of multithreaded benefit without a lot of the multithreaded headache. Golang goroutines and the producer/consumer model are very easily implemented. We wanted to utilize a language which was able to:

- Efficiently scale
- Work well with RMQ
- Be easy to learn and fun to use.

Golang fulfills all of these categories. The idea of channels in golang is almost identical to the consumption of RabbitMQ channels, and was very easy to hook into the golang flow.

Golang has the added benefit of being both type safe, and well supported by the community. The former makes it incredibly easy to debug and refactor code. The latter means that there are a whole set of profiling and testing tools available by default, so we did not have to go out and research what the best ones were.

1.1.2 RabbitMQ

We selected RabbitMQ early on as we wanted to do an event based system, and wanted to be able to communicate between components effortlessly. With an event based system, we wanted to utilize a communication protocol that would perform FIFO communication between microservices. Rabbit fills this need exactly, and the documentation is verbose enough that ramp up time is minimal. It is easily deployed with docker, and the management console is very easy to use and get a good picture of the system state. It also offers the ability to inject messages directly into queues and exchanges, as well as many other testing features.

1.1.3 Redis

Redis is a distributed, in memory key-value store that supports publish-subscribe events. We used Redis to provide caching for quotes, unhandled transactions and as a log message buffer. We used key TTLs to enforce quote validity windows. Although Redis operates as an in memory data store it writes changes to disk every sixty seconds in order to minimize data loss on system failure.

1.1.4 Postgres

Changes to user account state, retrieved quotes and user transactions are logged in a Postgres database for storage. Postgres offers full ACID compliance which allows the database to act as a "source of fact" for recreating the historical state of accounts in the system.

1.1.5 Websockets

Websockets allow asynchronous communication between the frontend and backend system components. Data can be passed to a webpage without requiring a page reload or other user-triggered action. This allows asynchronous events, like pending buy expirations or the fulfillment of a sell trigger, to be brought to the user's attention immediately.

1.2 Original architecture

The original architecture had a heavy emphasis on high throughput, as was the overall goal of the system. Figure 1.1 depicts the original design for system architecture.

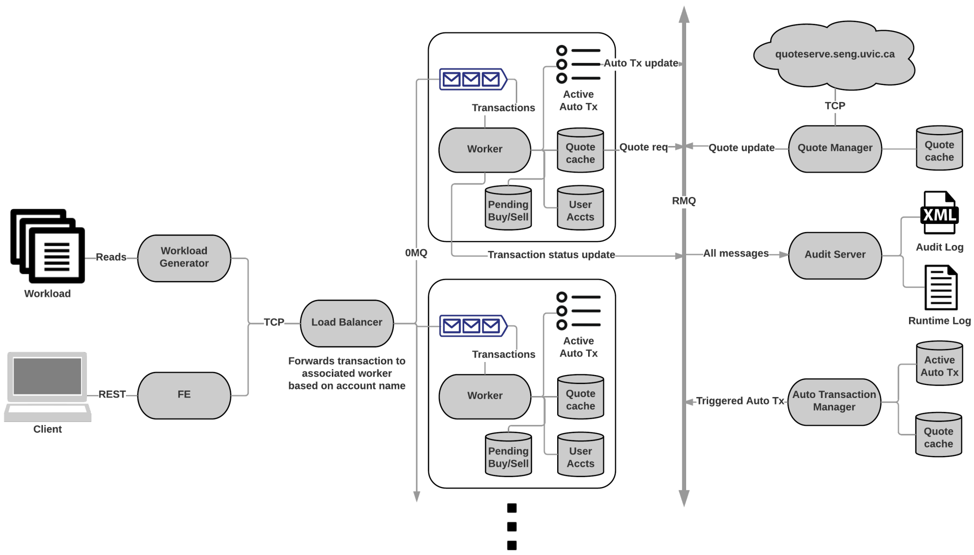


Figure 1.1: Original system architecture

Incoming traffic Transactions will be sent to the load balancer at the TCP socket level, using a pre-defined serialization format very similar to what is provided in the workload files.

Client frontend A frontend server will host static-ish pages that allows clients to log in, view their accounts and execute trades. Interaction should use REST but we'll probably end up sending data back and forth through web forms because it's faster to develop. Amount of polish and technology choice will heavily depend on how quickly we can scale to a full workload. Ideally, this should use a modern web development package like React or Vue.

Web page will do cursory input sanitization and validation (e.g. reject a purchase for negative dollars but checks against user account quantities such as stock holdings will occur later.)

Workload generator Reads a provided workload file and generates requests identical to those coming from the FE. Requests will have a flag that indicates the transaction should run to completion but return no data.

Load balancer Forwards the transaction to its worker based on the user ID. When the transaction is finished it returns the contents (which may only be an ACK) to the client.

The design goal for the load balancer is maximum throughput. It should be a stateless router. Zero Message Queue (0MQ) offers high throughput and a configurable broker that can scale horizontally.

Worker Transactions arrive from the load balancer and are place in a queue. The worker parses the transaction and executes it. It maintains user accounts (balance and stock holdings), a local quote cache and a list of active automatic transactions (ATXs). All of the components of a worker live on the same machine.

Performance can be scaled horizontally by adding more workers.

Quote cache The quote cache maintains a list of all active quotes in the system by listening to broadcasts from the Quote Manager. It will be implemented with a Redis store that uses TTL to automatically expire quotes.

User accounts There is no clear requirement for user accounts to exist on a persistent database. The state of a user account is recoverable from the Audit Server. There are no cross-account queries, aside from the system status dump that is performed by the Audit Server. The first development cycle will use an in-memory data structure to hold user account data. If performance suffers we'll examine a Postgres implementation.

Buy and sell Details for pending buy and sell actions will be stored in Redis with a TTL to enforce the transaction validity window.

Automatic transactions The worker maintains a list of each user's ATXs. This list has no functionality other than mirroring the state of the consolidated Auto Transaction Manager (ATM) for the worker's accounts. Updates to this list are echoed to the ATM for execution. The worker is responsible for maintaining the validity of ATXs (e.g. an ATX is not valid if it receives a trigger without a pre-existing amount).

When an ATX triggers, the ATM notifies the worker that owns the ATX and the worker can update the account state and active auto transaction list. This will be implemented on the same Redis store as the quote cache.

Logging Log events are sent to the Audit Server where they can be logged asynchronously.

Quote manager Serves concurrent requests for new quotes. On its own cache miss (which should be rare because the cache state is maintained at the worker level through quote update broadcasts) it gets a new quote from the legacy service. The fresh quote is stored into its local cache (Redis) and broadcast to all workers.

AutoTX manager Maintains a list of all active ATXs from workers. It receives quote update broadcasts and checks if trigger conditions are satisfied. Stocks that have not be refreshed recently will prompt to be updated. Since multiple workers can have ATXs for the same stock the periodic price check can be amortized across all workers.

Audit server Records all bus traffic and unicast audit events from other services.

Audit log Logs external quoteserver hits and parsed transactions only. The log will conform to the strict XML schema defined by Day Trading Inc. The purpose of this log is for transaction per second evaluation only.

Runtime log Each event is logged to a single line using a custom logging format that associates log messages to exact lines of code. This will provide a much finer grain event resolution than the audit log.

These events could be written to the audit log but the XML schema adds friction to log parsing. For example, a single event is spread across an unknown number of lines making it very difficult to process logs line-by-line using standard Unix utilities like `grep`, `tail` and `awk`.

1.3 Work plan

We held many meetings throughout the term on the subject of planning and task division. On average, we would meet once every week or two to modify design decisions and evolve the architecture. Whiteboarding of the design and architecture was documented.

1.3.1 Timeline

Cumulatively, we logged over 450 hours on this prototype. Figure 1.2 shows the week-by-week breakdown. On average, we spent 38.125 hours building the prototype.

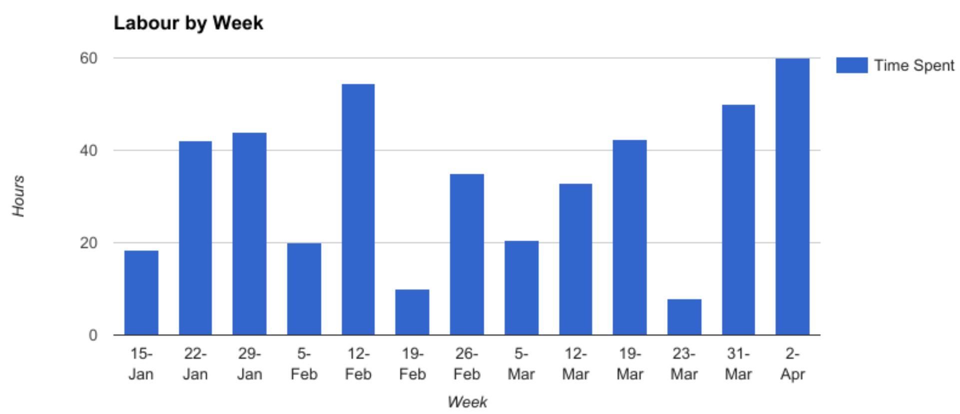


Figure 1.2: Work per week on prototype, all tasks

Figure 1.3 shows that over half of the work time was spent on implementation. Design sessions took the form of collaborative whiteboarding and brainstorming activities with the group as a whole.

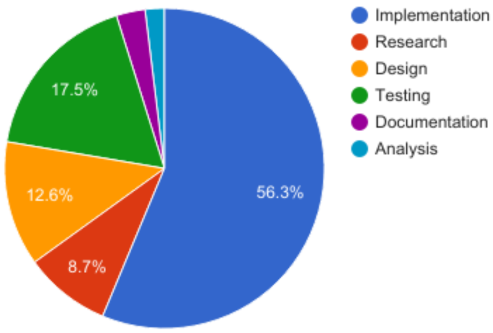


Figure 1.3: Areas of work

System testing was almost exclusively through code review, where implementations were examined by other group members for output validity and code quality.

