Advanced Systems Lab Report

Autumn Semester 2018

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Grading

Section	Points
1	
2	
3	
4	
5	
6	
7	
Total	

Todo list

1 System Overview (75 pts)

1.1 Class Overview

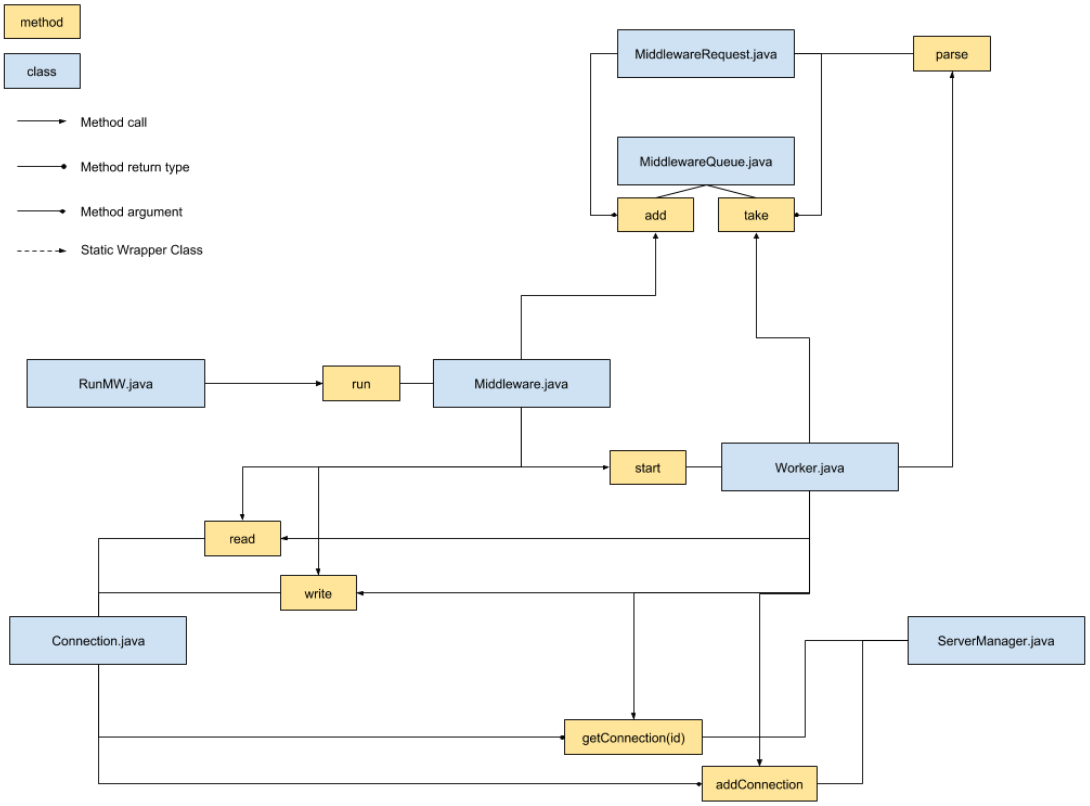


Figure 1: Class Diagram

We will start by looking at a class diagram of the middleware. In Figure 1 we can see all the classes that compose the middleware. The system is represented in its running state, i.e. all methods that are only used when starting up are omitted. In the following paragraphs we will look at each of the components in detail.

`RunMW.java` This class has a single responsibility. It parses the command line arguments and runs the middleware thread using these.

`MiddlewareRequest.java` This class represents a request coming from a client. The object holds all the relevant data of the request, i.e. all time measurements, whether or not the request was successful and the `Connection` object of the client that sent the request. In this class we implement the parsing method, that scans the command string and populates fields in the object. If the middleware is running in sharded mode, `MULTI-GET` requests will be sharded into a list of commands.

`Middleware.java` This class represents the net thread of the system. Its responsibilities are first to accept client connections and register them so that we can start accepting requests.

Second the thread also reads requests from already acccepted client connections and enqueues them in the `MiddlewareQueue`. To avoid busy waiting and accessing client sockets that do not have data to read we use a `Selector`. Basically this is a mechanism that allows us to register connections and the selector will deliver only the connections that have data ready to read. We also register the server socket with the selector and receive connections that are ready to be accepted. Using this we can maximize the utilization of the CPU time used by the net thread. We will look at the process of accepting connections and requests in detail in section 1.6

`MiddlewareQueue.java` In this middleware the `MiddlewareQueue` is a first class citizen, as are the workers and the net thread. This decision is made based on the fact that the queue should not be owned by either the net or the worker threads. The queue is not much more than a static wrapper around a `BlockingQueue`. The access to take a request out of the queue is synchronized, so that we avoid processing the same request twice.

`Worker.java` In this class the actual processing of the request is done. Depending on the type of the request that worker threads handle them differently. This will be adressed in detail in section 1.6. In general a worker thread takes a request out of the `MiddlewareQueue`, after that the worker calls the parse method offered by `MiddlewareRequest`. After that several new fields in the request object are populated, such as `RequestType` for example. The parsed request will then be scheduled on the memcached servers depending on the server mode and request type. The worker then waits for the responses from the memcached servers, parses the responses and then sends the appropriate response to the client. After finishing processing the request the worker will then log the relevant fields for the analysis in a CSV format.

`Connection.java` The connection class is a convenience wrapper around a `SocketChannel`. It represents both the client and server connections. It allows us to specify if a connection should be blocking or not. The goal of this class is that when using a connection we do not need to care about the configuration and how to read from the socket, instead we can just call the `read()` method and the different modes are handled internally.

`ServerManager.java` This class is used by the worker threads. The `ServerManager` holds the `Connection` objects for the memcached servers. This class offers the method `getConnection(int i)`, which will return the appropriate server connection based on the integer that is passed, such that the load is scheduled in a round robin fashion. We will see in section 1.6 how exactly that is handled based on the Id of the request. Even if the request will go to all memcached servers it still makes sense to choose the first server to send the request to based on round robin. This distributes the load even if we only have Set requests.

1.2 Message Parsing

As mentioned before the first thing the workers do with the request is parse it. Parsing means mainly two things here, first we will determine the type of request we are looking, this tells us how to further handle the request. Second, if applicable, we set the `MULTI-GET` Size. In the specific case of running the server in sharded mode and receiving a `MULTI-GET` Request we will split the keys in the request and depending on the `MULTI-GET` Size and number of servers populate a list of commands, this is known as "sharding" a command. The number of shards is exactly `min(multiGetSize, numServers)`

1.3 Response Parsing

In two cases, specifically when handling sharded `MULTI-GET` or `SET` requests we need to do some work before sending the request to the client.

In the case of `SET` requests we need to make sure that the key was set on all the three servers. That can be achieved by simply checking if all the responses equal `STORED\r\n`. If that is the case we send the same response back to the client. If not, it does not matter if we receive an error or if the key was simply not stored on some or all servers, we respond to the client with `NOT STORED\r\n` to let the client know that it should retry setting the key.

In the case of sharded `MULTI-GET` requests we need to combine the responses from all servers back to a single response and send it back to the client. This is done by simply removing the end marker from all responses, concatenating them and then adding the end marker back at the end. Finally we count the keys and record how many keys we have received to be able to calculate the miss rate and then we send the response on its way to the client.

1.4 Logs

To handle the logs in this multithreaded setting we use `log4j`. The logs from all the workers are consolidated into a single CSV file per middleware, this is handled by `log4j`. After finishing processing a request the workers will call the `toString()` method implemented by the `MiddlewareRequest` to produce a CSV log line. This log line is passed to `log4j`.

1.5 Queues

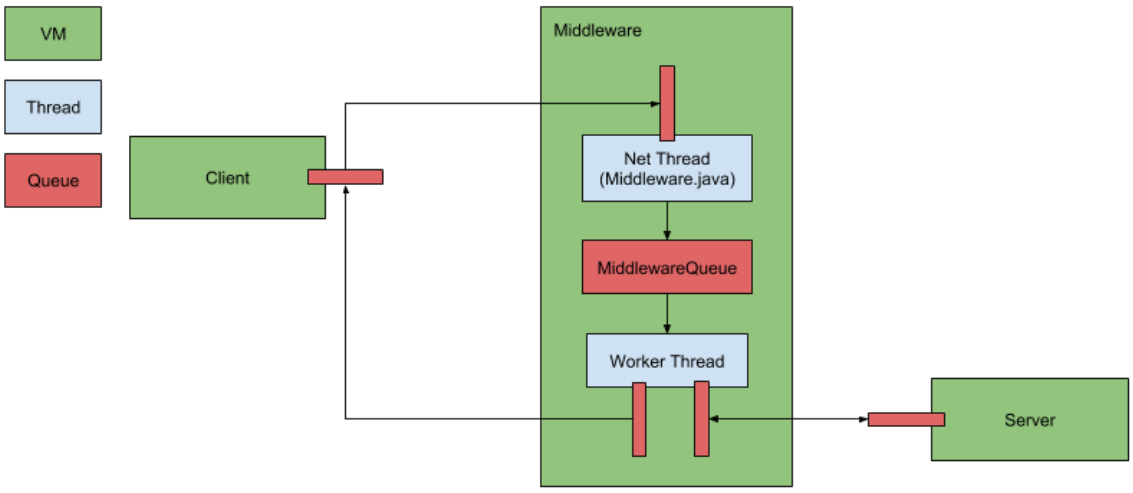


Figure 2: Threads and Queues

In Figure 2 we can see an illustration of threads and queues in the system. The arrow directions indicate the flow of requests. Arrows connecting different VMs represent sockets, thus the all queues except the MiddlewareQueue refer to socket queues. The illustration only shows one instance of a client, a server, and a worker thread. In the full system there are three instances of clients and servers. Depending on the configuration there are also many worker threads. The queues and connections for these variable components are also replicated for the number of instances.

