15-440 Spring 2018
Project 3: Implementation and Performance Tuning of a Scalable Web Service

Important Dates:

Project Handout:	Thursday March 22, 2018
Checkpoint 1 due:	Wednesday March 28, 2018, 11:59 PM EST
Checkpoint 2 due:	Wednesday April 4, 2018, 11:59 PM EST
Final Due:	Wednesday April 11, 2018, 11:59 PM EST
Submission Limits:	**10 Autolab submissions** per checkpoint without penalty (5 additional with increasing penalty)

You will learn to:

1. Identify potential bottlenecks in a distributed system.
2. Devise experiments to narrow down which is the current bottleneck.
3. Devise techniques to alleviate the current bottleneck.
4. Understand resource versus performance tradeoffs.
5. Identify scaling signals.
6. Experience multidimensional optimization with multiple parameters.
7. Cope with real-world nondeterminism that affects even very simple distributed systems.

Introduction

A critical advantage of Cloud-hosted services is *elasticity*, the ability to rapidly scale out a service without needing to purchase and install physical hardware. Cloud providers allow tenant services to add additional virtual servers on-demand, enabling them to meet changes in load (rate of arriving client requests). In this project, you will implement various techniques to scale out a simulated, Cloud-hosted, multi-tier web service (a web store front). You will then evaluate the system to understand what is the bottleneck at different loads, and use this information to decide when to scale out which components in order to improve performance. This is a critical skill to develop, as even a very simple distributed system (as implemented in this project) can have very complex behavior with respect to performance.

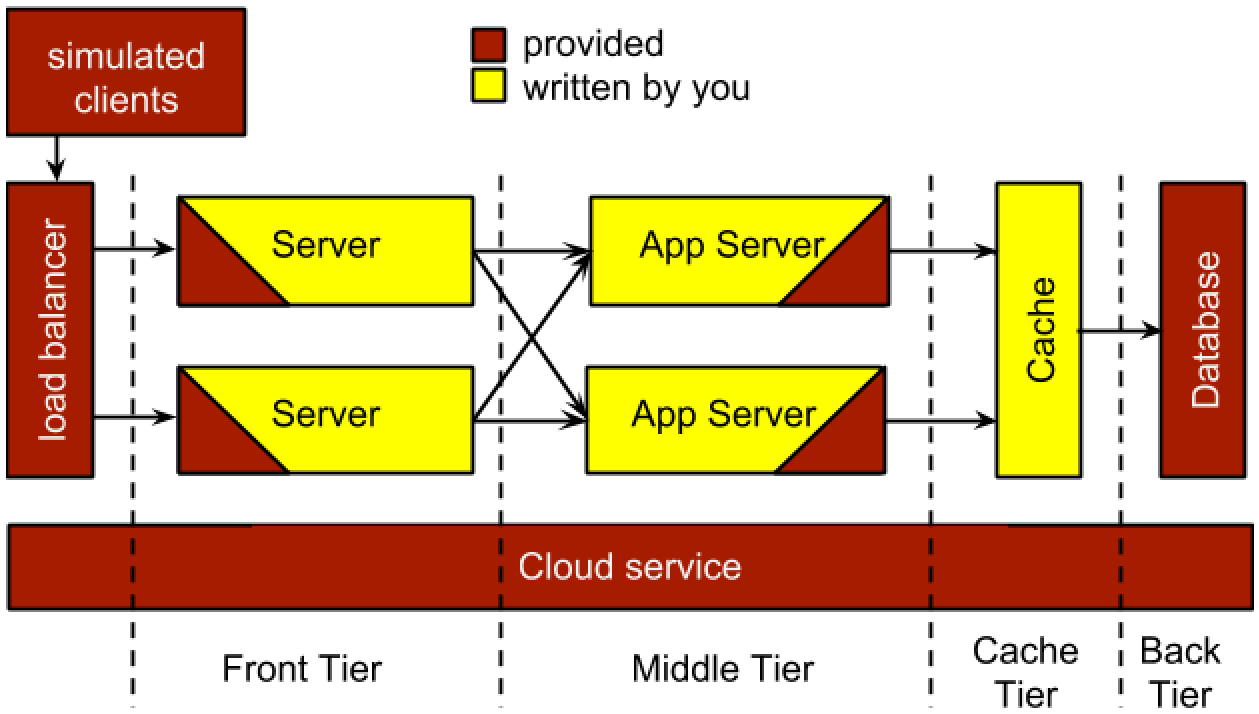
This project requires you to consider two types of scaling to meet request loads. First, you will look at scaling out a service by running multiple servers. Next, you will split the service into multiple tiers to improve performance. These tiers can themselves be scaled out independently. A critical question is: when should one scale out a tier by adding servers? This depends very much on the characteristics of the application itself. For example, at a given load, if you determine that the bottleneck limiting performance is the middle tier, then adding more servers for the middle tier will help. However, by doing this, you will likely shift the bottleneck elsewhere in the system, so adding even more middle tier servers will not help. Perhaps the bottleneck is now in the front-end, so you should consider adding more front-end servers. Or perhaps the bottleneck is now the database; in this case adding more servers to either front or middle tier will not help.