1.4 Final architecture

The final architecture, shown in Figure 1.4, was as a whole relatively similar to our planned architecture.

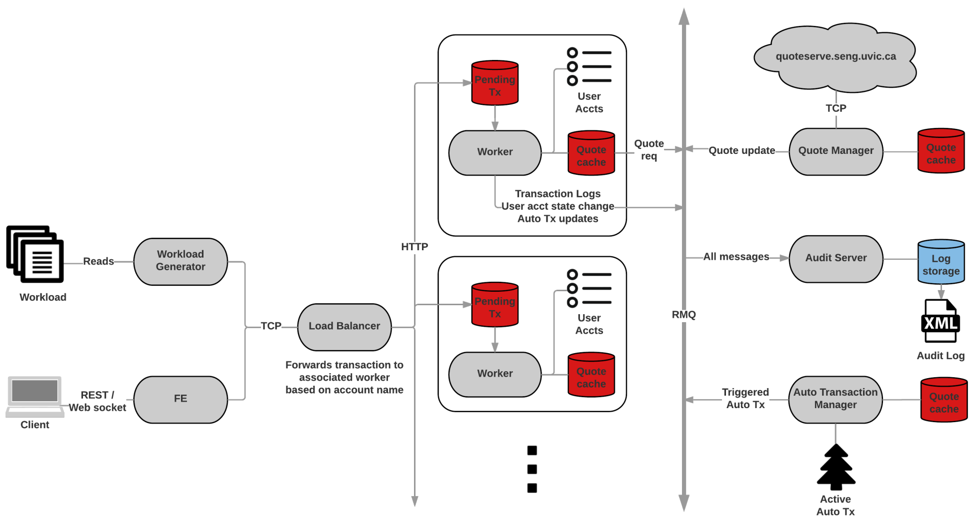


Figure 1.4: Final system architecture. Red databases are Redis caches, blue databases are Postgres.

1.4.1 Incoming traffic

The method of load balancing had to be modified to account for serving of the frontend and connection of the websockets. Request which enter the load balancer are given a session token, and are always routed back to the same worker. This allows us to skip the microservice which would be responsible for serving an ACID database of userdata. The root url serves an HTML page, which contains the login/create page if a user has not registered. Once at this page, a user is able to register/login, at which point a socket connection will be made to the backend. This socket connection will serve to asynchronously return the account state, as well as any output messages that need to be presented to the user. We opted for an entirely event based pattern instead of trying to modify a request/response style page loading to fit the event system on the backend. This allows all of our requests to be non blocking, and for the user to have the most up to date information all the time.

1.4.2 Frontend

The frontend consists of an authentication screen, and a loggedin view. Each action results in a post request getting sent to the API. Login maps to the `/login` API endpoint, create maps to the `/create` API endpoint, and all other actions map to the `/push` API endpoint. Login and create are responsible for user authentication. Once this is completed, the frontend also requests a consistent websocket connection over the `/ws` API endpoint. This websocket connection is added to the socket hub on the backend. Any time an event is completed on the backend, the socket hub returns the users socket connection and the event is fired over the socket to the users frontend. Each response contains two portions of data: The updated user state, and a message to display on the output screen. The updated user state is parsed on the frontend and displayed to the user.

1.4.3 Worker

The worker as a whole functioned relatively similar to the intended architecture. It stores account data, a local quote cache, and is the workhorse of the entire distributed system.

Account store

Accounts are stored on the worker in memory. Each worker is responsible for a sectioning of accounts. Once a user has created an account on a worker, all of its incoming requests will be routed through that worker until the account is terminated. While an in memory solution may not seem fault tolerant, all of the events are logged to an audit server, which can be used to replay events on another worker should the original worker crash or go down. In the case of total system failure, the audit logger uses a persistent storage, Postgres, and the system could be brought online simply be replaying all of the transactions from when the audit logger was last live, to when it last went dark.

Worker goroutines

The worker ended up divided into seven goroutines. Golang goroutines can be thought of simply as threads or processes which are time sliced.

`incomingTxWatcher` This was responsible for the http setup of the websocket handshaking, the frontend serving, as well as the `/push` API spinup.

`sendAutoTx` This goroutine spins up and pulls from two channels: `autoTxInitChan` and `autoTxCancelChan`. When a user correctly produces an auto transaction by setting and amount and then a trigger value, it is pushed into the channel and pulled by this go routine. In the case of an `autoTxInit`, we verify the local quote cache to determine if we can fire the trigger instantly, without the help of the autoTx manager.

If the trigger is valid already, it is fulfilled without leaving the worker. If not, we simply publish it to the autoTx manager through its initialization autoTx RMQ.

`AutoTxCancel` works similarly, except any cancel requests are simply sent straight to the worker. No trigger check is done, since there is no trigger check to do for a cancel.

`receiveAutoTx` This goroutine is the sister routine to `sendAutoTx`. `AutoTxFilled` types are sent back to the workers `autoTxQueue`, which is an RMQ direct exchange where the routing key is the worker ID. When these filled requests come in, they contain an `AutoTxKey`, an `AddStock`, and an `AddFunds`. The idea of this is that both buys and sells can be consumed on the same type, as the result of a buy is an amount of stock, and a remainder of cash, and the result of sell is an amount of stock (0) and a remainder of cash. By unifying these two types, its possible to eliminate the forking behavior that would exist otherwise.

`catchQuoteBroadcasts` This goroutine is relatively simple, as it simply consumes from the quote broadcast exchange and caches the quote into the workers quote cache.

`fetchNewTx` This goroutine is responsible for consuming operations out of the the workers Redis queue and pushing them into the `unprocessedTx` channel, which is then pulled from by the `txWorker`.

`txWorker` This goroutine is responsible for the brunt of the processing which occurs on the worker. Whenever an unprocessed transaction is pushed into the `unprocessedTx` channel, it is then processed by this worker. The command is then parsed into a command object, which contains an execute function based on which type of transaction it is. For example, add transactions will execute the add command in the backend.

`cleanAccountStore` Wakes every sixty seconds to remove expired buys and sells from all user accounts. This prevents the memory loss associated with a user who initiates a large amount of buys or sells but never confirms those actions.

1.4.4 Quote manager

Quote updates involve every part of the distributed system and are the best demonstration of the efficiency of event-sourced architecture. With event-sourcing, each service is free to define its own actions to events that occur in other parts of the system. Figure 1.5 shows a typical quote request process.

Workers generate requests for new quotes, specifying a stock and whether a cached response is allowed. (A BUY for a stock whose quote is about to expire can force a the retrieval of a fresh quote instead of passing the stale quote to the user.) The Quote manager pulls requests from `quote_req` RMQ queue and checks for a cached value. On a cache miss, or when forced by a worker, a new quote is requested from the legacy service using the timeout procedure detailed in 5.1.3.

Quotes are broadcast with a key consisting of the stock name and whether the quote was retrieved from a cache or from the legacy service (referred to as “cached” and “fresh” respectively). Each part of the system filters broadcast messages for its particular purpose. Workers and AutoTX managers need to maintain a local quote cache so they filter “fresh” quotes for

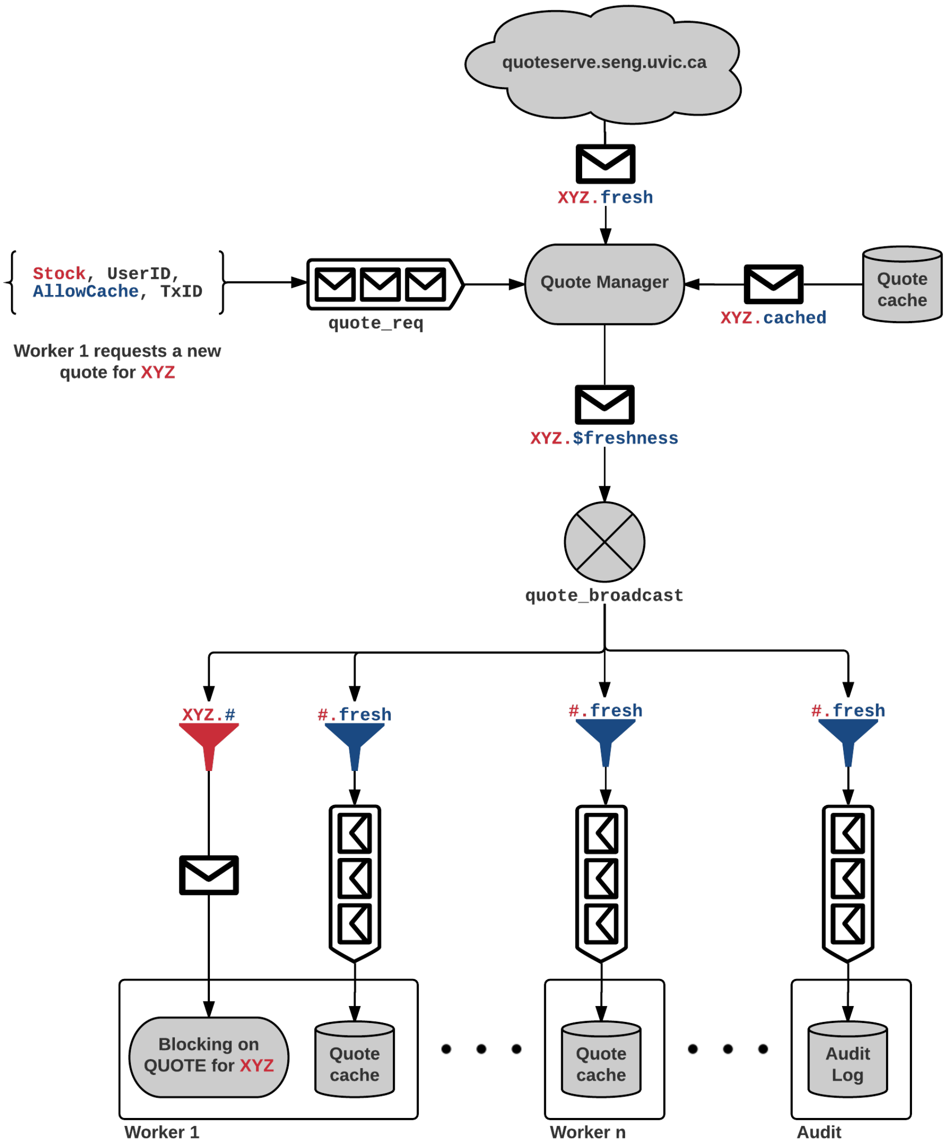


Figure 1.5: Service interactions for fulfilling a quote

cache updates. The Audit Logger records quote requests for billing with the same filter. The worker that generated the original request filters for the stock name. This allows two workers to request and block on updates for the same quote and race their requests. Both workers would resume execution when the first quote resolves.