1.6 Handling Requests

In this section we go into detail on how the middleware handles incoming connections and how the different types of requests are handled by the middleware. What follows are sequence diagrams that model the behaviour of the system for different request types. Important to note here, that again the system is assumed to be in a running state, all the setup methods are executed. Further there are some simplifications and abstractions in the diagrams to reduce clutter, for example not listing all arguments to a method call. Also not all method calls are illustrated, only the ones that are relevant on how we handle different requests. These abstractions should not impact the understanding of the middleware, I tried to design them as self explanatory as possible. Finally the sequence diagrams model the handling of one request, therefore we model only one client and one worker.

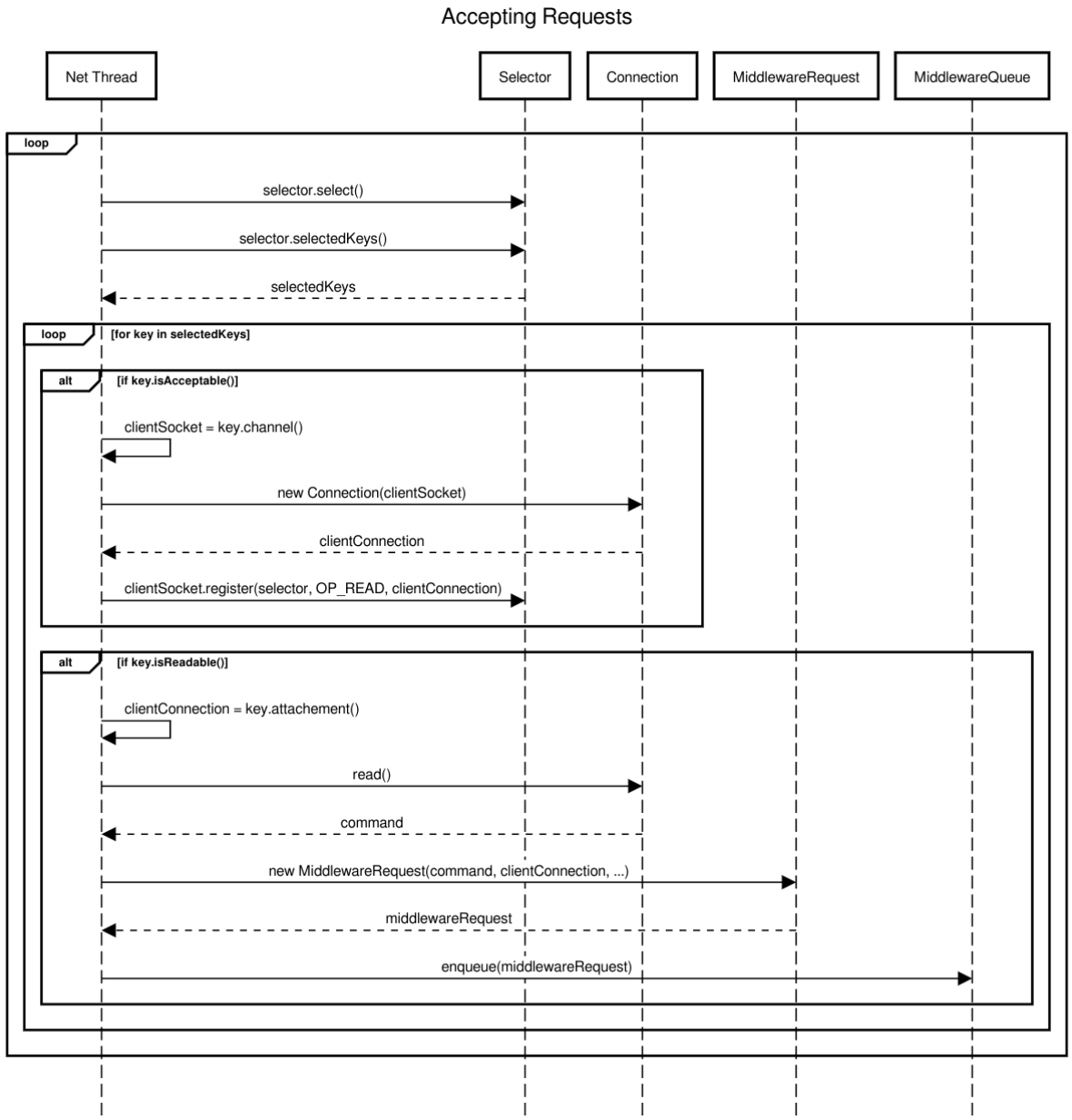


Figure 3: Accepting new connections and requests

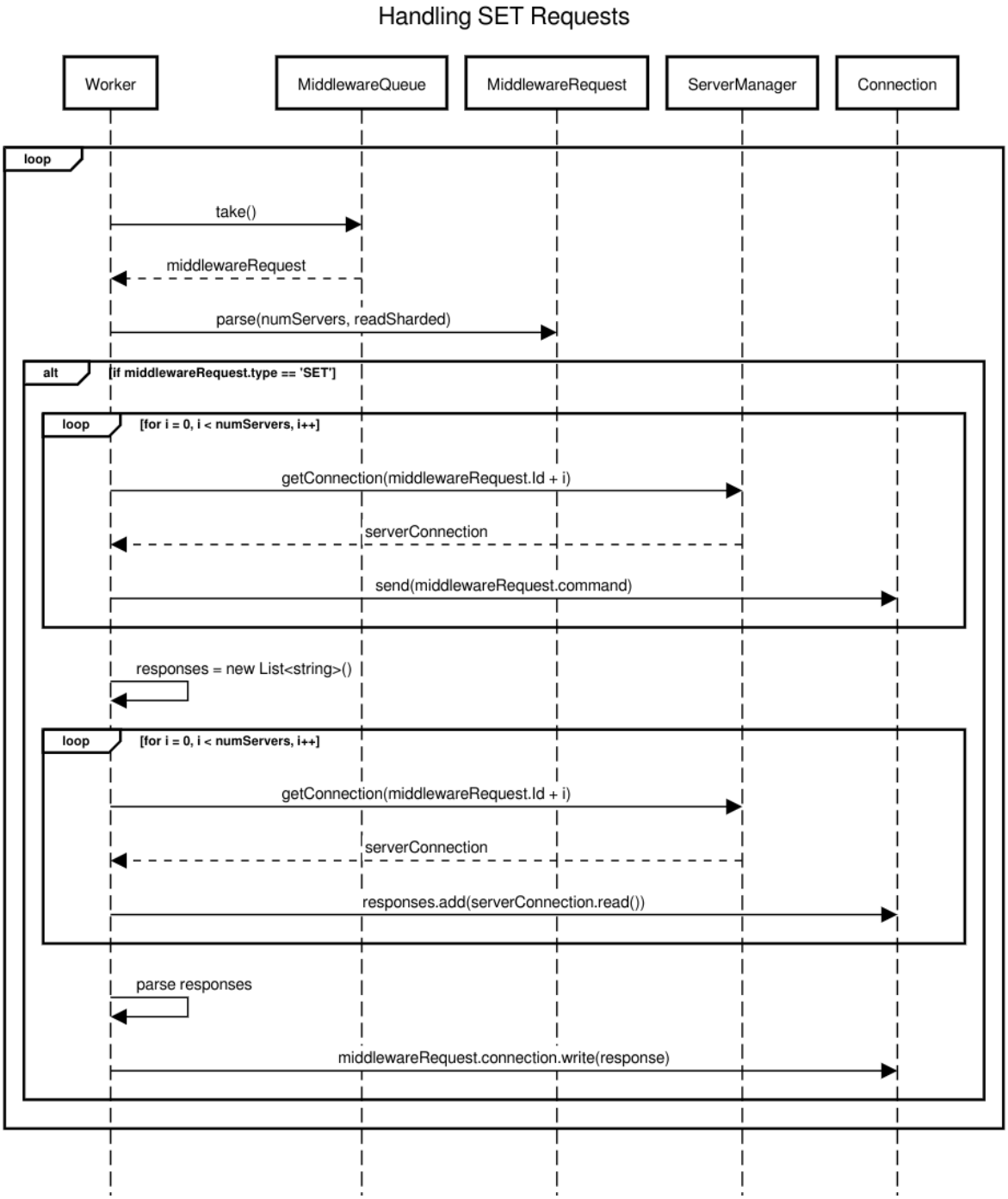


Figure 4: Handling `SET` requests

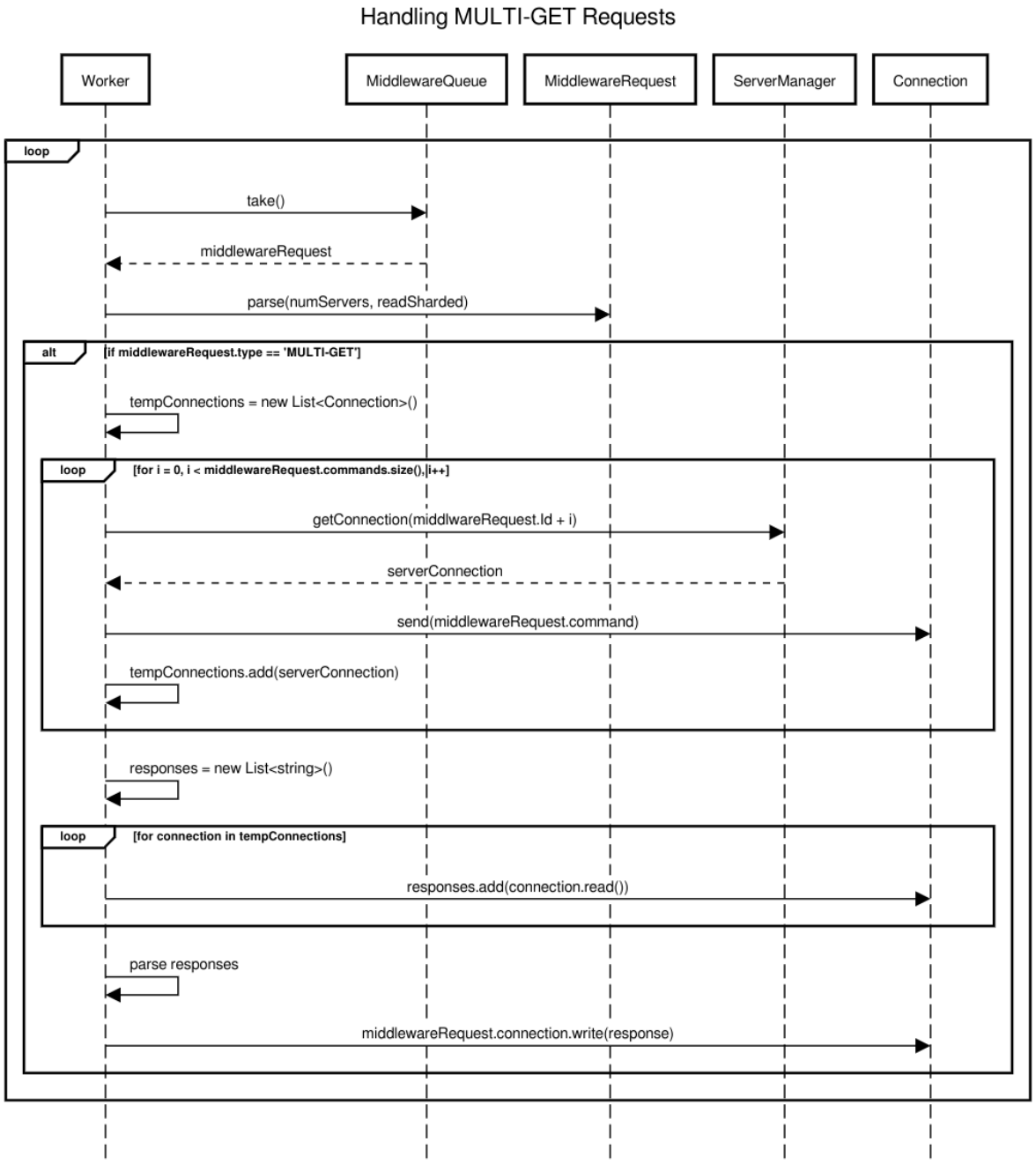


Figure 5: Handling `MULTI-GET` requests

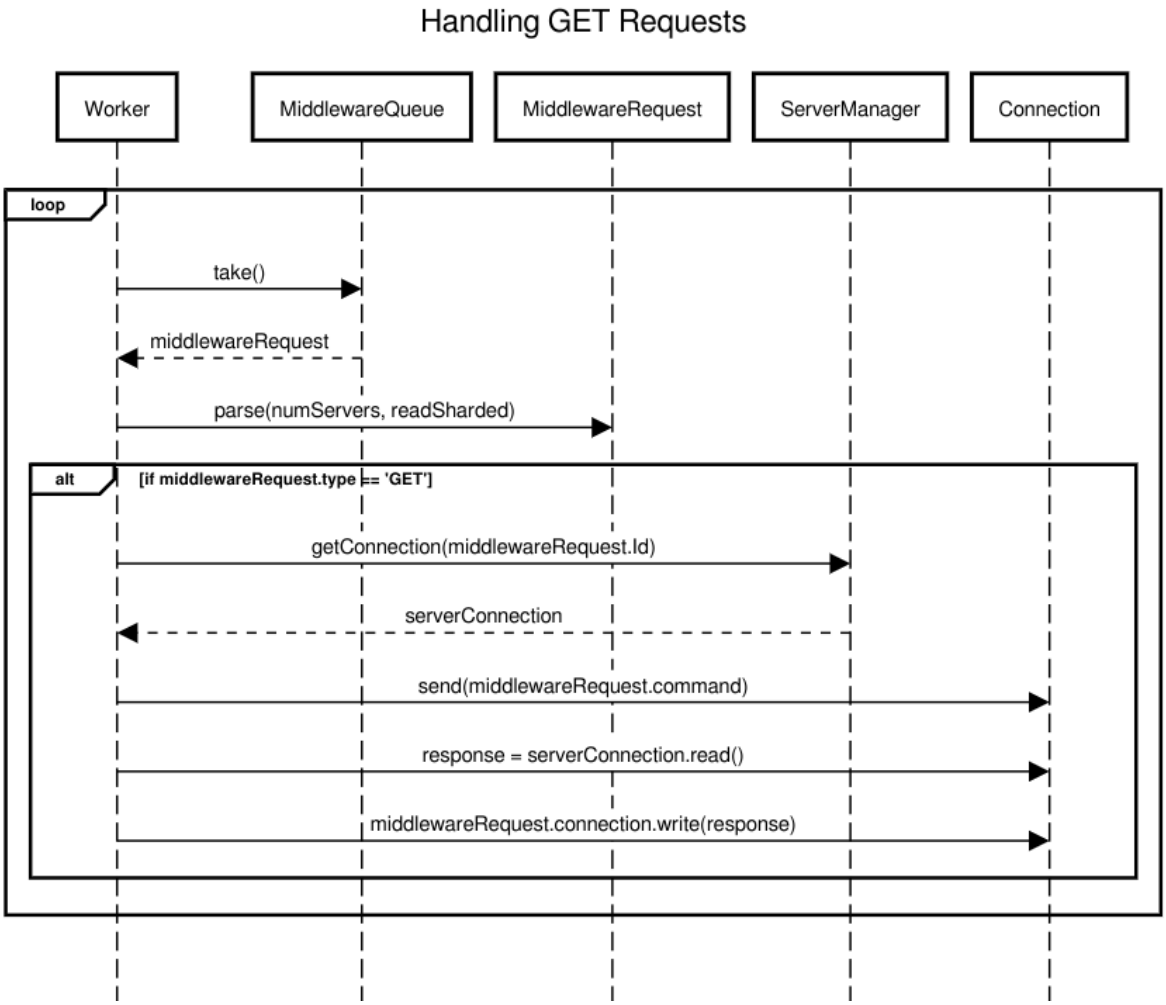


Figure 6: Handling `GET` requests

1.7 Measurements

Before getting into the analysis I want to lose a few words on the measurements and how they are handled.

No Middleware In this case we rely entirely on the output of `memtier_benchmark`. There we receive detailed numbers on number of requests and latency, however aggregated per one second intervals.

Middleware In this case we can use the detailed measurements from the middleware logs to produce the plots. The measurements use `System.nanoTime()` in combination with `System.currentTimeMillis()` to produce nanosecond Unix Timestamps. We can compute the response time for each request and aggregate the average over all the requests. When computing the average throughput we create a histogram based on the time a request was completed with the same number of bins as the duration of the experiment in seconds. After that we sum these values over all middlewares and compute the average over the seconds the experiments was running. All the plots use the 95% percent confidence interval as an error measure. Further

all the plots have the same configuration for the Y-Axis. In some few cases this might seem like the wrong choice, however it is intentional, such that we can compare plots across sections without the need to always check the axes for different scales.

2 Baseline without Middleware (75 pts)

