Department of Electrical Engineering and Computer Science

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

6.824 Spring 2004

Final Exam Solutions

The average score was 84, the standard deviation was 6.

I Short Questions

1. [5 points]: Consider the system described in the paper “Hypervisor-based Fault Tolerance.” Suppose the primary fails due to a power failure, the backup takes over, and then power to the primary is restored. You would like the primary to resume replicated execution so that the system could tolerate a subsequent failure of the backup. Is this likely to be easy with hypervisor-based fault-tolerance? Why or why not?

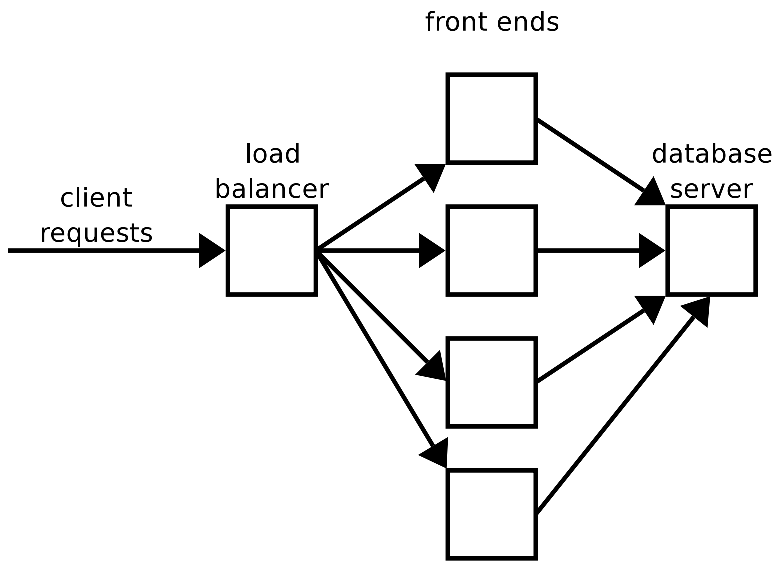
It would be difficult to install the correct state on the old primary. The backup would have been executing for a while, changing its memory, registers, disk etc. All of the backup’s state would have to be transferred to the old primary. Alternately, the old primary could be started afresh, and one could re-issue the entire history of operations over the life of the system.

2. [5 points]: The Coral paper (“Democratizing content publication with Coral”) mentions in Sections 2.3 and 4.2 that Coral’s “sloppy” DHT can store multiple different values for each key. What would break, or not work as well, if Coral’s DHT only stored one value for each key?

CoralCDN uses the multiple key feature to allow it to associate multiple proxies with each URL and with each IP address prefix. The choice provided by these multiple proxies helps CoralCDN spread the load of serving cached pages, and allows it to choose a proxy that’s close to the client.

II Performance

Samantha, a web site design consultant, is helping Acme Services build a web server system for on-line commerce. The system has three parts. A single load balancer routes each incoming HTTP request to a different front end server. Each front end server is in charge of generating personalized web pages for different visitors. The front end servers consult a back-end database server for information such as visitor preferences, shopping cart contents, and inventory levels.

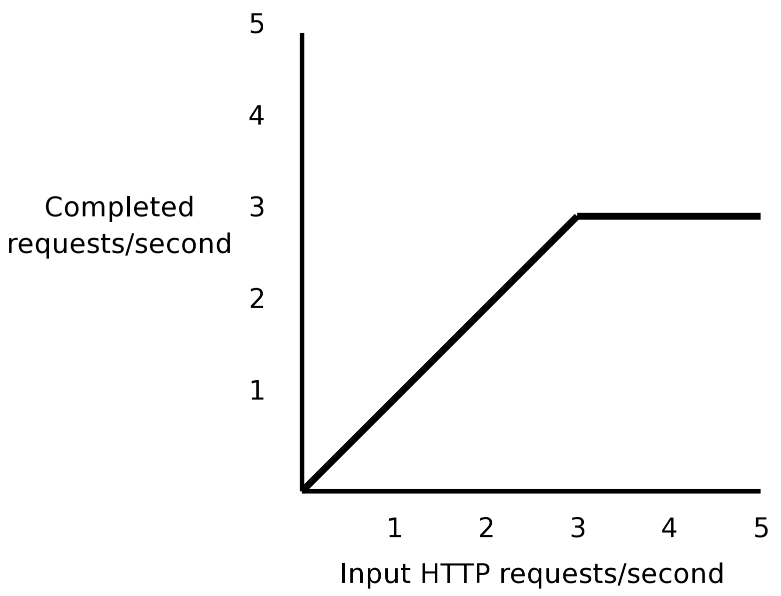


The load balancer sends HTTP requests to the front ends in round-robin order. The front ends communicate with the database server using UDP RPCs. Each client HTTP request involves the front end sending just one RPC to the database server. The front ends do not re-send these RPCs; if the front end gets no response after 100 seconds, it sends an error message to the HTTP client.