1.4.5 Audit logger

The audit logger required significant redesign in order to accommodate high throughput logging. Section 6.1.4 gives a thorough overview of the necessity of this design and its limitations.

1.4.6 AutoTX manager

The auto transaction manager was designed to be a central point where transactions could be confirmed and sent back to the respective workers. `AutoTxInit` messages are sent from the worker containing an `AutoTxKey` (`Stock`, `UserID`, `Action`) as well as an amount and a trigger. `AutoTxInit` objects are taken and inserted into an AutoTxStore, which contains a map of all `autoTxKeys` to `autoTxInits` (For cancellation of transactions), and a map of `TreeKeys` (`Stock`, `Action`) which maps a `Stock` and `Action` to a `Tree`. When multiple auto transaction buys for a stock ABC comes in, they are inserted into a left leaning red black tree. A red black tree was chosen because it excels at heavy read/write workloads and it is self balancing. The auto transaction manager is responsible for requesting quote updates for each stock which resides in its store.

The auto transaction manager is also subscribed to the same quote broadcast exchange as the other workers. When a new quote comes in, the buy and sell trees for that stock are observed. It is very simple to partition the tree into fillable transactions and unfillable transactions, because red black trees are binary search trees and are balanced and ordered by their very nature. For each fired trigger, the node is removed from both the tree and the map and then the `AutoTxFilled` transaction is sent back to the worker which instantiated it.

When `autoTxCancels` arrive at the autoTx manager, they are simply removed from the autoTx store.

While the auto transaction manager is the only place where user data meets, user data will never interact with any other user data, as comparisons are only done between the quote value and the amount specified by the user. This insures no cross contamination of data, or mismatching of auto transactions. Furthermore, all auto transactions have

Finish this sentence!

1.4.7 Load balancer

1.4.8 Docker

Chapter 2

Security

Authentication is performed via a backend service which verifies the identity of the users as they create accounts. Once created, a websocket connection is established for each session. These are cycled upon every new session for a user, and are managed by a socket hub service on the backend. The authentication protocol is hand rolled to provide the utmost security, and is managed by a backend distributed user map. Since users are isolated to the worker at which they are balanced to, hijacking a user account is impossible unless you are randomly distributed onto the worker in which the user resides. Furthermore, no confirmation is given as to whether a user account exists upon a failed password, so a rainbow tables password attack could in theory take an infinite amount of time.

These features were rigorously user tested across single and multiple instances. Password attacks were ran, and the only vulnerability discovered was the standard entropy password vulnerability, where the length of time raises exponentially with the number of characters in the password.

In the real would, certs would be used and additionally user credentials would be salted and hashed. These credentials would be stored in a secure database.

The system is audited by logging all of the user commands, including the user who initiated a dumplog. Through extremely thorough logging we're able to identify not only the root cause of any problem that can occur with the system, but also to perform vulnerability checks and inspections. In the future real time fraud prevention machine learning models could be applied to the authentication logs to ascertain what constitutes an attack.

Chapter 3

Test plan

3.1 User testing

Validate command pre/post conditions. Tested through FE?

Chapter 4

Fault tolerance

Chapter 5

Performance analysis

5.1 Decreasing quote retrieval time

The legacy quote server can delay for up to four seconds before sending a response. This delay is vastly greater than the typical command execution time of dozens of microseconds (see 5.3). The legacy server is the greatest barrier to high command throughput and dozens of hours of research and design was spent mitigating the effects of its delay.

5.1.1 Statistical analysis of legacy quote server

We sent a large number of serial requests to the quote server and recorded the response time with a shell script. Figure 5.1 shows the distribution of response times follow an exponential distribution with 65.75% of responses experiencing only network delay. The expected value of the response time is 563.3 ms.

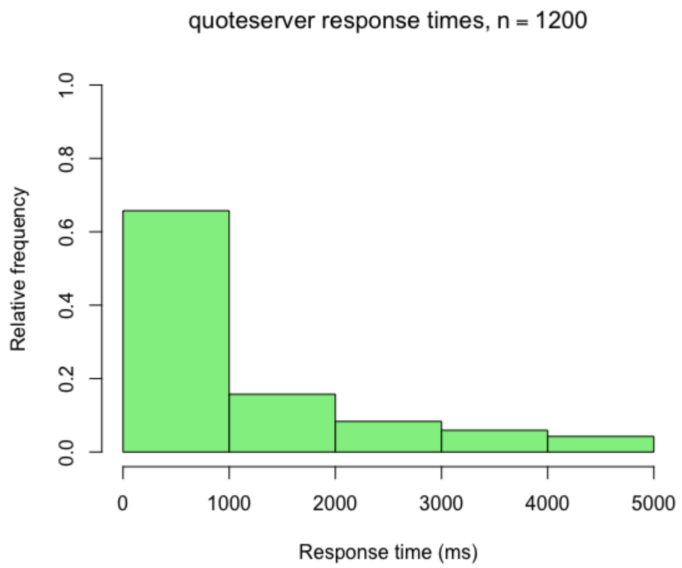


Figure 5.1: Histogram of legacy quote server response times with 1 s buckets

The one second buckets in 5.1 obscures the fact that results are clustered after whole second values. Removing the constant delay portion from each bucket yields the distribution (Table 5.1) of variable network and processing delays.

From this data we can conclude that if the legacy quote server has not sent a response after 30 ms then we will wait at least 1 s for a response.

Table 5.1: Legacy quote server network delays

Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
7 ms	9 ms	9 ms	9.414 ms	10 ms	26 ms

5.1.2 Using timeouts to ensure fast quote retrieval

We decided to use a request timeout strategy to minimize the total time spent waiting for a quote. If there was no response from the quote server after a given timeout we cancel the request by closing the socket connection and issue a new request. We used the tail of the network delay data (i.e. ..., 16, 16, 17, 17, 20, 26 ms) to set an initial timeout at 20 ms and used a 5 ms exponential backoff. This backoff strategy requires six iterations to exceed the expected delay of 563.3 ms. Exceeding 1 s total delay has a likelihood of 0.0299%. If the total timeout exceeds 4 s and there is still no response from the quote server then the service is assumed unreachable and the quote manager raises an error.

5.1.3 Timeout effectiveness

We implemented the timeout strategy in 5.1.2 and gathered response time data directly from the quote manager. Figure 5.2 shows frequency of retry attempts before a quote resolved. Strangely, the distribution does not match that of Figure 5.1 and the legacy quote server has an 89.35% likelihood (instead of 65.75%) of resolving in under 20 ms. Day Trading Inc. has assured us that the behavior of the legacy quote server is stationary so perhaps the change arises from our serial and timeout-retry request methods.

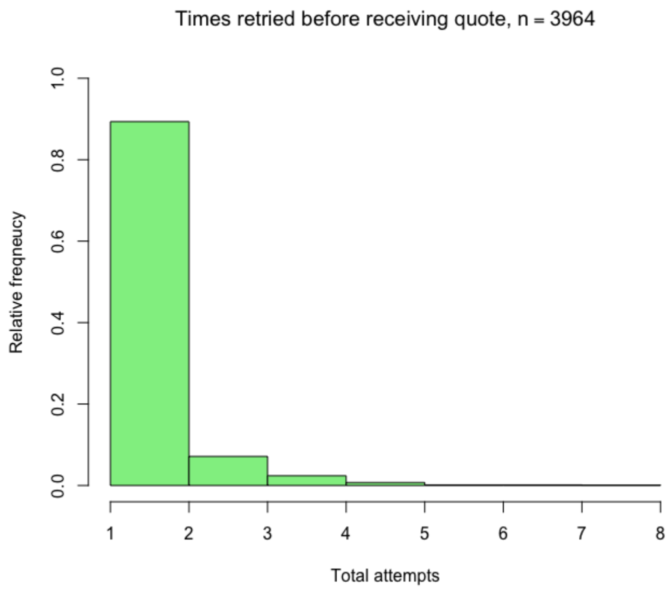


Figure 5.2: Quote retry attempt histogram

The distribution of total waiting times is shown in Figure 5.3. 89.18% of quotes are resolved before 50 ms.

Only three quotes take longer than 500 ms and none longer than 850 ms. This adds confidence to our derivation that waiting longer than 1 s for a quote should be a $\approx \frac{1}{3400}$ event.