Sanity Checks In the experiments where we can instrument the middleware we can compute a reasonably good estimate of the think time and therefore produce plots which show that the Interactive Response Time Law holds. In this section however we do not have this information. Here we used pings to get a rough estimate on the think time and used this to manually check if the response time holds for the data in the experiments using one and two memcached servers.

2.1 One Server

2.1.1 System Setup

For this experiment we will use the following system setup:

- 3 client machines with 1 memtier instance per machine. Each instance of memtier runs with 2 threads.
- No middlewares
- 1 memcached server

We vary the number of virtual clients per thread from 1 to 32.

2.1.2 Hypothesis

The objective of this experiment is to find out how much load a single server can handle. We expect that this can be accomplished since we have 3 load generating machines for one server.

2.1.3 Explanation

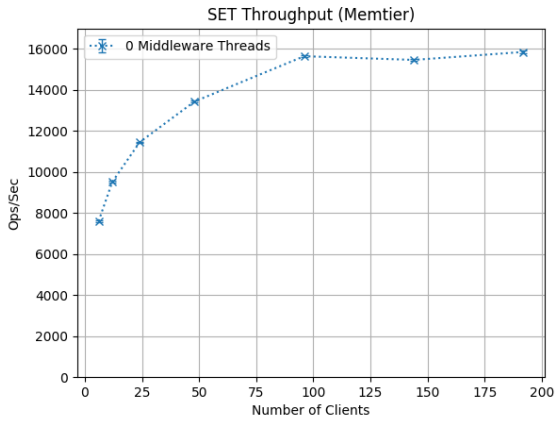


Figure 7: `SET` Throughput

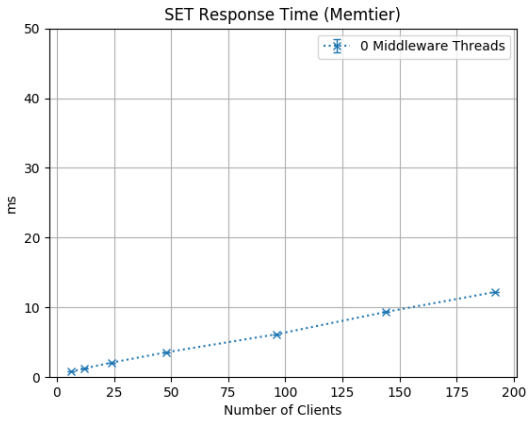


Figure 8: `SET` Response Time

Write-Only Workload As mentioned in the objective we want to find out how much, in this case write requests, one memcached server can handle, i.e. how many clients do we need such that the server is saturated. We can see that the server is saturated by two things:

- The throughput of the system does not increase anymore when increasing the number of clients. We can determine that easily by if the throughput plot shows a flat line after some point.
- The response time increases linearly. In an ideal system the response time stays flat when the system is not saturated. However in practice a lot of factors can influence the response time, so it might be increasing in a undersaturated system. What we look for in the response time plot is a "knee" which shows an increase in the amount the response increases per new client.

In general we will try to use the two conditions above to determine the point at which the system gets saturated. As we can see in Figure 7 we can achieve approximately 16000 ops/sec before the server is completely saturated, using 96 clients. In Figure 8 it is more difficult to identify the point at which the system is saturated. However we can see a small increase in the slope of the response time at 96 clients, which supports the claim done based on the throughput plot. Oversaturation does not occur in this experiment. Since this is the very first experiment we cannot yet compare it to much. The take away message here is that one memcached server can handle up to approximately 16000 write ops/sec and is saturated when using 96 clients. Also we conclude definitely that memcached is the bottleneck of the system in this configuration and using this specific workload.

interactive law check, maybe print a latex table when generating the plot with already filled in values for all experiments.