Each front end has a CPU fast enough to complete one client HTTP request per second. Since a front end may have to wait for the database server, each front end can keep track of many requests at the same time. Every time a front end receives a client HTTP request, it immediately issues an RPC to the database server. The front end can keep track of an unlimited number of client HTTP requests, and thus keep an unlimited number of RPCs in flight to the database server.

The database server is fast enough to process three RPCs per second. The database server has an input queue that can contain 100 RPCs: if RPCs arrive faster than the server can process them, the RPCs are placed on this queue. If an RPC arrives when the queue is full, the database server simply discards the RPC. The database server serves queued RPCs in the order that they arrived.

Samantha decides to measure the performance of this system. She collects lots of hosts to simulate clients, and sets up the clients so that she can control the total load (in HTTP requests issued per second) that the clients place on the server system. Samantha tests the system over a range of loads, measuring the number of client HTTP requests completed per second. Here is what she sees:



3. [5 points]: Why does the performance curve stop rising at 3?

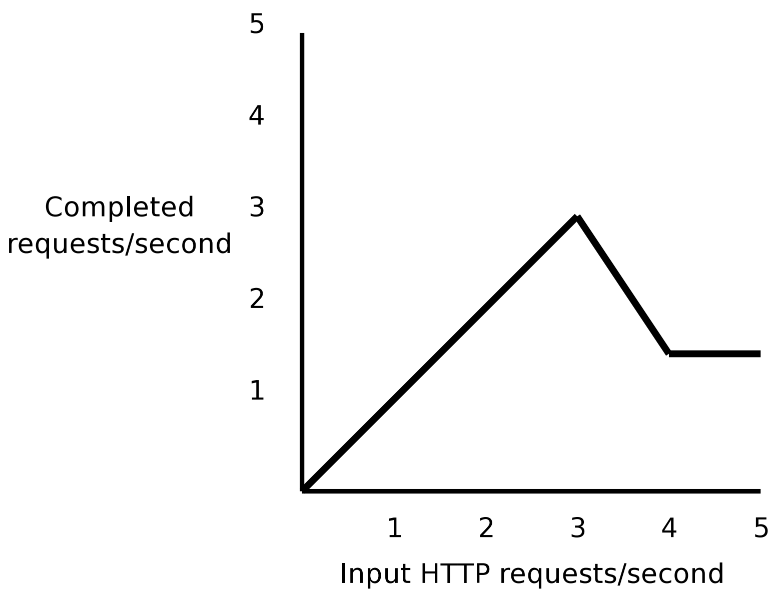
The database server can only finish three RPCs per second. Since each client HTTP request involves one RPC, only three of them can be completed per second.

4. [5 points]: When the input rate is 4 requests/second, the output rate is only 3 requests/second. What happens to the extra request per second?

The database server drops the extra RPCs because its input queue is full.

Samantha's employer, Henryk Acme, reviews her design and notices that the front ends do not re-send RPCs. Henryk demands that Samantha change the front ends so that they re-send an RPC if no response is received after five seconds. Samantha makes this change, but arranges that a front end re-sends an RPC at most once (for a total of two times at most). As before, a front end waits for 100 seconds after it sends the second RPC, then (if it still gets no response from the database server) the front end sends an error message to the HTTP client.

Samantha re-runs her performance tests and sees this result:



5. [5 points]: Why does the completion rate drop after 3 requests/second, instead of staying flat at y=3 as in the previous graph?

As soon as the request rate hits 3 per second, the database server's input RPC queue will be full most of the time. Since the queue has 100 entries, and each entry takes a third of a second to process, an RPC will stay on the queue for about 33 seconds. This is longer than the front end's timeout period of 5 seconds, which means that the front ends will send every RPC twice. Thus the database server will waste time executing some RPCs twice, and complete fewer than three useful RPCs per second.

6. [5 points]: Why does the completion rate level out at about 1.5 completions/second?

If the front end executes every RPC twice, it will complete only 1.5 useful RPCs per second. (Mike Walfish points out that the fraction of useful RPC completions will rise as the input load rises, since it's unlikely that both transmissions of a given RPC will encounter a non-full queue.)