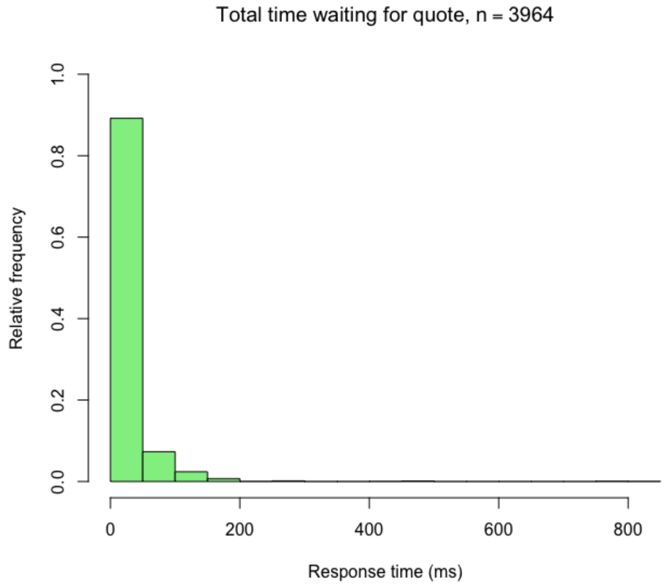


Figure 5.3: Total waiting time to retrieve a quote with 50 ms buckets

5.1.4 Minimizing lingering TCP connections

When a TCP connection is terminated with a FIN command the socket enters the TIME-WAIT state until the termination is acknowledged with a FIN-ACK command. The socket stays in the TIME-WAIT state for twice the connection MSL, typically two minutes. Each open socket occupies approximately 1 Mb of memory and is considered an open file. Thus, the number of open sockets is limited the the system memory and OS limitation on concurrent open files.

The legacy quote server timeout method necessarily leaves many connections in the TIME-WAIT state. When we first implemented the timeout method the quote manager would become unresponsive and crash as connections lingered in the TIME-WAIT state and the host had its memory occupied entirely with open TCP connections.

Changing connection methods in our application from the generic `Dial` method to the specific `DialTCP` method resolved the lingering connection issue. We suspect that `Dial` discards the connection in such a way that the FIN-ACK is not received by the socket and the OS maintains the connection for the entire double MSL period. This difference is behavior is undocumented and should be disseminated to developers who use Go in applications with high TCP socket turnover.

5.2 Worker scaling

Our domain decomposition recognizes that account actions are "embarassingly parallel" since accounts never interact with each other. Scaling to accommodate more users is as straightforward as adding more workers.

5.2.1 The sixty second golden window

Many of the business logic requirements inherit time limitations from the sixty second validity window for a quote. Therefore, if an entire workload can be completed in under sixty seconds then all quotes are valid for the entire run. This gives rise to a "golden window" of performance where workloads that complete in within the window have drastically higher TPS than those that miss the window.

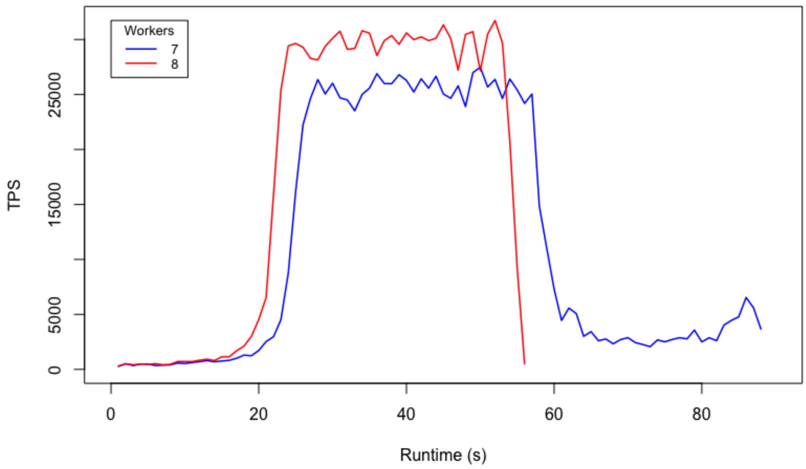


Figure 5.4: 1000 user workload: 8 Workers, 18k average TPS; 7 Workers, 10k average TPS

Even though approximately 90% of the commands are completed in 60 seconds by seven workers in Figure 5.4, the remaining 10% need new quotes and the retrieval delay adds over 50% to the total runtime. The penalty for missing the golden window is severe.

5.2.2 Scaling results

The 1000 user workload was used to test the effect of increasing the number of workers. Figure 5.5 shows that increasing the number of workers decreases the total time to retrieve quotes, increases the maximum TPS and decreases the total runtime.

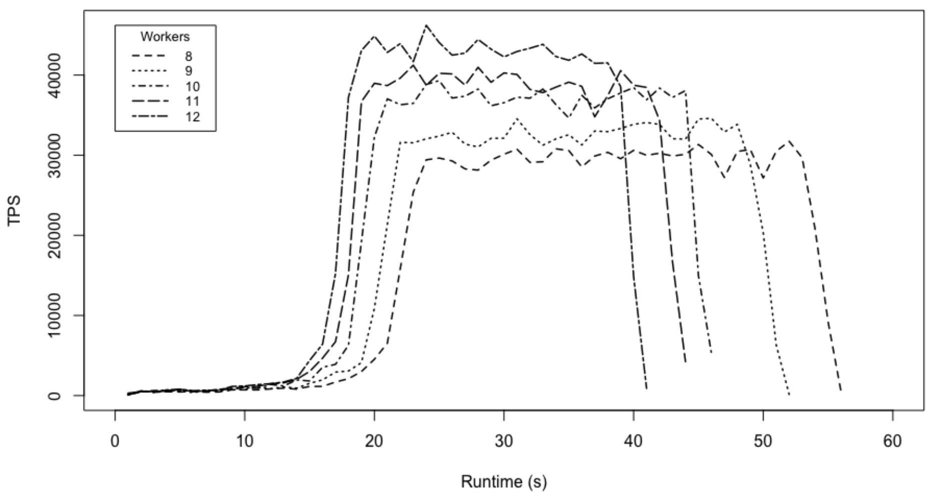


Figure 5.5: Scaling workers for 1000 user workload

With twelve workers we achieved a maximum 26.1k average TPS for the 1000 user workload and a peak TPS over 45k. (See 6.3.2 for why we did not add more workers.)

There are two distinct modes of operation for the system: quote-fetching and nominal[1]

[1]Specifically, the system is at "nominal TPS" when it is within 85% of max TPS.

operation. During quote-fetching, transactions in workers generate local quote cache misses and are blocked on responses from the quote manager. During nominal operation the workers have a full set of quotes cached locally and no longer have to block on responses from network services. The jaggedness in the nominal TPS region is noise from plotting a single run with each worker configuration.

The average TPS value during nominal operation indicates weak linear scaling with the number of workers. Again, repeated runs should decrease the error.

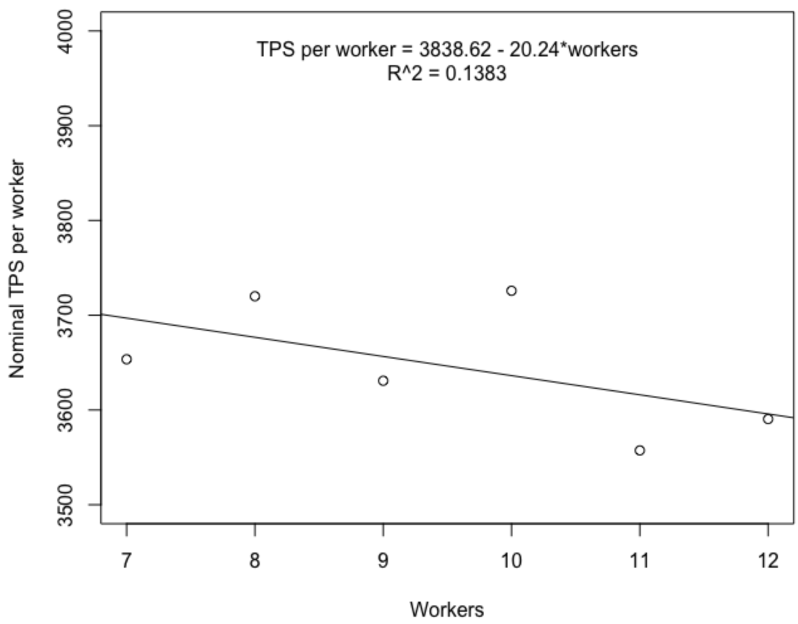


Figure 5.6: TPS scaling with workers for 1000 user workload

It's important to note that even when runtime exceeds the golden window the nominal operation speed of the workers is relatively constant. This indicates that successful methods for scaling the application will involve decreasing the time to reach nominal TPS and then adding more workers. Chapter 6 documents our efforts to realize this scaling.

5.3 Command execution time analysis

In order to determine the performance of individual commands we created a fork of the worker that logged elapsed wall clock times for *valid* commands. A valid command is properly formatted (e.g. no negative dollar amounts) and meets all account state pre-conditions. This assures a common execution path for results and prevents a multi-modal distribution caused by commands resolving early and avoiding lengthy inter-service communication delays. Results are summarized in Table 5.2.

Command execution times show two general patterns. Commands that do not use stock prices as pre-conditions (e.g. Add, Commit Buy, Set Sell Amount) resolve at a median time of $\approx 25\,\mu s$. Commands that do use stock prices resolve at a median time of $\approx 220\,\mu s$. The order of magnitude slow down is the result of storing stock values externally (but locally) in Redis. The retrieval delay is costly but is countered by offloading quote TTL enforcement.