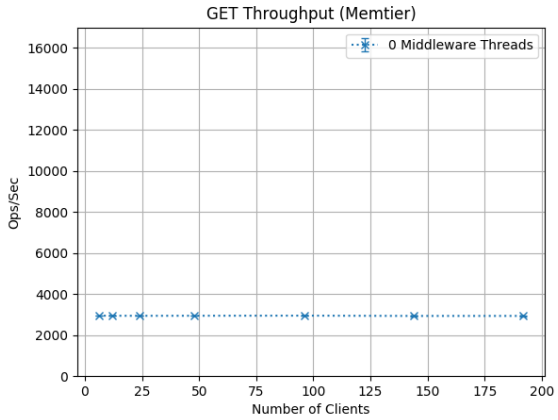


Figure 9: `GET` Throughput

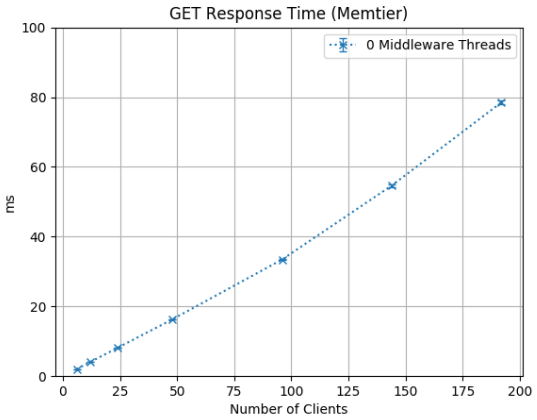


Figure 10: `GET` Response Time

Read-Only Workload In Figure 9 we see that the system can handle approximately 3000 read ops/sec. As we have seen above the memcached server performs massively better for `SET` requests. The reason for this is rather straight forward. When handling `SET` requests the server can just store the record. Usually this is done by hashing the key and storing the value in some sort of hash table, which is a operation that takes $O(1)$ time, since memcached stores all values in memory. However when handling `GET` requests the server must hash the key, which is still done in constant time, but after hashing the server must actually retrieve the associated value from memory and send it to the client, which takes $O(s)$ time where s is the size of the

stored value. The memcached server seems to be saturated even when using only 6 clients. The saturation can is clearly depicted in Figure 9. This hypothesis is also supported by the response time, we can see that from the start the response time increases linearly, without increasing the slope at some point during the experiment. Oversaturation does not occur in this experiment even when using 192 virtual clients.

Since we could not identify an undersaturated phase of the system we ran an additional experiment. The setup was that we used only one load generating machine with only one instance of memtier running only one thread. The virtual clients were varied from 1 to 6, since above we saw an saturation at 6 clients we would expect this experiment to reveal an undersaturated memcached server.

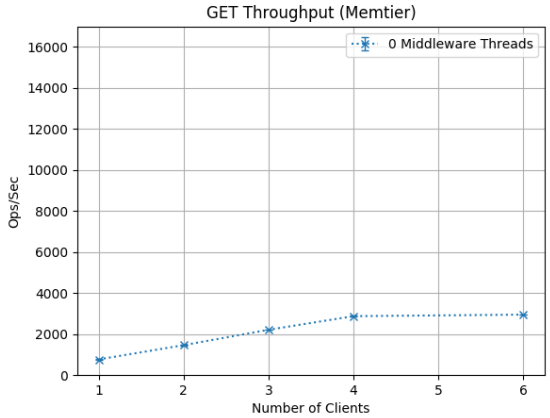


Figure 11: `GET` Throughput

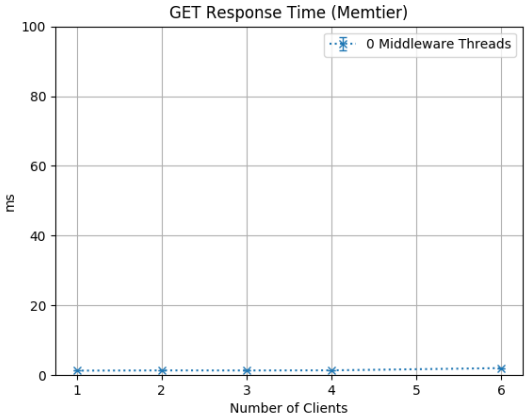


Figure 12: `GET` Response Time

As we can see rather clearly in Figure 11 the memcached server is already saturated using only 2 clients in total. Also in Figure 12 we can identify the response time starting to increase after two clients.

2.2 Two Servers

2.2.1 System Setup

For this experiment we will use the following system setup:

- 1 client machines with 2 memtier instances per machine. Each instance of memtier runs with 1 threads.
- No middlewares
- 2 memcached servers

We vary the number of virtual clients per thread from 1 to 32.

2.2.2 Hypothesis

Now we have two servers in this experiment and only one load generating machine. Since before the server was the bottleneck in the last experiment we expect the server to be able to handle twice the read load than in the previous experiment. For a write load the server performed very well, and we needed a lot of clients to saturate the servers. In this case we expect memtier to be the bottleneck of the system.

2.2.3 Explanation

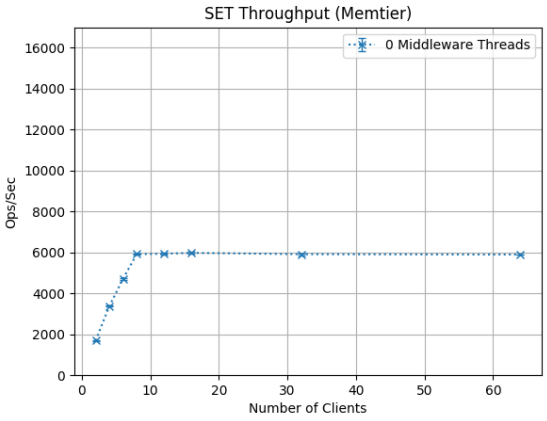


Figure 13: `SET` Throughput

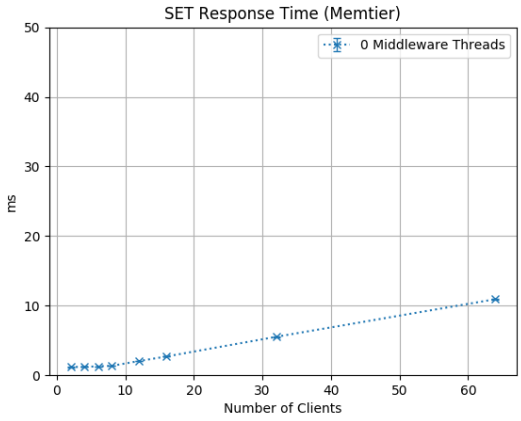


Figure 14: `SET` Response Time

Write-Only Workload In these two plots we can see both conditions for a saturated phase very clearly. After 16 clients the throughput does not increase at all anymore and reaches a maximum of approximately 6000 write ops/sec. This can be supported by looking at the response time, where we can clearly see the "knee" in the plot after 16 clients. From the previous section we know that one memcached server can handle approximately 16000 write ops/sec which means, since here we have 2 servers, if the servers were the bottleneck we should see double that number. This would lead to the conclusion that the only other participant must be the bottleneck, namely memtier. But in Figure 14 we can see that "knee" in the graph, indicating that the memcached server could be the bottleneck. I still conclude that memtier is the bottleneck, since if we compare the absolute values with Figure 8 we quickly see that a saturated memcached server produces response times a lot higher than what we measured in this experiment. An ideal server would show a constant response time, but comparing the roughly 9ms we measured here for 92 clients with the approximately 35ms measured with only one server, we can conclude that we are not dealing with saturated memcached servers here.

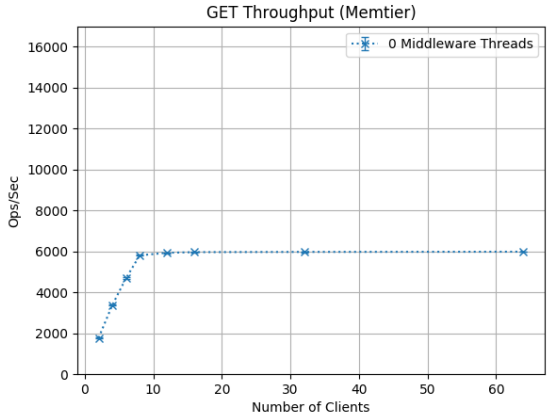


Figure 15: `GET` Throughput

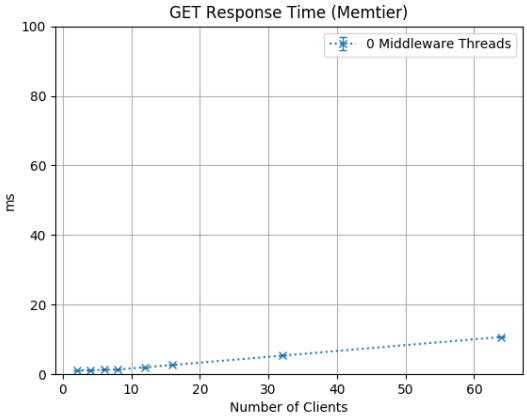


Figure 16: `GET` Response Time

Read-Only Workload Again here we can clearly the the saturation of the system. However the system is already saturated using only 8 clients in total. This is not surprising since we know from before that `GET` requests are more expensive for the server than `SET` requests. What is interesting however is that we can produce almost exactly the same amount of read operations per second than write operations. From this we conclude that the generation of the payload for `SET` requests produces a negligible overhead on the client machines. However here it is not as clear cut as before that memtier is the bottleneck. As we saw in Figure 9 one server alone can handle approximately 3000 ops/sec, therefore we expect that two saturated memcached servers together can serve about 6000 ops/sec. In Figure 15 we see that in this case we achieve approximately 6000 read ops/sec. This is the exact value we expected from memcached, however it is also the maximum number of requests a client machine can produce. Therefore it is difficult to say exaclty whether memtier or the memcached server are the bottleneck of this system. When we look at Figure 16 we can see that after 8 clients there is an increase in slope, which would indicate that the servers are the bottleneck, since the response time should, in theory, stay constant when the system is undersaturated. In this case it is really difficult to conclude with certainty whether the server or memtier is the bottleneck, in this case the components are matched together very well. Still, there is one argument that paints memtier as the bottleneck. Again we can compare the response time we measure with two servers and compare it to the response time when the memcached server was saturated. The response time in the one server case is a lot higher compared to the response time in this experiment. This argument lets us conclude fairly certain that memtier must be the bottleneck, since we would measure similar response times as before with saturated server.