III TreadMarks

Look at the paper "TreadMarks: Distributed Shared Memory on Standard Workstations and Operating Systems," by Keleher et al. Suppose you are running the following parallel shared-memory program on three workstations, $W1$, $W2$, and $W3$.

```
A1() {
  x = 1;
  Acquire(L1);
  y = 1;
  Release(L1);
}

A2() {
  Acquire(L1);
  z = y;
  Release(L1);
}

A3() {
  Acquire(L1);
  printf("x=%d y=%d z=%d\n", x, y, z);
  Release(L1);
}
```

At about the same time, $W1$ executes `A1()`, $W2$ executes `A2()`, $W3$ executes `A3()`. The variables `x`, `y`, and `z` all start out containing zero. `Acquire()` and `Release()` are the functions that TreadMarks supplies to acquire and release locks. `L1` is the name of a lock. There are no failures, the network delivers all messages, and there is no other activity in the system.

7. [5 points]: Workstation $W3$ prints three numbers. Given TreadMark's consistency algorithms, only some outputs from $W3$ are possible. For each of the following outputs, write "yes" if it is a possible output, and "no" if it is not.

```
x=0 y=1 z=1  No. x=0 means A3 executed before the y=1 in A1.

x=1 y=1 z=0  Yes. A3 executed after A1 and before A2.

x=1 y=0 z=1  No. W2 would have told W3 about y=1 as well as z=1.
```

Now consider this shared-memory TreadMarks program:

```
B1() {
  x = 1;
  printf("x=%d y=%d\n", x, y);
}

B2() {
  y = 1;
  printf("x=%d y=%d\n", x, y);
}
```

Workstation $W1$ starts executing `B1()` at about the same time as workstation $W2$ starts executing `B2()`. `x` and `y` start out containing zero. There are no failures, the network delivers all messages, and there is no other activity in the system.

8. [5 points]: Is it possible for $W1$ to print "x=1 y=0" `and` for $W2$ to print "x=0 y=1"? Describe how this might occur, or explain how TreadMarks prevents it from occurring.

This could occur. Neither program acquired any locks, so neither will learn about the other's writes to variables.

Finally, suppose you now run this shared-memory TreadMarks program:

```
C1() {
  Acquire(L1);
  x = 1;
  Release(L1);
  Acquire(L2);
  y = 1;
  Release(L2);
}

C2() {
  Acquire(L1);
  printf("xa=%d\n", x);
  x = 2;
  Release(L1);
}

C3() {
  Acquire(L1);
  printf("xb=%d\n", x);
  Release(L1);
  Acquire(L2);
  printf("y=%d\n", y);
  printf("xc=%d\n", x);
  Release(L2);
}
```

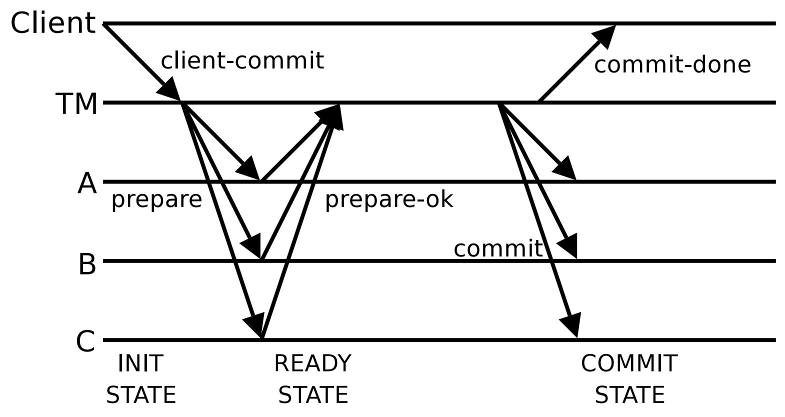
At about the same time, $W1$ starts executing `B1()`, $W2$ starts executing `B2()`, and $W3$ starts executing `B3()`. `x` and `y` start out containing zero. There are no failures, the network delivers all messages, and there is no other activity in the system.

9. [5 points]: Suppose you run this parallel program and it prints "xa=1", then "xb=2", then "y=1". Is it possible for the next printout to be "xc=1"? Describe how this might occur, or explain how TreadMarks prevents this from occurring.