There are several interesting anomalies in Table 5.2. The first is the paucity of data from Sell commands. This is because the set of pre-conditions is the largest for any command: the user must have already purchased stock *and* chosen a sell amount that resolve for pseudo-random stock prices.

Table 5.2: Command execution times gathered from 3 runs of the 1000 user workload

Command	n	Execution time percentile (µs)				
		50%	95%	99%	99.9%	99.99%
Add	168 227	24.9	35.7	54.3	176.7	1 977.6
Buy	197 897	217.5	427.8	488.2	65 650.4	230 294.0
Cancel Buy	38 812	25.7	36.0	53.9	189.3	2 197.3
Cancel Sell	41	27.3	31.9	50.4	55.1	55.6
Cancel Set Buy	102 925	21.5	30.8	46.8	169.5	1 979.1
Cancel Set Sell	102 642	21.5	30.8	46.8	177.8	1 998.6
Commit Buy	121 658	27.1	37.9	55.8	188.6	1 996.4
Commit Sell	92	25.7	33.1	39.4	73.0	76.3
Display Summary	225 298	21.3	30.2	45.9	161.9	1 953.0
Dumplog	3	45 754.6	45 926.5	45 941.8	45 945.3	45 945.6
Quote	355 578	213.1	429.7	809.8	218 334.6	293 673.5
Sell	152	220.7	420.8	455.4	481.6	485.2
Set Buy Amount	238 759	22.2	31.6	47.5	160.7	1 986.2
Set Buy Trigger	229 465	22.0	31.5	47.7	171.9	1 972.5
Set Sell Amount	196 997	22.1	31.6	47.9	164.4	1 979.5
Set Sell Trigger	190 648	22.0	31.5	47.6	159.9	1 982.9

Next, the 99.99% values for the non-stock, high-frequency commands increase by an order of magnitude compared to the 99.9% values. Since execution of these commands doesn't involve any external services the delay is likely the result an ill-timed application garbage collection cycle. Since this delay doesn't manifest in the tails of the low-frequency events (e.g. Cancel Sell) the likelihood of being slowed by a garbage collection event is $\approx \frac{1}{30000}$.

Dumplog data is largely uninformative, given the extremely small sample size. The execution time results from a path that necessarily interfaces with external services and is subject to communication delay.

Buy and Quote do exhibit bi-modal behaviors despite the experiment setup. This is a result of quote cache hits and misses having execution times that differ by several orders of magnitude. Histograms for all of the commands are presented in Appendix A.

Chapter 6

Capacity planning

Progressing through the series of workload files stresses different parts of the trading system architecture. Workload files differ by the number of unique users, quotes and total transactions. Early workload files have few unique users and quotes but rapidly increase the number of transactions. The primary design goal becomes minimizing individual transaction times. Later workloads rapidly increase the number of unique users and quotes, exposing inefficiencies in different parts of the system that were often the result of optimizing a design for high transaction throughput for early workloads.

This chapter outlines the often surprising manner in which our system failed as we progressed through the workloads, and the design changes that followed. Most often, the manner of failure was the result of an assumption that would be true at smaller scales but became invalid at a later point.

6.1 Logging throughput

The 1000 user workload was the first occasion for our system to operate at nominal TPS for a significant portion of its runtime.

Since each transaction needed to write at least one entry to the audit log the volume of log messages was unprecedented. Controlling the “firehose” of log messages was the most significant architectural redesign. It included several false starts and, ultimately, reached a workable but flawed solution.

6.1.1 Limits of logging to a flat file

From the initial prototype through the 100 user workload, the audit service wrote directly to an `.xml` file that could be submitted for validation. Log messages were removed from RMQ and stored in memory for writing by separate threads. However, running the 1000 user workload exceeded the rate that the audit service could clear messages from RMQ, causing a significant backlog of messages to develop. As the total message backlog size approached 700k the rate that messages could be exchanged slowed, causing a slowdown in the rest of the system as execution was blocked on message exchange. Soon after, services would fail as they lost their connection to the RMQ server.

As noted in the “Production Checklist” section of the RMQ user guide[1], performance is heavily tied to available RAM. As the backlog increases RMQ will begin swapping RAM to disk to ensure persistence. The IO penalty for writing to disk causes an intense slowdown. Since the worker services generating the logs are not capable of throttling they eventually push RMQ into resource exhaustion and failure.

[1]https://www.rabbitmq.com/production-checklist.html

Direct to file logging was never intended for production use. Creating per-user dumplogs would be onerous since there was no direct method for searching or sorting the log file. Leaving the log file implementation in place for most of the project allowed us to focus development efforts on optimizing the quote manager and implementing the auto transaction service. Letting RMQ fail illuminated the "danger zone" for RMQ on the lab machines. Different audit logger refactors could be compared for effectiveness by monitoring the RMQ backlog.

6.1.2 Logging directly to an RDBMS

The first refactor involved inserting logs into Postgres and writing to a file on an as-requested basis. This solved the problem of creating per-user log files but throughput was significantly worse than writing direct to a file. With direct to file, the 100 user workload with 100k transactions generated 2k backlogged messages on RMQ. With the Postgres refactor, the 100 user workload resulted in a 20k message backlog. No attempts at larger workloads were made after this poor result.

This performance slowdown is not surprising. The flat file and RDBMS both store the preformatted `.xml` entry for the event. In addition, the RDBMS stores extra data about the user name, transaction type and creation time to enable queries. The RDBMS is storing more data than the flat file. In addition, the RDBMS suffers a performance penalty from indexing data on insertion. While there are methods to mitigate these problems, such as connection pooling, the performance degredation was extreme enough to justify larger service refactors.

6.1.3 Processing logs with ELK

An RDBMS enables rich querying and enforces data integrity — useful features that are not relevant for storing an append-only log. Moreover, the indexing that provides those useful features introduces a performance penalty that limits throughput. Specialized log storage solutions forgo rich indexing in order to maximize write throughput.

The Elasticsearch - Logstash - Kibana (ELK) suite of applications from elastic.co[2] is a popular distributed log storage method. Logstash consumes and transforms data for indexing and storage in Elasticsearch. Kibana is a graphical monitoring suite that provides information about the logging rate and health of the logstash and elasticsearch services.

A prototype was created that deployed the ELK stack in separate Docker containers collocated with the audit logger. Logstash consumed messages directly from RMQ and sent them to Elasticsearch for indexing and storage. The prototype had abysmal performance. With the 45 user workload there was a 7k (out of 10k total) backlog. Development was abandoned at this point.

The poor performance of the ELK stack was directly related to its resource limitations. Each part of the ELK stack performs better with more available RAM. Collocating all services severely limited the available RAM. Also, ELK requires a non-trivial amount of JVM and OS tuning to provide optimal resource availability. Although there are guides for this process it was unclear how to apply their recommendations on the tower of abstractions in the production environment: a docker OS on a VM OS on a host OS, each needing their own tuning.

The Elasticsearch scaling guide[3] recommends adding more shards (i.e. independent instances which maintain a partition of the data) to increase write throughput. This throughput solution — a distributed system within a distributed system — directly links scaling to resource demand. Scaling Elasticsearch would likely reduce the number of systems available to host workers and limit the maximum TPS. The problem of high log throughput would be solved by removing the ability to create logs at a high rate.

[2]https://www.elastic.co
[3]https://www.elastic.co/guide/en/elasticsearch/guide/current/scale.html

6.1.4 Buffered logging

The problem with the RDBMS solution in 6.1.2 is fundamentally a mismatch between the production and consumption rate of log messages. The solution to this problem is to place a buffer between the producer and consumer.

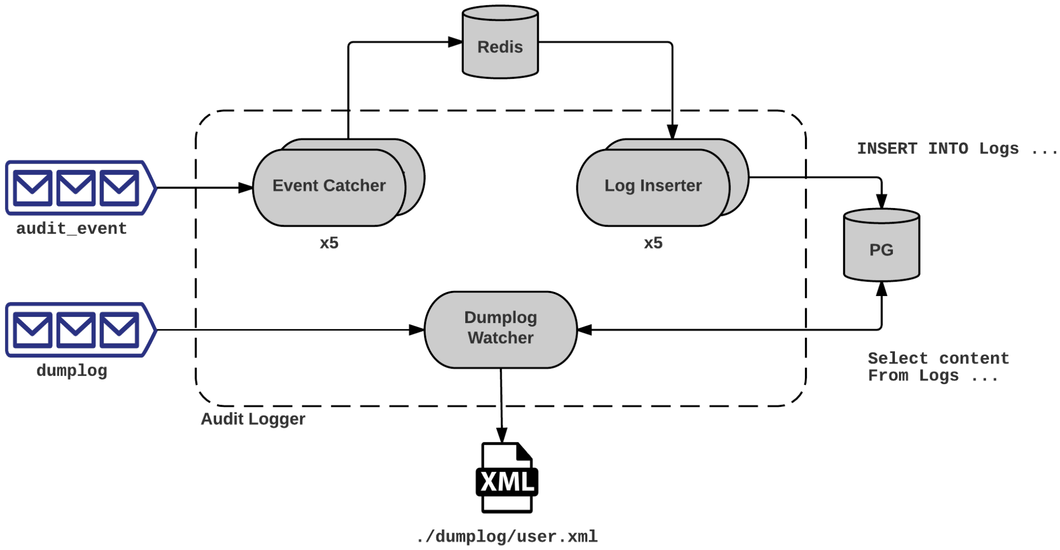


Figure 6.1: Buffered audit logger

Figure 6.1 shows how multiple `Event Catcher` workers remove incoming log messages from RMQ and place them in Redis. `Log Inserter` workers remove items from Redis and store them in Postgres. With this design, the 1000 user workload only reached a 20k backlog of messages and had no observed performance degradation. Although a run would finish in around 45 s it would be upwards of 6 min to finish insertion into Postgres. When a message for a dumplog was processed it would display messages had successfully migrated to Postgres but was unaware of those still in Redis. This is a soft violation of the business requirement that a dumplog should show all transactions proceeding itself. We believe this is acceptable since, in actual use, there is no clear "end of work" to capture. All log messages will make it into Postgres for querying so the requirement is *eventually* satisfied.