2.3 Summary

Maximum throughput of different VMs.

	Read-only workload	Write-only workload	Configuration gives max. throughput
One memcached server	2875 (4 Clients)	15643 (96 Clients)	Write-Only, 96 Clients
One load generating VM	5810 (8 Clients)	5920 (12 Clients)	Write-Only, 12 Clients

When we look at the Read-only workload we can see that when we double the amount of servers from one to two the throughput also doubles. This indicates again that in the first experiment

the server is the bottleneck. Further we can see that one server is already saturated with 4 clients, whereas when using two servers we can handle up to 8 clients with approximately double the requests before being saturated, which again supports the conclusion that the server was the bottleneck in the first experiment.

Looking at the Write-only workload it looks a bit different. We can see that when using less client machines the throughput decreases drastically, even if we use two servers. As mentioned before this indicates that a client machine cannot generate more load. This is because the clients will likely reach their hardware limit at some point, the resources of one machine are shared by too many virtual clients.

Important to mention is that the numbers above to not always correspond to the absolute maximum throughput observed during the experiments. For example the Write-only workload recorded a maximum throughput of 15850 at 192 clients, however we know that the system was saturated already with 96 clients, therefore the maximum throughput at 192 has little meaning.

Summarizing the sections up to now we have a few key take away messages:

- One memcached server alone can handle a lot more `SET` requests than `GET` requests, more than 5 times as much.
- One memcached server alone can handle about 16000 `SET` ops/sec and approximately 3000 `GET` ops/sec
- One client machine alone can generate up to approximately 6000 ops/sec
- For one client it does not really matter if it is generating `GET` or `SET` requests, when measuring how much ops/sec can be produced.

The absolute numbers here should only be used as an approximate measure, even just restarting the VMs can produce different results. The idea is to get a sense on the relation between the different configurations and approximate numbers.

3 Baseline with Middleware (90 pts)

3.1 One Middleware

3.1.1 System Setup

For this experiment we will use the following system setup:

- 3 client machines with 1 memtier instances per machine. Each instance of memtier runs with 2 threads.
- 1 middleware
- 1 memcached server

We vary the number of virtual clients per thread from 1 to XX.

real number

3.1.2 Hypothesis

Similar to the first experiment we will find out how much load a single middleware can handle We assume for now that one memcached server is more performing than the middleware and therefore it should not be a problem that we only use one server. We will see later if this assumption is justified. In this experiment we only use one server, therefore the middleware should

not generate any overhead for synchronizing `SET` requests across multiple servers. Therefore we expect also in this case that `SET` requests will have a higher throughput than `GET` requests. Also as we increase the number of worker threads, more clients should be needed to saturate the system.

3.1.3 Explanation

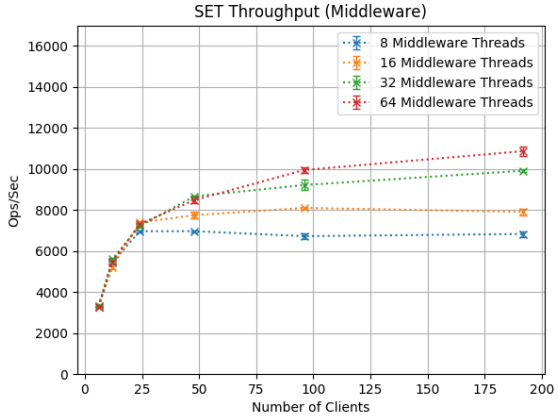


Figure 17: `SET` Throughput

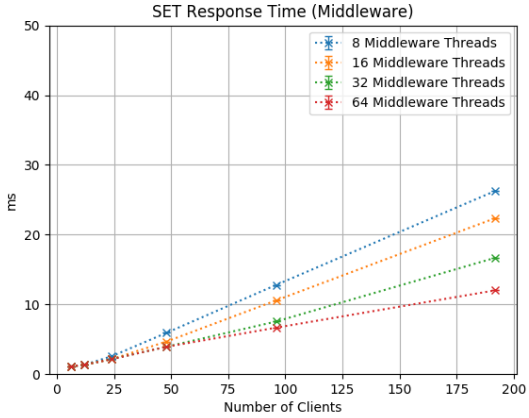


Figure 18: `SET` Response Time

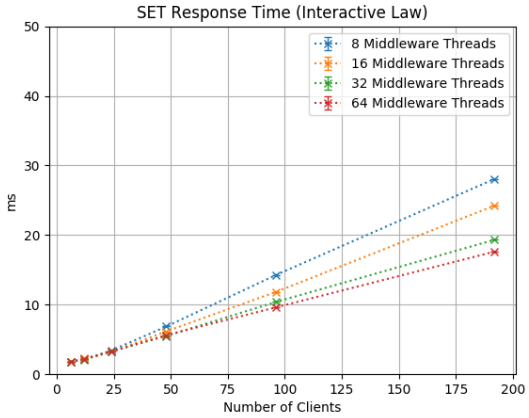


Figure 19: `SET` Response time IRTL

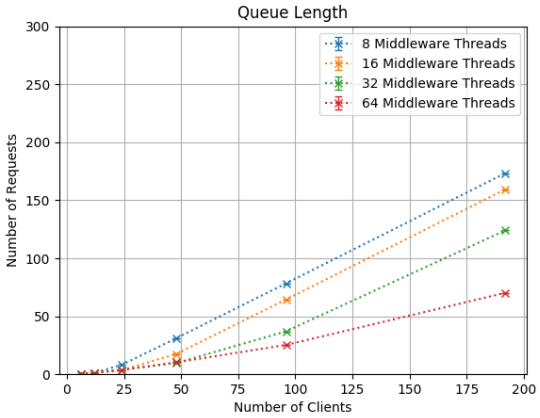


Figure 20: `SET` Queue Length

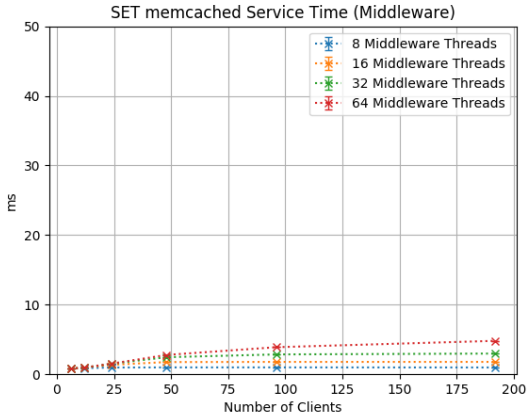


Figure 21: `SET` Service Time of memcached

Write-Only Workload Before discussing the system I quickly want to mention Figure 19, throughout the report we will find these plots for all experiments. The Interactive Response Time Law gives us a relationship between the throughput and the response time of the system. The exact formula is:

$$R = \left(\frac{N}{X}\right) - Z$$

Where R is the response time, X the throughput, N the number of clients and finally Z is the so called think time. It is the time a client needs to produce another request. Using the data collected inside the middleware we can estimate this time, by looking at how long it takes after a worker has responsed to the client until a new request from the same client is received in the net thread. The rest of the variables are measured by the middleware as well. Now we can estimate the response time based on the throughput, think time and the number of clients. These plots should serve as a sanity check for the measurements. However since the think time is estimated, also the resulting response time will be an estimation on the real response time. As long as the response time from the interactive law and the measured response time behave similarly, we can assume that the response time and throughput measured is realistic. In the following experiments I will include this plot, but I will not mention it every time.

Now if we look at Figure 17 we can see that the system is saturated when using 24 clients with 8 threads, 48 clients with 16 threads, XXclients using 32 threads and XXwith 64 worker threads. The same can be seen in Figure 18 where we can see the response time fan out at the same number of clients. As we can further see in Figure 17 the maximum throughput we can achieve is approximately XXops/sec. From the experiments using only one server we know however that one memcached server can handle up to approx. 16000 ops/sec. This would indicate that the middleware is the bottleneck in all worker thread configurations in this experiment. This conclusion can be supported by Figure 21 where we can see that the service time of the server stays mostly flat, it does not stay perfectly constant however it rarely does in real systems. We can also look at the Figure 20 and see a similar behaviour in the queue length. As long as the system is undersaturated the queue length should not increase significantly, after the system is saturated the queue length will increase linearly similar to the response time. Therefore we can conclude here that the middleware is the bottleneck, and that the middleware can handle up to XX`SET` ops/sec, as long as the middleware does not need to coordinate those requests across multiple servers. Oversaturation did not occur in this experiment.