You will need to run experiments to benchmark the service at varying conditions to find the bottlenecks and determine the optimal number of servers (in each tier) for a given load (client arrival rate). This is sufficient for optimally scaling the service when the load is predictable or does not change (checkpoint 1). However, for dynamic or unexpected workloads as seen in the real world (and checkpoints 2 and 3), your code will need to monitor the system at run time, and add or remove servers as needed. Minimizing the number of servers used to handle a particular workload is important, as these resources are not free. Finally, this project also requires you to deal with the real-world issue of nondeterminism -- each run may be slightly different even for the same input conditions.

We will provide a simulated cloud service. This provides methods to start, stop, and get status of “VMs”. In our simulation these VMs are actually processes that run the Java server class you will write. The cloud service also provides a simulated load balancer – once your servers register with this, it will deliver client requests to all of the servers in a round-robin fashion (i.e., a request is given to the next server in line, after which the server moves to the end of the line).

The web service will be a simulated online store. Your server needs to handle requests from clients. These can be either a browse request (to provide information on items and categories of items), or a purchase request to buy an item. We will provide a ServerLib class that handles most of this for you -- a simple “processRequest” method will handle generating and sending back replies to the clients. Your Server class needs to instantiate the ServerLib class and then register as a frontend with the cloud service (in order to receive requests). The main loop of your server needs to pull the next request from the input queue, and call the processRequest method of ServerLib. ServerLib itself will get the information needed to process requests from a “database” (also hosted in the cloud) that contains the lists of items, categories, prices, etc. This database serves as the back-end tier of the service; your Server class will form the front-end and middle tiers.

The system will simulate clients arriving at random intervals. Each client will perform one or more “browse” requests, and may follow up with a purchase, but only if the replies are received within a short time. If the client request is dropped, or takes too long, or results in an error, the client will leave unhappy. Your goal is to minimize the number of “unhappy” clients (any that result in status other than “ok” or “purchased”) while simultaneously minimizing the amount of cloud resources (total VM time) consumed.



Requirements/Deliverables

We will provide:

- We provide several components for this project. These require that the project be implemented in Java, in a Unix / Linux environment, e.g., Andrew Unix servers
- We will provide the simulated cloud service that provides interfaces for starting and stopping "VMs" (these are actually implemented as processes).
- We will provide code to simulate requests from clients.
- We will provide a simple database populated with categories, items, prices, etc. for the web store.
- We will provide you a Java class (ServerLib) that provides methods to access the Cloud VM services, to get the next client request, and to process a client request. This will handle interpreting the requests and generating the replies.

You will create:

- You will create a Server class that implements a `main()` method. This server should instantiate ServerLib, and use it to get and process requests from clients. This server should operate in the multiple roles (Server, App Server, and Cache) indicated in the figure above.

Your code should do the following:

- Your Server class will implement a `main()` method. This will be run by the Cloud class as a separate process once at the start, and again for each call to `startVM()`.