This method has an upper limit to its effectiveness since the Redis buffer could run out of storage space under periods of sustained high TPS. The boundary of the buffer memory was not encountered during any testing and we cannot speculate about its value. In order to determine the limits we would need a workload file larger than the final workload. Alternatively, we could induce a period of sustained high TPS by removing the requirement to re-fetch expired quotes and concatenate existing workloads.

6.1.5 Alternate solutions

When the buffer method in 6.1.4 reaches its limit there are several possible development paths for proceeding forward:

1. *Agglomerate messages*: Message traffic can be reduced by combining multiple log events into one message. Workers would only emit messages for logging at fixed intervals or after a certain number of events (whichever comes first) and reduce the overhead associated with creating, sending and processing RMQ messages. The optimal message size would have to be determined through experiment.

2. *RMQ scaling*: RMQ is capable of its own distributed deployment. Increasing resources available to the message bus would allow more messages to be stored before removal into the buffer.

3. *Robust message passing*: Apache's Kafka[4] provides functionality similar to RMQ but is optimized for message storage and large backlogs. This allows consumers to operate at different rates and removes the need to process log messages faster.

6.2 Quote manager scaling

The system's TPS grows almost $10\times$ once a full set of quotes has been retrieved. Further increases to average TPS could be gained by decreasing the time spent fetching quotes. The methods in 5.1 brought the quote server response time to its lower limit so further efficiency could only come from horizontally scaling the quote managers. Intuitively, doubling the number of quote managers should decrease the total time to retrieve all quotes by half, provided the workload is split evenly. If only it were so simple.

6.2.1 Building a "snoopy" quote manager

With one week until the final deadline we decided to refactor the quote manager to participate in a multi-quote manager environment. We ported the "snoopy caching" functionality from the worker and audit logger into the quote manager. The "snoopy" quote server could listen to quote broadcasts and update its local cache accordingly. With this functionality, multiple quote managers could act as workers servicing requests from a single RMQ queue.

A message header with the ID of the quote manager that serviced the request was added to all quote broadcasts. The quote manager cache updaters would discard messages that originated from its own quote manager. This is inefficient but necessary because RMQ does not allow an "anti-match" for message routing keys. That is, one cannot specify, "Capture all messages *except* ones that follow this pattern."

Total development effort was approximately one hour.

6.2.2 Performance analysis

Figure 6.2 shows that TPS correlates *negatively* with the number of snoopy quote managers. This is very counter-intuitive and deserves reflection.

Comparing the single quote manager deployment in multi and single architectures gives a sense of the overhead associated with discarding quote broadcasts. The relation becomes less clear when two and three quote managers are used: the system benefits from having to retrieve fewer quotes per quote manager but adding quotes to the cache also has a delay. The benefits from horizontal scaling start to manifest when three quote managers are used, but it takes the form of, "things stopped getting worse," instead of "performed better than a single quote manager."

The single architecture quote manager is very fast because it already functions like a multi machine quote manager. Each new request spawns a thread that handles communication with the legacy service. Most of the threads are blocking on a response from the legacy service making it very likely that a new thread will find the application in an idle state. Since workers block on the completion of a quote command the maximum number of simultaneous quote requests is equal to the number of workers. Hence, the number of threads requesting quotes in the quote manager is capped, thus preventing thread creation runaways and CPU starvation in the quote manager. Adding more quote managers doesn't increase the number of simultaneous quotes that can be requested by workers.

[4] https://kafka.apache.org

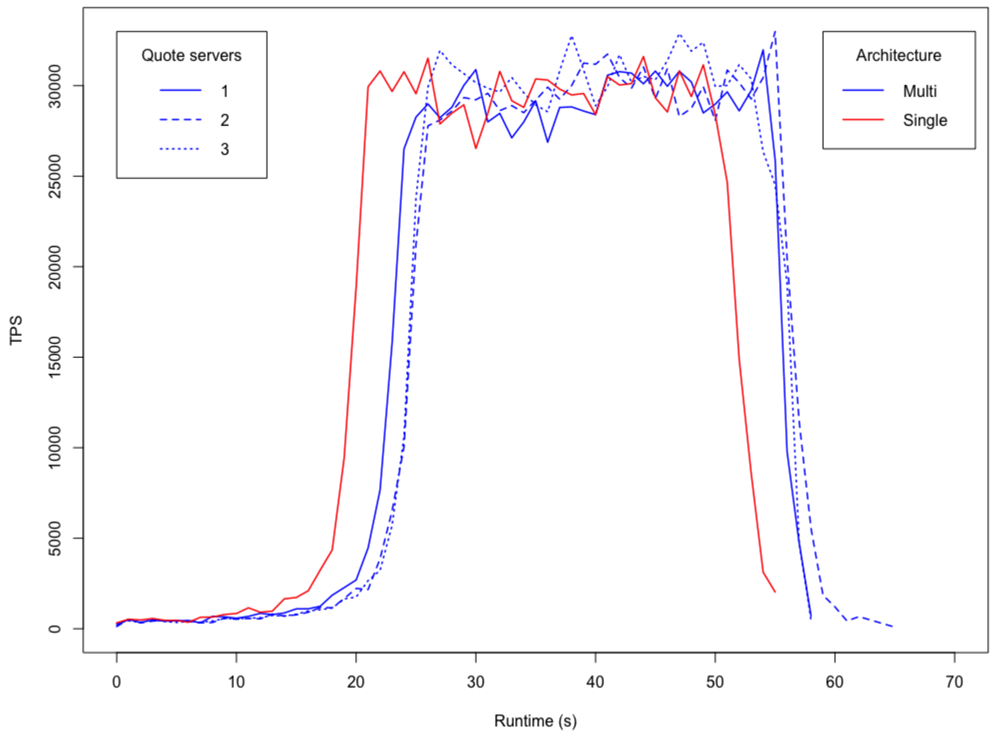


Figure 6.2: Performance of multi and single quote manager designs on 1000 user workload

6.2.3 Alternate solutions

The snoopy quote manager was implemented because it was a small amount of development effort for a large potential payoff. There is another way to implement multiple quote managers, although it is more complicated: quote symbols could be hashed to associate with unique quote managers. This prevents the need for quote managers to do snoopy caching. However, it introduces problems with scaling since the hash will depend on the number of available quote managers.

The snoopy quote manager can scale easier since failures would be independent. As the number of workers continues to grow, Figure 6.2 should be re-run to determine the break point between the communication overhead and the increased capacity for simultaneous quote requests.

6.3 Worker loading

To run the workload files we loaded sections of 3300 transactions into workers in a round-robin manner. By measuring the total number of transaction in a worker's backlog at each loading cycle we could determine the limits of our round-robin loading method.

6.3.1 Worker backlog analysis

The curves in Figure 6.3 have two distinct parts: an upward slope that becomes steeper as the number of workers before coming to a maximum and either plateauing, as with eight workers; decreasing at a fixed rate, as with nine to eleven workers, or; decreasing and leveling out, as with twelve workers. It's important to note that the x-axis represents loading cycles and not a uniform time scale. Round robin loading cycle times increase as the number of workers increases.

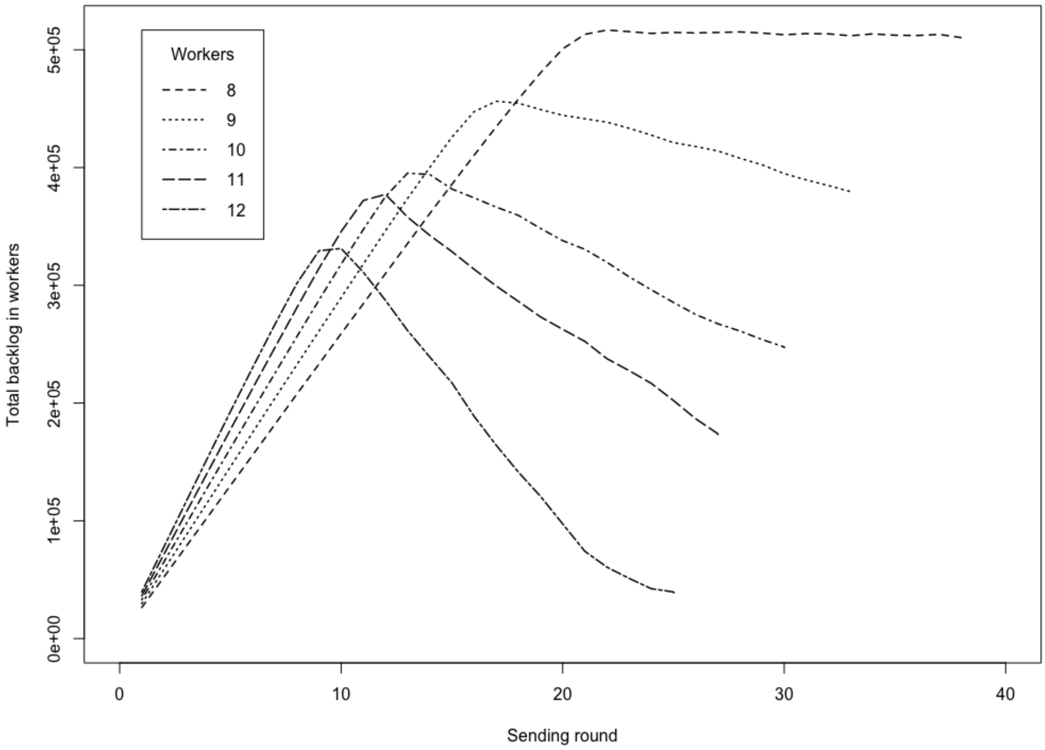


Figure 6.3: Total worker backlog for 1000 user workload

The slope of the curve represents the ratio of transactions coming in to a worker over transactions completed between successive cycles. Essentially, this is

$$\frac{3300\,\text{transactions per cycle} \times \text{cycles per second}}{\text{transactions per second}}$$

The peak in the curves occurs when the system has retrieved a full load of quotes the transactions per second increases drastically. For eight workers, the slope is approximately 1, indicating that the input and output rates are equal. The work in 5.2.2 indicates that the transaction input rate must be approximately 3600 transactions per second for each worker. As the number of workers increases, the number of transactions per second for a worker stays (mostly) constant but the cycles per second decreases. The leveling off with twelve workers indicates that the workers are starved for transactions near the end of the run.