This could not occur. The xa=1 means that C2 acquired L1 after C1 set x=1; the xb=2 means that C3 acquired L1 after C2 released it. Thus C2 would have sent C3 a version vector that included C1's assignment to x. C3 then knows when it acquires L2 from C1 that it already knows about any writes C1 performed before C1 release L1, and thus C3 knows to ignore C1's write to x. Equivalently, the version vectors tell C3 to order C2's write to x after C1's write to x.

IV Two-Phase Commit

The figure below shows a successful execution of two-phase commit. The client asks the transaction manager (TM) to organize an atomic transaction involving servers A, B, and C. A transaction is atomic if either all three servers execute their part of the transaction, or none of them execute it. The TM sends prepare messages over the network to the three servers asking them if they are willing to perform the transaction. Each server that is willing (in this case all of them) sends a prepare-ok message to the TM. If the TM collects prepare-ok messages from all three servers, the TM sends a commit message to each server, and then sends a commit-done message to the client. A server executes the transaction when it receives a commit message.



If a server receives a prepare message and thinks it won't be able to commit, it returns a prepare-abort message to the TM, and the TM sends abort messages to all the servers and an abort-done message to the client.

For example, in a banking application, a transfer transaction might involve server A debiting account #1, server B crediting account #2, and server C appending an audit record to a file. When server A receives the prepare message, server A must check that the account #1 exists and contains enough money; if it does, server A sends a prepare-ok; if it does not, server A sends a prepare-abort. If server A send a prepare-ok, it must lock account #1 to ensure that it continues to contain enough money. If A then receives a commit message, it debits the account and then releases the lock. If A receives an abort from the TM, it just releases the lock.

The tricky part about two-phase commit is how to handle server or TM failures. The immediate symptom of a server or TM failure will be that one or more hosts will block: they will wait indefinitely for a message from the failed host. For example, if server A fails before sending its prepare-ok message, then the TM will block waiting for that message. A host may block even if there are no host failures, for example if the network breaks or drops packets or delays packets. When possible the participants would like to avoid blocking forever. The general approach is to have each host impose a timeout on how long it is willing to wait for each message, and to take some action after a timeout in order to attempt to resolve the transaction (either committing or aborting it). In some cases this works, but in other cases the participants have to wait for the failed host to re-start.

For all of these questions you should assume that there is never any confusion about which transaction a message is part of (because the messages carry transaction IDs). You should also assume that all participants follow the protocol to the best of their ability.

10. [5 points]: Suppose that the TM has sent all the prepare messages but has not yet received a prepare-ok (or prepare-abort) from server A. Would it be correct for the TM to abort the transaction at this point, sending abort messages to the servers and an abort-done message to the client? Why or why not?

Yes. No server has executed the transaction since the TM hasn't sent any commit messages yet. Thus it's still OK to abort.

11. [5 points]: Suppose again that the TM has sent all the prepare messages but has not yet received a prepare-ok (or prepare-abort) from server A. Would it be correct for the TM to commit the transaction at this point? Why or why not?

No. Server A might be unable to execute the transaction. Perhaps server A sent a prepare-abort that the network lost or delayed, or perhaps server A has crashed.

12. [5 points]: Suppose that server A has received the prepare, sent the prepare-ok, but has not yet received a commit or abort message. Server A contacts server B and discovers that server B has received a commit message. Would it be correct for server A to execute its part of the transaction at this point, as if it too had received a commit message? Why or why not?

Yes. The TM must have sent commit messages to all the servers, so it's OK for server A to pretend it received the message.

13. [5 points]: Suppose again that server A has received the prepare, sent the prepare-ok, but has not yet received a commit or abort message. Server A contacts server B and discovers that server B has also received the prepare, sent a prepare-ok, but has not yet received a commit or abort. Server A cannot reach server C. It turns out that it's not correct for A to either abort or commit in this case; it must wait until it can contact the TM and find out whether the TM decided to abort or commit. Describe two sequences of events that are consistent with A's observations: one in which the TM decides to commit the transaction, and another in which the TM decides to abort the transaction.

Commit case: C sent a prepare-ok to the TM, the TM sent commit messages to the servers and commit-done to the client, server C received the commit and executed, the network lost the commit messages to the other two servers, then TM and C crash.

Abort case: C sent a prepare-abort to the TM, the TM sent abort messages to the servers and abort-done to the client, the network lost the abort messages to the other two servers, then TM and C crash.

14. [5 points]: Suppose again that server A has received the prepare, sent the prepare-ok, but has not yet received a commit or abort message. This time server A contacts both server B and server C and discovers that both of them have received the prepare, sent a prepare-ok, but have not yet received a commit or abort. Would it be correct for server A to execute its part of the transaction at this point, as if it too had received a commit message? Why or why not?