- Your Server needs to be able to operate in up to 3 different roles: as the front end (pulling requests off of the input queue and sending them to the middle tier), as an app server / middle tier (actually handling the requests using the `processRequest()` method of ServerLib), and as a cache (cache read-only operations on the database). Note that the cache aspect is only needed for the final submission. For the first checkpoint, each server instance will do the front and middle tier operations.
- Your Server class needs to use Java RMI to communicate between instances acting as front and middle tiers, to implement the caching proxy to the database, and to coordinate with each other the roles each instance will play. For the database cache, you will need a class that extends `UnicastRemoteObject`, implements the `Cloud.DatabaseOps` interface, and passes cache misses or modify operations to the actual database object, which you can get using `getDB()`. Your database cache does not need to worry about updating or invalidating cached entries.
- Your Server needs to call the `startVM()` method of ServerLib to launch an additional Server instance. A single Server instance will be launched at the beginning of a run, but your code needs to explicitly request any additional "VMs" of your server to be started.
- Your Server should exit cleanly if it is no longer needed, or another instance should use the `stopVM()` method of ServerLib to forcefully terminate such instances. Servers that don't terminate will continue to use resources and accrue "costs" in the cloud service.
- Your Server needs to ensure most clients don't time out. Clients will expect browse requests to be serviced within 1 second, and purchases within 2 seconds. Different operations will incur various time costs, including getting a request from the input queue, dropping a request, processing a browse request, and processing a purchase request. There will also be a fixed time delay for new Server instances to start (booting the "VM"). Each database operation also incurs some time overhead.
- Your server will be provided three command line arguments: <cloud ip>, <port>, and <VM id>. The first two specify the IP address and port of the Java RMI registry provided by the Cloud class. Your code will pass these to the constructor of the ServerLib class, which will mediate access to the Cloud service. The third provides the VM id for this instance of your Server.

Submission and grading:

- You will be graded on the correctness and performance of your system. The number of clients that timeout or are explicitly dropped will be assessed, along with the total cloud costs (total VM time).
- This project will use an autograder to test your code. See below on how to submit.
- You need to submit a plot (pdf) of benchmarking results with Checkpoint 1. See below.
- You need to submit a short (1-2 pages) document detailing your design for the final checkpoint. See below.
- The late policy will be as specified on the course website, and will apply to the checkpoints as well as the final submission.
- Coding style should follow the guidelines specified on the course website.

Checkpoint 1 (17%) Due: 11:59 PM, Wednesday March 28, 2018

Checkpoint 1 requires you to implement a simple scale-out of the "web server". Here, the system is two-tiered: your server is the frontend, the database (accessed by ServerLib) is the backend. There is no cache tier, and the middle tier functions are performed by the frontend. Each server is monolithic – i.e., like the sample code, the main loop takes the next request off of the queue and processes it immediately. Your code will need to launch several of these server "VMs" to meet the client demand. For this checkpoint, you can statically decide how many servers to launch based on "time of day" reported by the simulation. You need to do benchmarking on your own to determine the optimal number of servers for a given arrival rate. You do not need to react dynamically to load changes. However, your code does need to be able to coordinate which server is responsible for starting the other VMs, etc. You will be graded on the number of unhappy clients (those whose requests are dropped, take too long, or incur other errors), as well as the total resources (VM time) consumed by your system. (12%)

As performance testing is an important aspect of designing a scaling system, you will also be graded on a simple benchmark. In this benchmark you will run your system on a trace described by a rand_spec of "c-1000-sss" where sss is any random seed you wish. First run with just 1 server and measure the number of unhappy clients. Then repeat for 2, 3, 4, … servers. Create a plot, where the number of unhappy clients is on the Y-axis and the number of servers on the X-axis (make sure to label the axis of your plot and to export to a high-resolution or vector format). Submit a PDF that contains this plot and a one-paragraph description of results to autolab. Be sure to note the shape of the curve, any "knee" or bend in the curve, and explain what the plot suggests is a good number of servers for this load. (5%)

Checkpoint 2 (35%) Due: 11:59 PM, Wednesday April 4, 2018

Checkpoint 2 requires you to implement a 3-tier system. In this simulation, performing both the front end operations (managing the input queue) and application / middle tier operations (processing the requests) in the same "VM" is less efficient than performing these in separate ones. So, to take advantage of this, your Server class should split these operations into separate "VMs." You will need to start multiple instances (using the startVM mechanism) and use Java RMI to pass requests between the front and middle tiers and to coordinate the roles of your Servers. You should scale out the front and middle tiers separately to minimize the number of VMs needed to meet the demand. You will be graded on the number of unhappy clients (those whose requests are dropped, take too long, or incur other errors), as well as the total resources (VM time) consumed by your system.