The change in the rising slopes is also affected by the increased cycle time but the correlation is less direct. During loading, the transactions per second is significantly lower than 3300 and constant regardless of the number of workers. The slope increases with the number of workers because the capacity for transactions in the system increases (i.e. each worker has its own cache). As the cycle times become longer this decreases the slope.

6.3.2 Worker starvation analysis

Figure 6.4 shows how workers entering starvation at different times. All workers have identical backlogs up until the peak where higher-numbered workers operate at nominal TPS earlier. This is because the low-numbered workers early in the round-robin cycle are “alone” for longer with the transaction list and are more likely to encounter uncached quotes. High-numbered

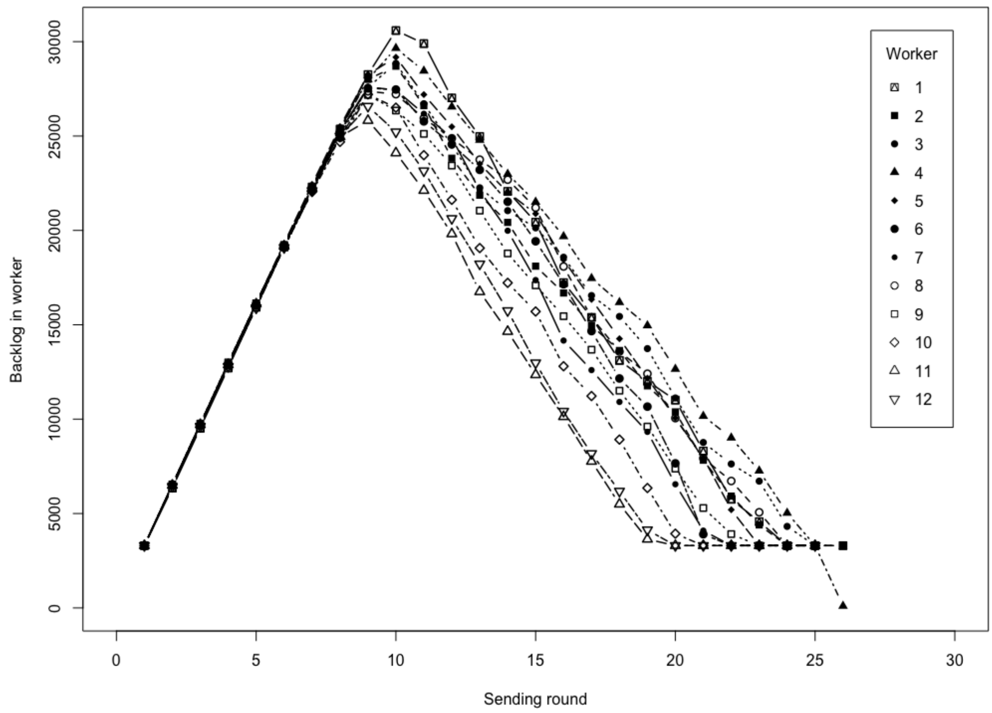


Figure 6.4: Workers entering starvation during a 1000 user workload

workers benefit from the pre-caching. Unfortunately, they enter starvation approximately ten cycles before loading finishes and represent an inefficient use of resources.

The rates of descent are mostly uniform, with the exception of worker 4 (machine B133). Consistently, this machine performed worse than its peers. This could be the result of hardware aging and general, spooky "cruft" on the machine or a non-uniformity in the workload distribution. The latter is unlikely since worker 4 was slow regardless of the total number of workers.

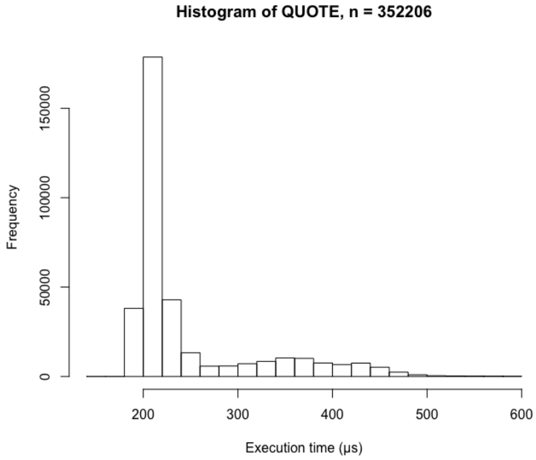
We did not undertake any tests with thirteen workers because of these results with twelve — adding more workers would cause the system to enter starvation earlier and would be a poor use of resources.

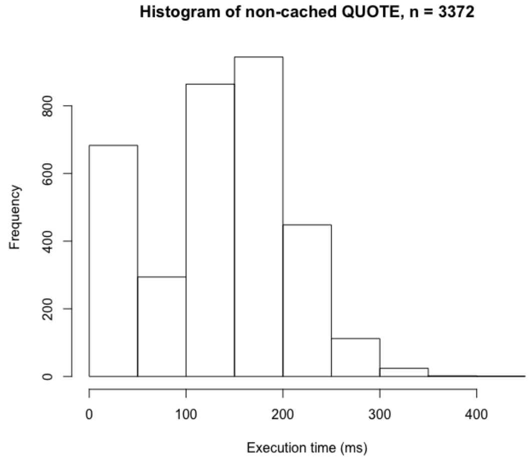
6.3.3 Alternate solutions

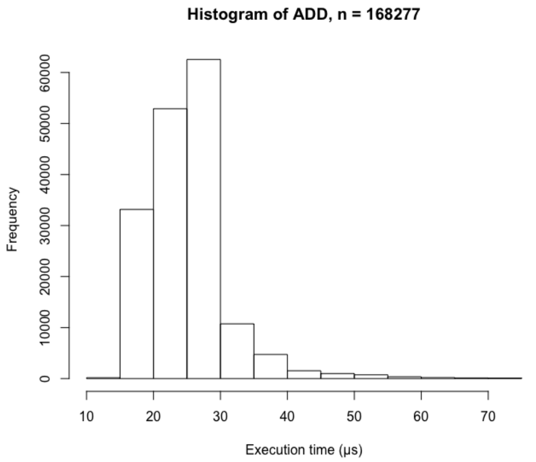
The ideal operating state is when the incoming and outgoing transaction rates are equal. In order to achieve this state we would have to implement a feedback system with the transaction loader. The number of backlogged transactions in a worker could change the number of transactions sent in a loading cycle.

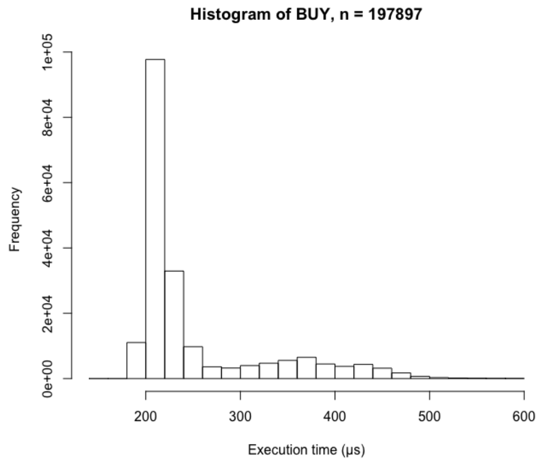
Though not trivial, this is a very tractable solution. However, we feel it would be overly specific to the testing environment. Could an actually existing trading system exert backpressure on user loads to throttle demand? This seems unlikely, or at least one that would lead to frustrated users. Further testing should involve a dynamic *stream* of transactions that could exhibit richer behavior like cyclic demand cycles and surges. Though the same risk of overfitting the prototype software to the test environment is present, the fidelity has increased and the solutions should be more generally applicable.