It would not be correct for A to execute the transaction. The TM might have timed out waiting for one of the prepare-ok messages and decided to abort. (The "too" is a typo.)

V Frangipani

Suppose you have a file service that uses the system described in “Frangipani: A Scalable Distributed File System” by Thekkath et al. You have four Frangipani servers, $S1$, $S2$, $S3$, and $S4$, as well as some clients and Petal servers. The Petal servers are separate computers.

Suppose you start with two empty directories, “d1” and “d2”. The following sequence of events occurs:

A. A client asks $S1$ to create a file “d1/a”, and $S1$ returns a successful reply.

B. A client asks $S1$ to create a file “d2/b”, and $S1$ returns a successful reply.

C. A client asks $S2$ to delete file “d2/b”, and $S2$ returns a successful reply.

D. $S1$ stops executing unexpectedly, and does not reboot.

E. $S3$ runs the recovery demon for $S1$, and recovery completes.

There is no activity in the system except activity caused by these events, and there are no failures other than the crash of $S1$.

15. [5 points]: After recovery is complete, will file “d1/a” exist, not exist, or can you not predict? Please explain your answer.

It will exist. When S1 gave up the lock on d2/b to S2, S1 would have flushed its in-memory log to Petal, including the log record describing the creation of d1/a. The recovery demon will see that log record and re-execute the create.

16. [5 points]: After recovery is complete, will file “d2/b” exist, not exist, or can you not predict? Please explain your answer.

d2/b will not exist. If S2 hasn’t given up its lock on d2 by the time that the recovery demon finishes, then next time anyone looks at d2/b S2 will write its changes to d2 to Petal before giving up the lock. These changes will override any changes to d2 made by the recovery demon. If S2 gave up its lock and wrote its changes to d2 before the recovery demon ran, then the recovery demon will see that the version number for d2 in S1’s log is less than the version number for d2 that S2 wrote to Petal, and the recovery demon will ignore that log entry.

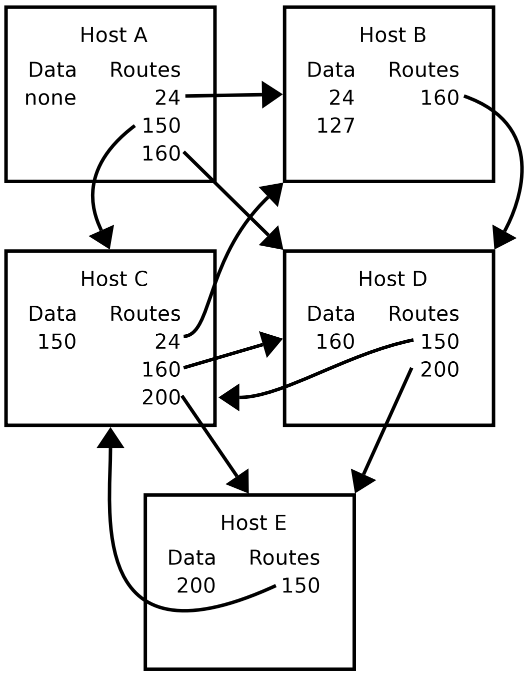
17. [5 points]: Suppose (as would probably be the case) that $S2$ holds an exclusive lock on “d2” when recovery starts. Does the recovery demon need to acquire the lock on “d2”? Why or why not?

No, the recovery demon does not need to acquire the lock on d2. The version number mechanism is sufficient for the recovery demon to decide which log records it can replay.

VI Freenet

A Freenet host ("Freenet: A Distributed Anonymous Information Storage and Retrieval System") contains a routing table and a data store. Both are indexed by numeric keys. A routing table entry contains the IP address of a Freenet host, while a data store entry contains the data (file) associated with the corresponding key.

Here are five Freenet nodes, each labeled with its routing table and data store. The keys are in decimal.



For example, host B's routing table contains an entry with key 160 referring to host D, and B's data store contains two files, one with key 24 and one with key 127.

18. [5 points]: What sequence of hosts would be visited by a query from A for key 200? Assume a hops-to-live limit of 20.

A D E

19. [5 points]: What sequence of hosts would be visited by a query from A for key 127? Assume a hops-to-live limit of 20.

A C D C (D) E C (E) (D) (C) E (C) B. The parentheses mark nodes to which the query back-tracks after failure.