Final (48%) Due: 11:59 PM, Wednesday April 11, 2018

Scaling out the front-end and application servers should let the system scale with load until the database itself becomes a bottleneck. To help alleviate this bottleneck, in your final submission, you will add a caching tier, creating a 4-tier system. This new tier will implement a write-through cache of the database that handles most of the read operations for the "browse" requests, saving database processing capacity for the purchases. Your cache should implement the same interface as the database, and pass through purchase transactions and any misses. Your server can tell ServerLib to use your cache by invoking a second variant of the processRequest method that takes a database interface object reference as a parameter. Your server code will need to coordinate all of these roles and pass requests and database queries between “VMs” using RMI. Grading will be similar to Checkpoint 2, but you should expect higher and more variable client loads. Your code should dynamically scale up and down the number of server “VMs” based on the observed load. (28%)

You will also need to write and submit a 1-2 page document, describing the major design aspects of your project, including how you coordinate the roles of the different server instances, how you decide how many in each tier to run, when you decide to add or remove servers, and how you implemented the database cache. You are encouraged to include any plots from your benchmarking that indicate how many servers are needed for different arrival rates. Discuss what you have learned about scaling a service by adding tiers and by scaling out the tiers. Highlight any other design decisions you would like us to be aware of. Please include this as a PDF in your final tarball. (10%)

Your final source code will also be graded on clarity and style. (10%)

Submission Process and Autograding

We will be using the Autolab system to evaluate your code. Please adhere to the following guidelines to make sure your code is compatible with the autograding system.

First, untar the provided project 3 handout into a private directory not readable by anyone else (e.g., ~/private in your AFS space):

```
      cd ~/private; tar xvzf ~/15440-p3.tgz
```

This will create a 15440-p3 folder with needed libraries, classes, and test tools. You should create your working directory in the 15440-p3 directory. It is important that from your working directory, the provided java classes should be available at ../lib.

Write your code and Makefile in your working directory. You must use a makefile to build your project. See the include sample code for an example. You will need to add the absolute path of your working directory and the absolute path of the lib directory to the CLASSPATH environment variable, e.g., from your working directory:

```
      export CLASSPATH=$PWD:$PWD/../lib
```

Ensure that by simply running "make" in your working directory, your server and support classes are built. Please name the class implementing your server "Server". Make sure the java and generated .class files are in your working directory (i.e., not in a subdirectory). Your server class should implement main. Do not place your classes in a java package! Leave them in the default package. This naming convention and relative file locations are critical for the grading system to build and run your programs.

To hand in your code, **from your working directory**, create a gzipped tar file that contains your make file and sources. E.g.,

```
    tar cvzf ../mysolution.tgz Makefile Server.java
```

Of course, replace these with your actual files, and add everything you need to compile your code. If you use subdirectories and/or multiple sources, add these. Do not add any files generated during compilation (e.g. the .class files) -- just the clean sources. Also, do not add the class files that we have provided -- these will be installed automatically when grading. To work correctly with Autolab, when extracted, your tarball should put the Makefile and sources in the current working directory.

You can then log in to **https://autolab.andrew.cmu.edu** using your Andrew credentials (see link at bottom of the login page). Submit your tarball (`mysolution.tgz` in the example above) to the autolab site. Each checkpoint shows up as a separate assessment on the Autolab. For CH1 and your final submission, include your write up as a PDF file in your tarball.

How to Use the Supplied Classes

Cloud class

We will provide a class called Cloud. This is the main class for the simulated service, and will start the Java RMI registry and all of the other classes and processes. To run the program, ensure your CLASSPATH is set correctly (and includes both the lib directory and the directory with your Server class), then execute:

```
java Cloud <port> <db_file> <rand_spec> <hour> [<duration>]
```

Here, <port> specifies the port that the Java RMI registry should use. The <db_file> parameter specifies a text file that will be loaded as the contents of the backend database. A sample file (db1.txt) is provided in the lib directory. The <hour> parameter is the time of day to be reported by the simulation (0-24). The optional <duration> parameter indicates the number of seconds to run the experiment (default=30 seconds).