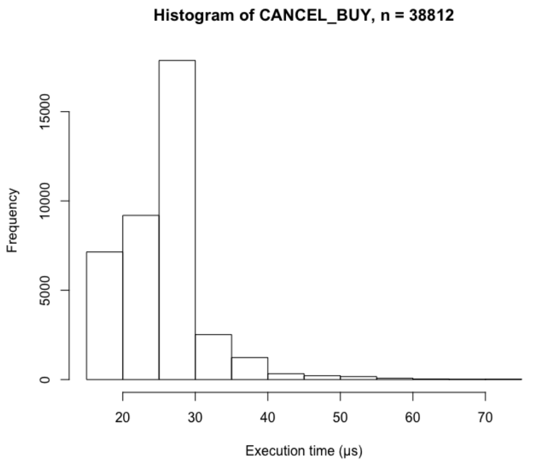
Appendix A Command runtime distributions

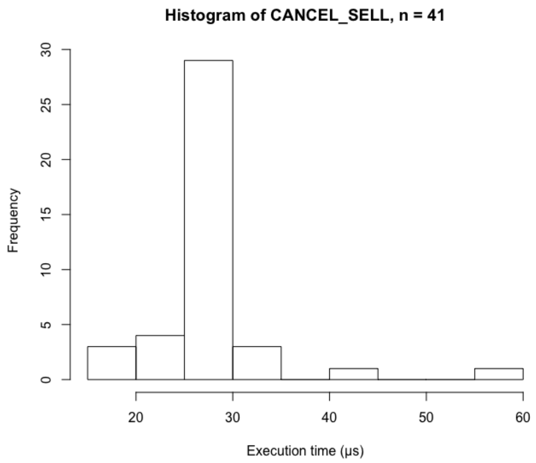


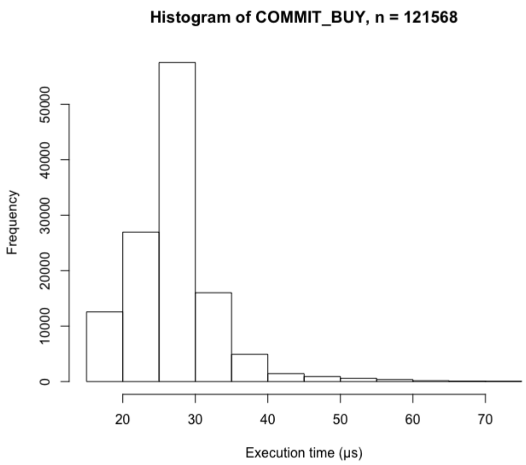


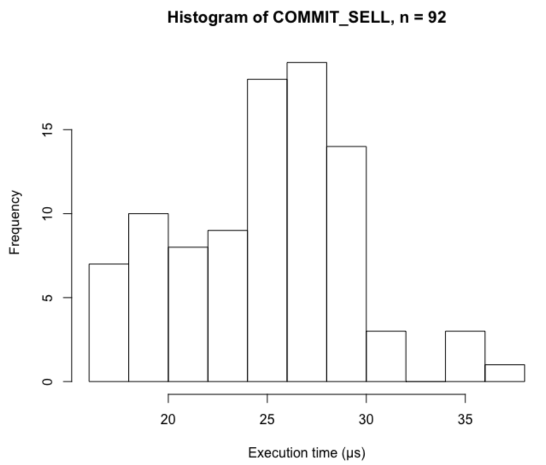


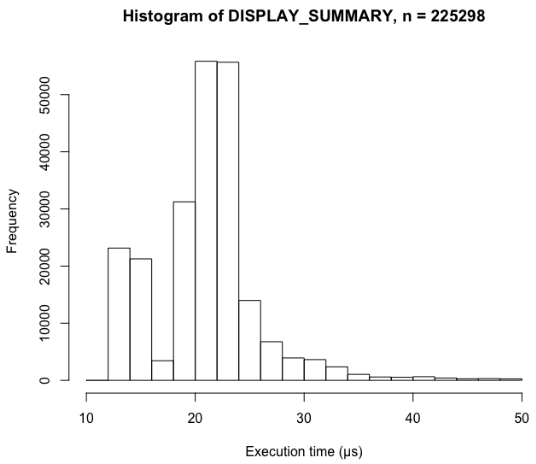







Histogram of COMMIT_BUY, n = 121568
Frequency
0
10000
20000
30000
40000
50000
20
30
40
50
60
70
Execution time (µs)


Histogram of COMMIT_SELL, n = 92
Frequency
0
5
10
15
20
25
30
35
Execution time (µs)


Histogram of DISPLAY_SUMMARY, n = 225298
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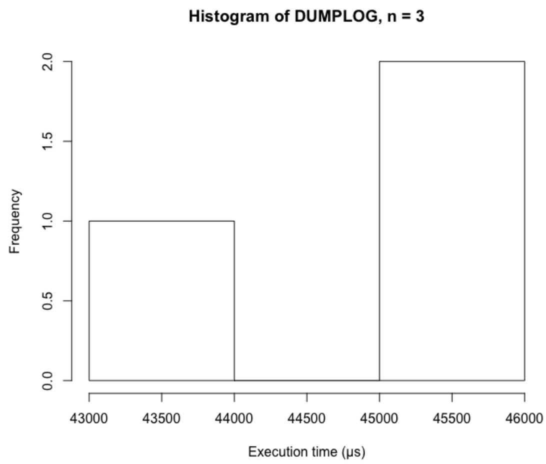
30000
40000
50000
10
20
30
40
50
Execution time (µs)


Histogram of DUMPLOG, n = 3
Frequency
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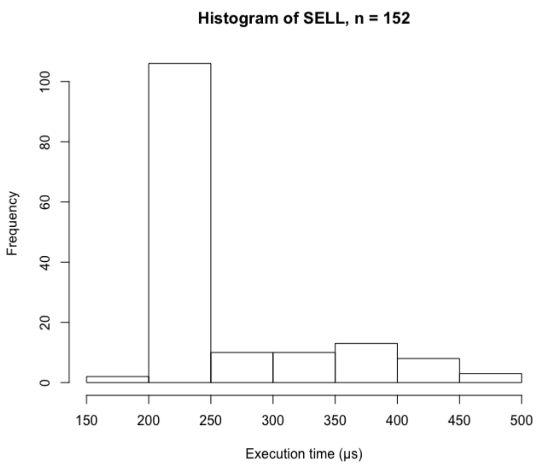
0.5
1.0
1.5
2.0
43000
43500
44000
44500
45000
45500
46000
Execution time (µs)


Histogram of SELL, n = 152
Frequency
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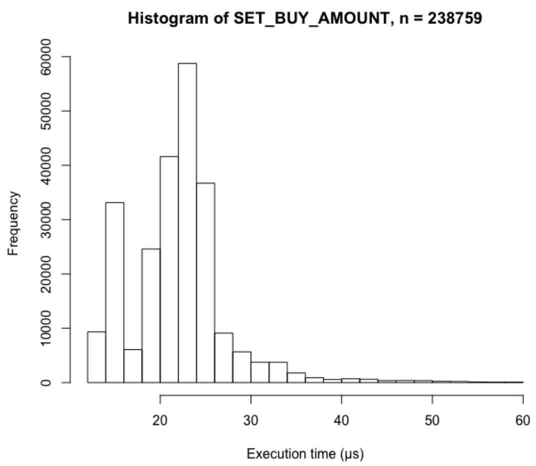
20
40
60
80
100
150
200
250
300
350
400
450
500
Execution time (µs)


Histogram of SET_BUY_AMOUNT, n = 238759
Frequency
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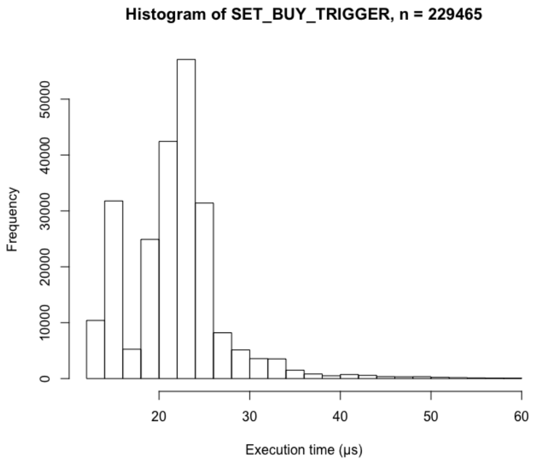
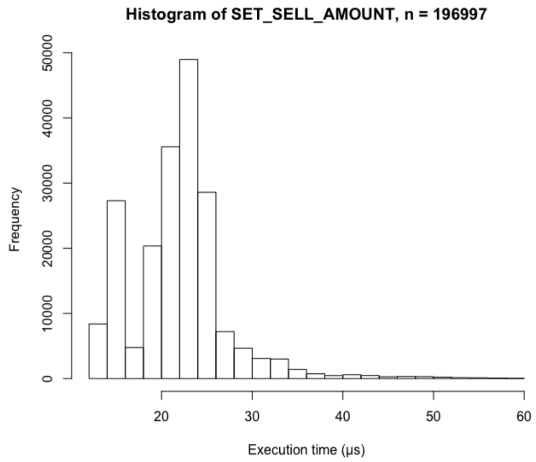
30000
40000
50000
60000
20
30
40
50
60
Execution time (µs)


Histogram of SET_BUY_TRIGGER, n = 229465
Frequency
0
10000
20000
30000
40000
50000
20
30
40
50
60
Execution time (µs)


Histogram of SET_SELL_AMOUNT, n = 196997
Frequency
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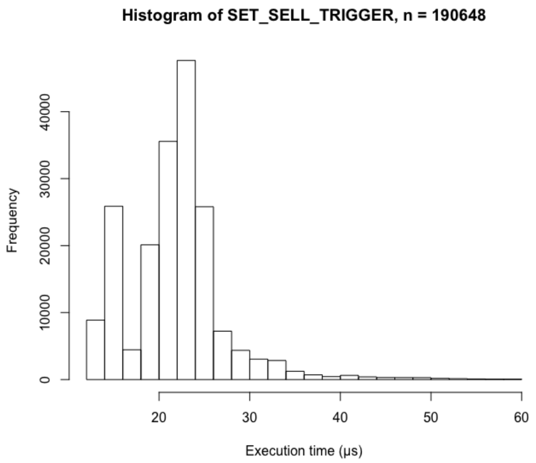
30000
40000
50000
20
30
40
50
60
Execution time (µs)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30000
40000
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30
40
50
60
Execution time (µs)