real number

real number

real number

real number

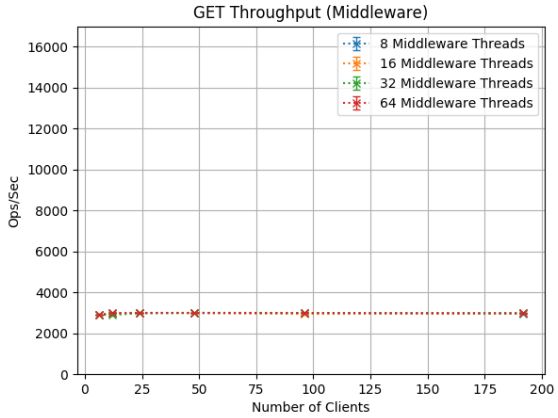


Figure 22: `GET` Throughput

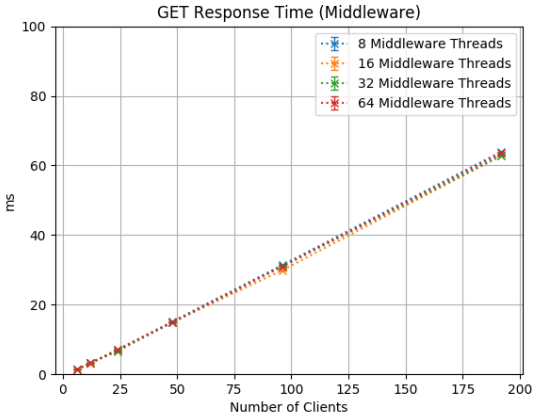


Figure 23: `GET` Response Time

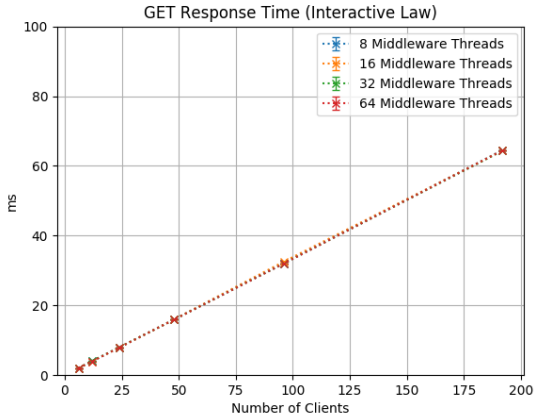


Figure 24: `GET` Response time according to Interactive Law based on Throughput

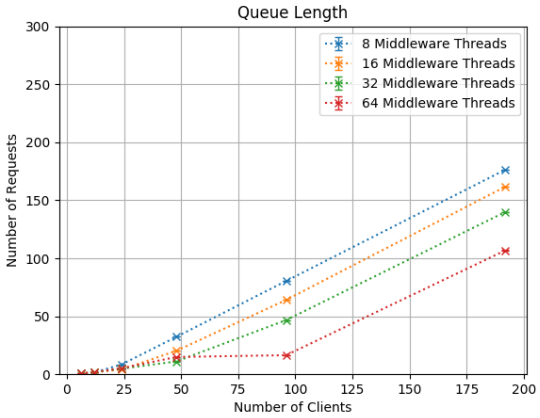


Figure 25: `GET` Queue Length

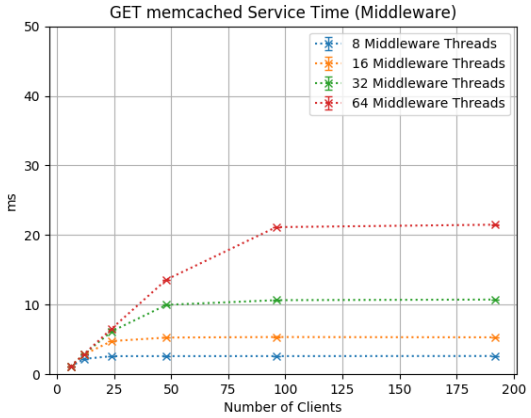


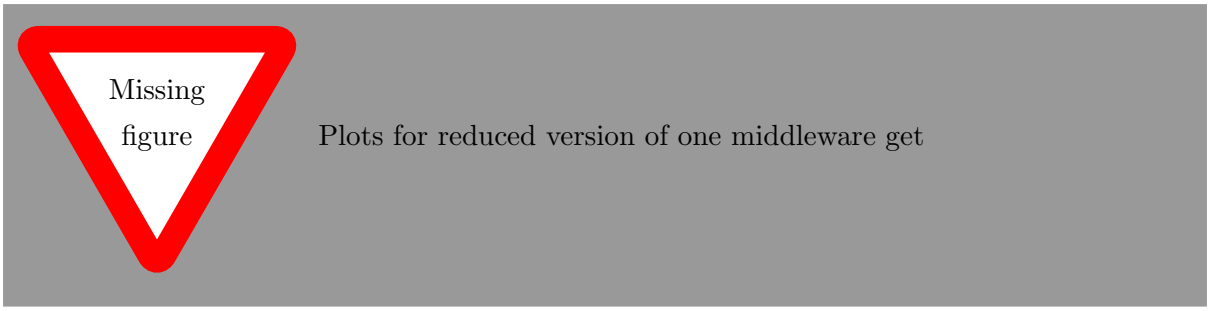
Figure 26: `GET` Service Time of memcached

Read-Only Workload In the first experiments we learned that one memcached server can handle up to 3000 ops/sec. Here we see this value again in Figure 22, therefore we suspect that the memcached server is the bottleneck. The response time also behaves similarly as in the experiment using only one server. But in this case we can again look at Figure 26 and see how the service time for the memcached server behaves. We can quickly see that at first it is correct that memcached is the bottleneck, since the service time increases linearly with the number of clients. However at some point the service time stays flat. Specifically at 24 clients using 8 threads, at 48 clients for 16 and 32 threads, and finally at 96 clients for 64 threads.At first glance it might seem that the middleware is the bottleneck since the service time of the servers does not increase anymore.

check numbers after experiment run

What happens inside the middleware, is that each of the workers is processing a request at all times. For the memcached server that means that it sees only 64 clients, which are behaving similarly to the memtier clients, namely sending a request as soon as the previous request is completed. Again we can use support this conclusion by looking at Figure 25 where we see the queue length increase at the same point where the service time of memcached does not increase anymore, showing that the worker threads cannot handle more requests. But here it is important to compare this to the first experiment where we only used one server. In Figure 10 we can see that we have a similar response time as we do now, meaning the middleware does not add any significant overhead. The middleware starts buffering requests from clients, but the bottleneck is still the server. Since in this case we handle `GET` requests exactly the same as we would handle `SET` requests we can say with confidence that the middleware would process these requests at the same rate, which is a lot higher than what we are seeing in this experiment. Using these arguments we conclude that, here too the server is the bottleneck of the system. Again oversaturation did not occur.

Also in this experiment we could not really see the system in a undersaturated phase. For that we ran another experiment with the same configuration as in section 2.1.3.



3.2 Two Middlewares

3.2.1 System Setup

For this experiment we will use the following system setup:

- 3 client machines with 2 memtier instances per machine. Each instance of memtier runs with 1 threads.
- 2 middlewares
- 1 memcached server

We vary the number of virtual clients per thread from 1 to XX. real number

3.2.2 Hypothesis

We expect this configuration to handle twice the load as with one middleware before becoming saturated, assuming the server will not bottleneck the system. Again we only use one server, therefore we expect again in this case that `SET` requests will have a higher throughput than `GET` requests. Further as we increase the number of worker threads, more clients should be needed to saturate the system.

3.2.3 Explanation

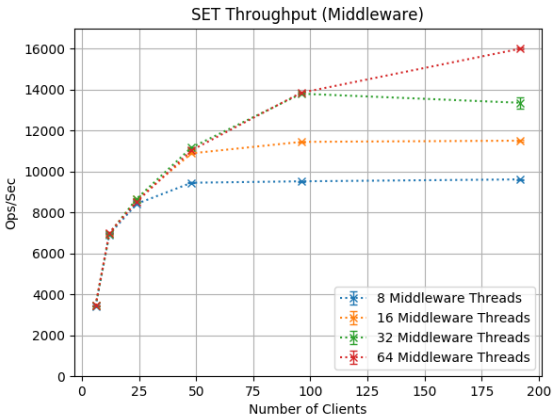


Figure 27: `SET` Throughput

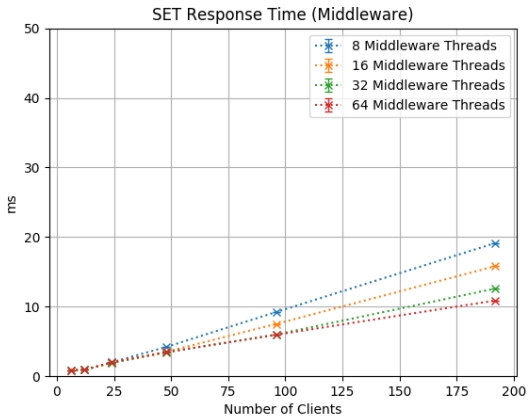


Figure 28: `SET` Response Time

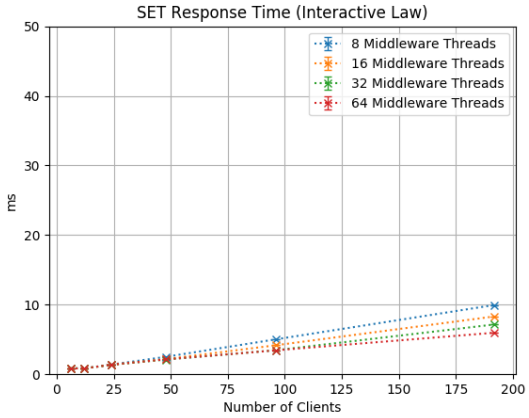


Figure 29: `SET` Response time IRTL

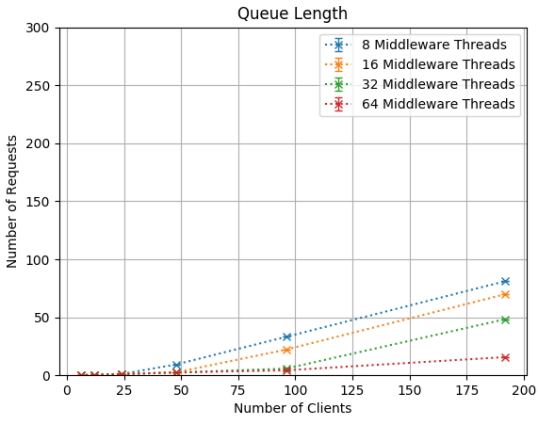


Figure 30: `SET` Queue Length

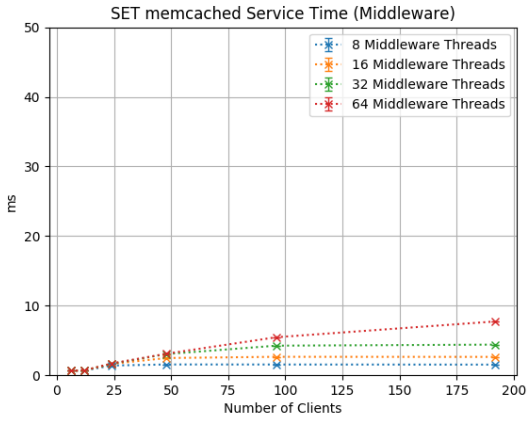


Figure 31: `SET` Service Time of memcached

Write-Only Workload By looking at Figure 27 we see that we can handle approximately XXclients for threads, XXclients for 16 threads, XXclients for 32 threads and finally XXclients for 64 threads before the system is saturated. From section 2.1.3 we know that one server can handle approximately 16000 write ops/sec. Therefore we can assume that the server is not the bottleneck before the middlewares before we reach approximately 16000 ops/sec. We can confirm that by looking at 31 which shows that for 8, 16 and 32 threads the service time of memcached stays almost constant, indicating that the server is not saturated. Even though the server is not saturated and the service time is almost constant, the response time still increases. That means that in these cases the middleware must be the bottleneck, since we have 3 load generating machines, which are able to produce plenty of requests to saturate the memcached server. We can further support this conclusion by looking at the queue length in the middleware, there we can see at the same threshold the requests begin to wait in the queue indicating that the above conclusion is sound.