Finally, rand_spec indicates the arrival pattern for the simulated clients. There a few options:

- **c-*xxx-sss*** - Constant arrival rate with interarrival time *xxx* ms, and random seed value of *sss*.
- **u-*aaa-bbb-sss*** - Uniform random interarrival times, between *aaa* ms and *bbb* ms; random seed value of *sss*.
- **e-*aaa-sss*** - Exponential random interarrival times, mean of *aaa* ms (Poisson arrivals); random seed value of *sss*.
- ***spec1,duration1,spec2,...*** - Use multiple specifications, one after another. *Spec1*, *spec2*,.. are one of the above specifications. *Spec1* will be used for *duration1* seconds, followed by *spec2* for *duration2* seconds, etc. The last spec in the sequence should not have a duration specified. Note that there are no whitespaces in the specification string.

Once started, the Cloud class will start a Java RMI registry and register itself. It will then start a "VM" (actually a process) for the database, which will be initialized with the contents of the db_file supplied on the command line. Next, a single process is started that executes your

Server class. Finally, the simulated clients are started. The simulation will run for 30 seconds (or the specified duration), and the client results, total revenues, and total VM time used are reported. Client results include: failed to connect, timeout, explicitly dropped, made purchase, ok (everything went well, but no purchase made), and bad purchase (client timed out, but purchase went through anyway). You want clients to result in either purchase or ok status.

ServerLib class

The ServerLib class needs to be initialized by your server, and provides methods to access to all of the Cloud services and to handle requests. Its constructor needs the IP address and port of the Java RMI registry set up by the Cloud, and provided to your Server class as command line arguments.

Cloud / VM operations:

- startVM() - launch another "VM" that executes your Server class; returns VM id
- endVM(id) - force stop VM indicated by id; your Server process can also just exit cleanly to stop the associated VM
- getStatusVM(id) - returns status of VM indicated by id; this can be NonExistent, Booting, Running, or Ended
- getTime() - returns the simulation time of day (hours, 0-24)
- getDB() - returns the remote object implementing the database

Note: there is no method to get the VM id of the current process. This value is passed as the third argument to your Server class main() when it is started.

Front End operations:

- register_frontend() - register with load balancer and start receiving client requests
- unregister_frontend() - stop receiving requests; this is needed before your Server changes roles or exits so requests are not lost
- getNextRequest() - gets the next client request from the input queue of this Server
- getQueueLength() - returns number of requests in the queue for this Server
- dropHead() - drops the next request in the queue of this Server
- dropTail() - drops the last request in the queue of this Server

Middle tier operations:

- processRequest(r) - handle request r, using the default database, and send back reply
- processRequest(r,db) - handle request r, but using the provided db (e.g., your cache), and send back reply
- drop(r) - drop the request r

Database

The database used in this simulation is actually a key-value store. The interface is defined in Cloud.DatabaseOps. This provides 3 methods:

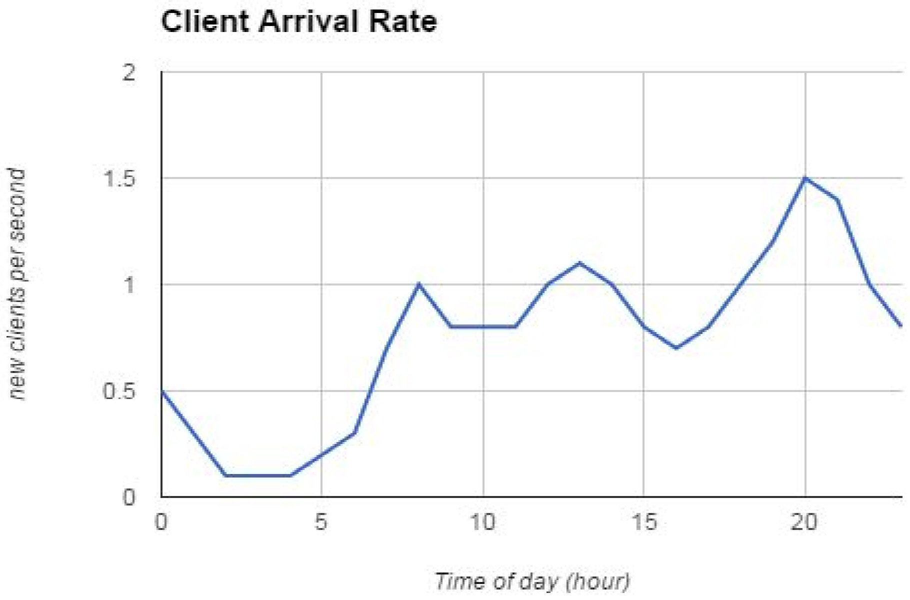
- get(key) - returns the value (string) associated with the supplied key (also a string)

- set(key, value, auth) - inserts the key value pair; this is a restricted operation that requires a password (auth string)
- transact(item, price, qty) - purchase specified item at the specified price and quantity; returns true on success, or false otherwise

Your Server generally does not directly use the database. Instead, the processRequest method of ServerLib will access the database. However, for the final submission, you will need to implement a cache for the database that implements this interface. You should cache read operations (get), and pass through any misses or write operations (transact) to the database. You do not need to worry about invalidation or update of cached entries.

Diurnal load curve

The number of clients accessing web sites typically varies by the time of day. Often, this is a regular pattern based on sleep, work, and meal times of customers. For this project, assume the diurnal load cycle below. You can tune the number of Servers you use based on the "time" reported by the simulation (getTime()). However, be aware that the actual load can vary from the average in this chart, so you should use this as a starting point, but adjust the number of Servers based on the observed load, queue lengths, etc.



Notes / Hints

- The focus of this project is performance tuning and analysis. You may not have to write much code to create solutions. Prepare to spend the majority of your time on testing and developing tools to find bottlenecks and sources of wasted VM time.
- Repeat your experiments (especially for the randomized-arrival workloads). Randomness and high variability can mislead your intuition. Longer runs may also help

in this regard. Although by default, the simulation runs for only 30 seconds, you can choose to run for much longer by specifying the fifth parameter to the Cloud class.

- You should try running your system at various loads (adjust the rand-spec value to change the arrival rate of clients) to determine how many clients you can handle with different number of servers.
- You should use Java RMI to communicate between different instances of your Server class. You do not need to create your own registry, though -- you can use the one set up by the Cloud class.
- If you have instantiated an object that has an RMI interface (ie., it extends UnicastRemoteObject), your process will not terminate cleanly unless you stop the object's remote interface. You can create a shutdown method for your object that calls:

  ```
  UnicastRemoteObject.unexportObject(this, true);
  ```

  This will turn off its RMI server, and let the process terminate.
- Note that `unregister_frontend()` only tells the load balancer to stop sending any more requests to the particular server. Any requests sent to the server before this call are not lost and will be put in the server's queue. These will still need to be handled by the server.
- The Cloud class initially launches 2 "VMs" -- one for the database, and one as your initial Server. Thus, the database will be VM 0, and your first Server instance will be VM 1.
- The <hour> parameter to the Cloud class specifies the simulated time of day (just the hour, from 0 to 23). This is the value that getTime() will return. It is not used in any other way. It is useful only for Checkpoint 1 to let your code know which part of the diurnal load curve to use to select number of servers.
- Hint: You can use drop if there is no way to handle the client in time. This can be used to drop some requests when the queue is too long (and would cause every client to timeout).
- Note that at the end of a simulation run, the Cloud class will kill all of your Server processes in some arbitrary order. Because of this, your code may get RMI exceptions due to blocking RMI calls that fail due to the server going away. These exceptions are expected and ok if they occur only at the end of a run.
- Remember that a client will go away unhappy if his request was dropped, took too long to get a reply, or if some error occurred. Happy clients are those that end up with status "purchased" or "ok"; all others are unhappy clients. You need to try to minimize unhappy clients.
- Note that the arrival rate in the diurnal load curve and as specified in <rand_spec> parameter to the Cloud class refer to arrivals of new clients. This is not the same as the request rate. Since each client may make multiple browse or purchase requests, the request rate will generally be higher than the client arrival rate.
- Hint: the DB cache is intended to be trivial to implement. Don't worry about making it perfect as you did in Project 2. Here, you don't even need to worry about invalidation or updates to cached items. Just pretend items don't change, and pass through any operations other than reads (gets).