real number

real number

real number

real number

However the configuration using 64 threads behaves differently. First we can see that when the system is saturated we can handle approximately 16000 ops/sec which, as mentioned before, should saturate the server. If we again turn to the service time we can see that at the same time

when we reach 16000 ops/sec the service time of memcached starts to increase linearly, therefore letting us conclude that the server is the bottleneck after we reach XXclients. Again we can further support this conclusion using Figure 30 where we can see that the queue length does increase, however combining this with the increasing service time, again supports the statement that the middleware is not the bottleneck using 64 threads.

real number

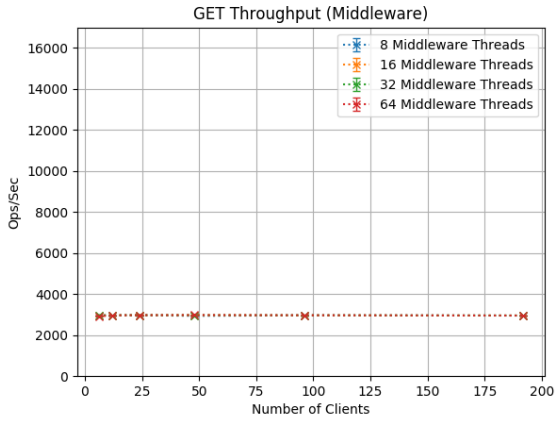


Figure 32: `GET` Throughput

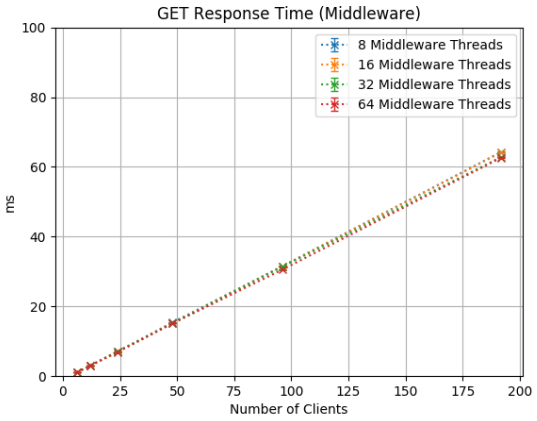


Figure 33: `GET` Response Time

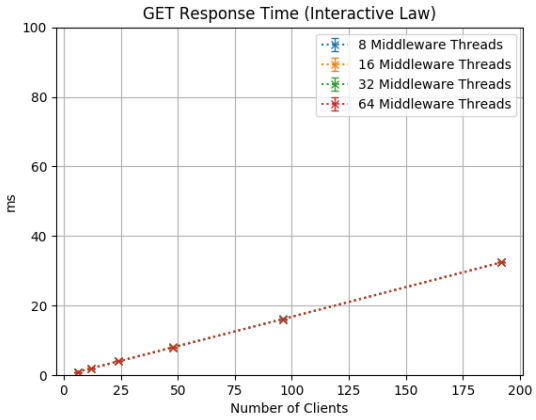


Figure 34: `GET` Response time according to Interactive Law based on Throughput

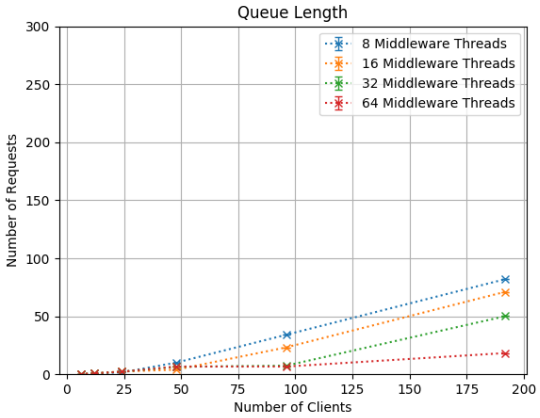


Figure 35: `GET` Queue Length

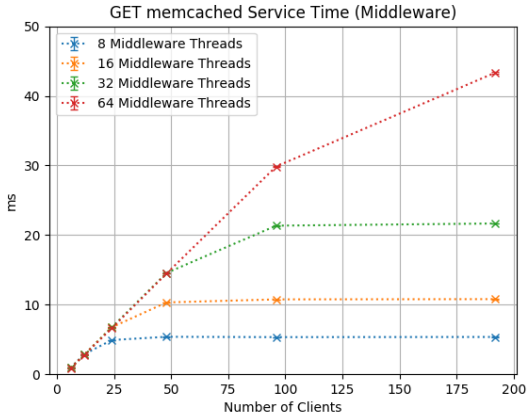


Figure 36: `GET` Service Time of memcached

Read-Only Workload Again we use only one server here, so we expect the system to be saturated again at approximately 3000 ops/sec. We can verify this in Figure 32. As usual by looking at the throughput plot using one server we cannot really identify the bottleneck, since it is saturated from the start, which can again be confirmed by the linearly increasing response time in Figure 33. If we would only look at the throughput and response time measured by the middleware it looks like the system behaves exactly the same even when using two middlewares. Therefore we again look at the internals of the system. We see a similar behaviour as in the previous section when looking at Figure 27, but the difference is that we seem to be able to handle approximately double the number of clients before the service time of the servers does not increase anymore. This is not really surprising, since now we use double the amount of worker threads. However we do not measure double the throughput. This is explained by the fact that the middleware is not completely parallelized, therefore when adding more worker threads we have diminishing returns. That means that we need twice the number of clients such that are worker threads are constantly busy with handling requests. Using the same argumentation as in section 3.1.3 we can again conclude that the memcached server is the bottleneck in this configuration. Also like in the previous experiments with only one server we cannot see an undersaturated phase of the system. Therefore we ran another reduced experiment where we again only use 1 to 6 total clients.

Plots for reduced version of two middlewares get

3.3 Summary

Based on the experiments above, fill out the following table. For both of them use the numbers from a single experiment to fill out all lines. Miss rate represents the percentage of GET requests that return no data. Time in the queue refers to the time spent in the queue between

the net-thread and the worker threads.

Maximum throughput for one middleware.

	Throughput	Response time	Average time in queue	Miss rate
Reads: Measured on middleware				
Reads: Measured on clients			n/a	
Writes: Measured on middleware				n/a
Writes: Measured on clients			n/a	n/a

Maximum throughput for two middlewares.

	Throughput	Response time	Average time in queue	Miss rate
Reads: Measured on middleware				
Reads: Measured on clients			n/a	
Writes: Measured on middleware				n/a
Writes: Measured on clients			n/a	n/a

Based on the data provided in these tables, write at

4 Throughput for Writes (90 pts)

4.1 Full System

4.1.1 System Setup

For this experiment we will use the following system setup:

- 3 client machines with 2 memtier instances per machine. Each instance of memtier runs with 1 threads.
- 2 middlewares
- 3 memcached servers

We vary the number of virtual clients per thread from 1 to 48.

4.1.2 Hypothesis

This is the first experiment where the middleware has to coordinate across multiple servers. We therefore expect a smaller throughput for `SET` requests for the full system than the configuration in the previous experiment. The reason is that inside the middleware, when handling `SET` requests the request is first sent to all three servers and then waited for. That means we generate a small overhead by having three send and read operations, this overhead should make itself visible in the throughput of the system.

4.1.3 Explanation

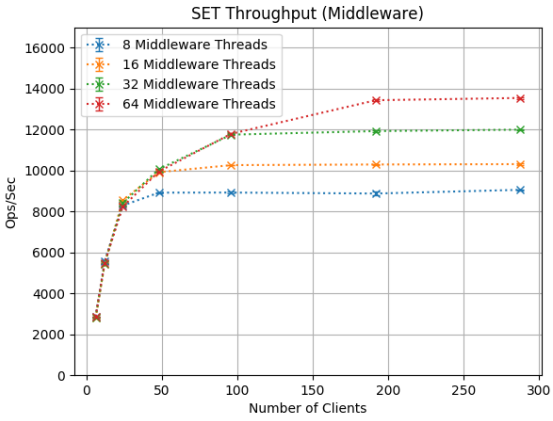


Figure 37: `SET` Throughput

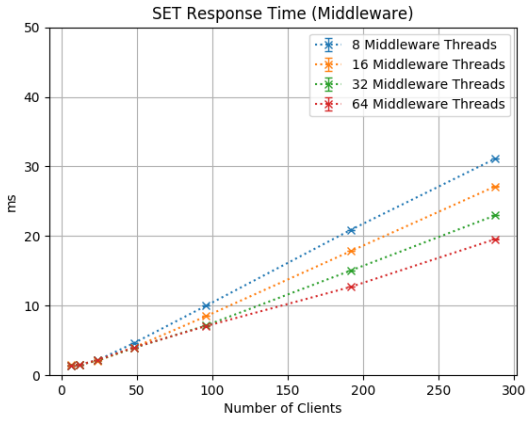


Figure 38: `SET` Response Time

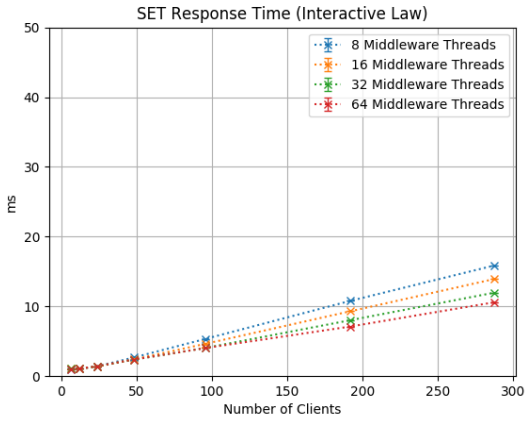


Figure 39: `SET` Response time IRTL

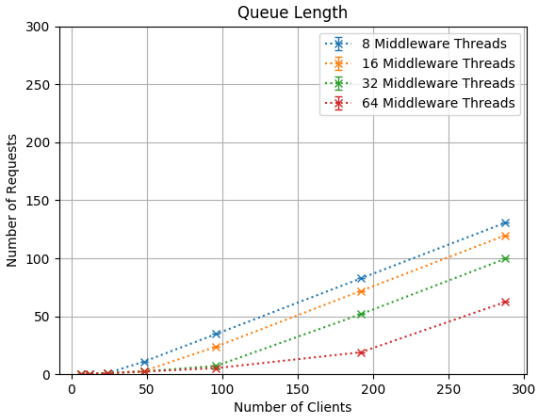


Figure 40: `SET` Queue Length

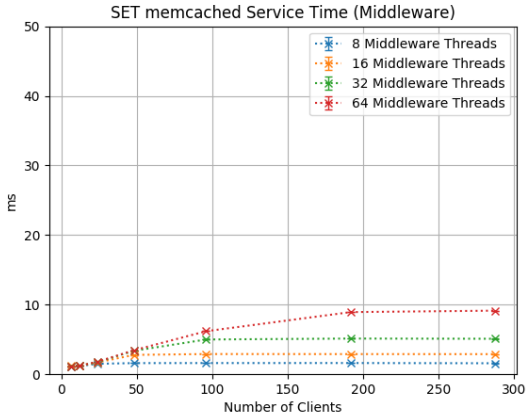


Figure 41: `SET` Service Time of memcached

As we can see very nicely in Figure 37 we can saturate the system for each configuration of worker threads. Specifically it needs 24 clients for 8 threads, 48 clients for 16 threads, 96 clients for 32 threads and finally 192 clients for 64 threads. The same thing can be seen in Figure 38 showing that the slope of the response time increases for each worker thread configuration at the same thresholds as mentioned before. Also since we know from previous experiments a memcached server can handle up to approximately 16000 ops/sec. In this case we reach a maximum of nearly 14000 ops/sec using 64 threads. This is a first indication that the middlewares are the bottleneck of the system. However Figure 41 shows similar behaviour of the memcached server as in the previous experiment when the server became the bottleneck which can be seen in Figure 26 But we need to be careful here, since in Figure 26 we measure response times that are a lot higher than in this case. That supports the suspicion that the middleware is the bottleneck of the system. As a last confirmation we can again look at the queue length in Figure 40 where we can see that the requests begin to wait in the queue when the middlewares are saturated. This supports the hypothesis made that the middleware has an overhead for coordinating `SET` requests across multiple servers. We can further see that the more clients and less threads we use, the queue gets longer and longer, which explains the increase in response time, even if the server is not saturated. Oversaturation does not occur in this experiment.

4.2 Summary

Maximum throughput for the full system

	WT=8	WT=16	WT=32	WT=64
Throughput (Middleware)	8290	9920	11753	13435
Throughput (Derived from MW response time)	11046	12031	13412	15117
Throughput (Client)	8254	9865	11693	13365
Average time in queue	0.45 ms	0.96 ms	1.89 ms	3.44 ms
Average length of queue	1.04	2.78	7.23	18.99
Average time waiting for memcached	1.51 ms	2.79 ms	5.00 ms	8.93 ms

Same as before the values in the table do not completely reflect the absolute maximum throughput recorded. The numbers are the throughput recorded when the system goes into the saturation phase. The absolute maximum throughput is not an accurate representation of the performance of the system.

The derived throughput is calculated as $X = N/R$, where X is the derived throughput, N the number of clients, and R the response time.

Overall we can say the system behaves as expected. Increasing the worker threads also increases the throughput. However when doubling the worker threads the throughput does not double as well. As mentioned before this is due to the fact the the middleware is not completely parallelized, therefore we have diminishing returns in terms of throughput and adding more worker threads.

Looking at the derived throughput we can quickly see that the this estimation is higher than the actual measured throughput. This has to do with the fact that we derive this throughput based on the response time we measure on the middleware, this does not take into account the latency of the requests between the client machines and the middlewares. Other than that also here we can see that the throughput increases with the number of worker threads.

The throughput measured on the clients is also slightly different from the throughput we measured on the middleware. This is due to the fact that the binning for the throughput histograms per second is done based on two different measurements. However this is to be expected and as long as the difference is insignificant as it is there is no problem with that.

Further we can see that when we increase the number of worker threads the waiting time for memcached increases as well. This is explained by the fact that the more threads are running in the middlewares, the more requests are concurrently sent to memcached.

This fact directly influences the time in queue as well as the queue length. The longer requests are being processed by memcached, the longer the worker threads need to wait for a response. That means that the requests need to wait longer in the queue before being dequeued by a worker, which in turn explains the increase in queue size. All in all there are no real surprises, the system behaves as we would it expect to behave.

5 Gets and Multi-gets (90 pts)

For this set of experiments you will use three load generating machines, two middlewares and three memcached servers. Each memtier instance should have 2 virtual clients in total and the number of middleware worker threads is 64, or the one that provides the highest throughput in your system (whichever number of threads is smaller).

For multi-GET workloads, use the `--ratio` parameter to specify the exact ratio between SETs and GETs. You will have to measure response time on the client as a function of multi-get size, with and without sharding on the middlewares.

5.1 Sharded Case

Run multi-gets with 1, 3, 6 and 9 keys (memtier configuration) with sharding enabled (multi-gets are broken up into smaller multi-gets and spread across servers). Plot average response time as measured on the client, as well as the 25th, 50th, 75th, 90th and 99th percentiles.

Number of servers	3
Number of client machines	3
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	2
Workload	ratio=1:<Multi-Get size>
Multi-Get behavior	Sharded
Multi-Get size	[1..9]
Number of middlewares	2
Worker threads per middleware	max. throughput config.
Repetitions	3 or more (at least 1 minute each)

5.1.1 Explanation

Provide a detailed analysis of the results (e.g., bottleneck analysis, component utilizations, average queue lengths, system saturation). Add any additional figures and experiments that help you illustrate your point and support your claims.

5.2 Non-sharded Case

Run multi-gets with 1, 3, 6 and 9 keys (memtier configuration) with sharding disabled. Plot average response time as measured on the client, as well as the 25th, 50th, 75th, 90th and 99th percentiles.

Number of servers	3
Number of client machines	3
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	2
Workload	ratio=1:<Multi-Get size>
Multi-Get behavior	Non-Sharded
Multi-Get size	[1..9]
Number of middlewares	2
Worker threads per middleware	max. throughput config.
Repetitions	3 or more (at least 1 minute each)

5.2.1 Explanation

Provide a detailed analysis of the results (e.g., bottleneck analysis, component utilizations, average queue lengths, system saturation). Add any additional figures and experiments that help you illustrate your point and support your claims.

5.3 Histogram

For the case with 6 keys inside the multi-get, display four histograms representing the sharded and non-sharded response time distribution, both as measured on the client, and inside the middleware. Choose the bucket size in the same way for all four, and such that there are at least 10 buckets on each of the graphs.

5.4 Summary

Provide a detailed comparison of the sharded and non-shareded modes. For which multi-GET size is sharding the preferred option? Provide a detailed analysis of your system. Add any additional figures and experiments that help you illustrate your point and support your claims.

6 2K Analysis (90 pts)

For 3 client machines (with 64 total virtual clients per client VM) measure the throughput and response time of your system in a 2k experiment with repetitions. All GET operations have a single key. Investigate the following parameters:

- Memcached servers: 1 and 3
- Middlewares: 1 and 2
- Worker threads per MW: 8 and 32

Repeat the experiment for (a) a write-only and (b) a read-only workload. For each of the two workloads, what is the impact of these parameters on throughput, respectively response time?

Number of servers	1 and 3
Number of client machines	3
Instances of memtier per machine	1 (1 middleware) or 2 (2 middlewares)
Threads per memtier instance	2 (1 middleware) or 1 (2 middlewares)
Virtual clients per thread	32
Workload	Write-only and Read-only
Multi-Get behavior	N/A
Multi-Get size	N/A
Number of middlewares	1 and 2
Worker threads per middleware	8 and 32
Repetitions	3 or more (at least 1 minute each)

7 Queuing Model (90 pts)

Note that for queuing models it is enough to use the experimental results from the previous sections. It is, however, possible that the numbers you need are not only the ones in the figures we asked for, but also the internal measurements that you have obtained through instrumentation of your middleware.

7.1 M/M/1

Build queuing model based on Section 4 (write-only throughput) for each worker-thread configuration of the middleware. Use one M/M/1 queue to model your entire system. Motivate your choice of input parameters to the model. Explain for which experiments the predictions of the model match and for which they do not.

7.2 M/M/m

Build an M/M/m model based on Section 4, where each middleware worker thread is represented as one service. Motivate your choice of input parameters to the model. Explain for which experiments the predictions of the model match and for which they do not.

7.3 Network of Queues

Based on Section 3, build a network of queues which simulates your system. Motivate the design of your network of queues and relate it wherever possible to a component of your system. Motivate your choice of input parameters for the different queues inside the network. Perform a detailed analysis of the utilization of each component and clearly state what the bottleneck of your system is. Explain for which experiments the predictions of the model match and for which they do not.