Department of Electrical Engineering and Computer Science

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

6.033 Computer Systems Engineering: Spring 2018

Quiz I

There are **15 questions** and **11 pages** in this quiz booklet. Answer each question according to the instructions given. You have two hours to answer the questions.

- The questions are organized (roughly) by topic. They are not ordered by difficulty nor by the number of points they are worth.
- **If you find a question ambiguous, write down any assumptions you make.** Be neat and legible.
- Some students will be taking a make-up exam at a later date. **Do not** discuss this quiz with anyone who has not already taken it.
- You may use the back of the pages for scratch work, but **do not** write anything on the back that you want graded. We will not look at the backs of the pages.
- Write your name in the space below. Write your initials at the bottom of each page.

This is an open-book, open-notes, open-laptop quiz, but you may **NOT** use your laptop, or any other device, for communication with any other entity (person or machine).

Turn all network devices, including your phone, off.

CIRCLE your recitation section:

10:00	1. Mark	3. Muriel	5. Karen			
11:00	2. Mark	4. Muriel	6. Karen			
12:00	7. Howard	9. Sam				
1:00	8. Howard	10. Sam	11. Mark	13. Peter	15. Tim	17. Adam
2:00	12. Mark	14. Peter	16. Tim	18. Adam		

Name: SOLUTIONS

I Naming

1. [6 points]: Mark is designing an operating system, and is considering three different virtual-addressing schemes. In all schemes, his virtual addresses are 32 bits:

- **Vanilla Scheme:** "Standard" paging, where addresses are made up of 16-bit page numbers and 16-bit offsets. [PAGE | OFF]
- **Chocolate Scheme:** A one-level hierarchy, where addresses are made up of an 8-bit outer-page number, an 8-bit inner-page number, and a 16-bit offset. [OUT | IN | OFF]
- **Strawberry Scheme:** A two-level hierarchy, where addresses are made up of an 8-bit outer-page number, an 8-bit inner-page number, an 8-bit second-inner-page number, and an 8-bit offset. [OUT | IN1 | IN2 | OFF]

For each of the following, circle all that apply.

A. Which scheme(s) results in the largest virtual address space?

(a) Vanilla Scheme
(b) Chocolate Scheme
(c) Strawberry Scheme

All virtual addresses are 32 bits ⇒ All vir. addr. spaces are 2^{32}

B. Which scheme(s) has the largest pages?

(a) Vanilla Scheme 2^{16}
(b) Chocolate Scheme 2^{16}
(c) Strawberry Scheme 2^{8}

Size of page = $2^{\text{size of offset}}$

C. Assume that initially, **no** page tables are allocated. Then, a single virtual address translation takes place (no other translations take place). Which scheme(s) will result in the smallest amount of memory dedicated to page tables? Assume that individual page table entries are the same size in each scheme.

(a) Vanilla Scheme
(b) Chocolate Scheme
(c) Strawberry Scheme

(a) $\{2^{16}$
(b) $\{2^{8} \rightarrow \{2^{8}$
(c) $\{2^{8} \rightarrow \{2^{8} \rightarrow \{2^{8}$

Note that chocolate uses least space for page tables, but must allocate a full 2^{16} bits for a single page.

2. [6 points]: Circle True or False for each of the following questions about DNS.

(a) **True / False** A DNS name (e.g., `mit.edu`) may be associated with multiple IP addresses, but each IP address has to be associated with a single DNS name.

(b) **True / False** DNS caching reduces the time to resolve an IP address, but does not reduce DNS traffic on the Internet. Don't have to traverse entire hierarchy

(c) **True / False** A DNS request for the IP address of a host `foo.com` will be resolved to the same IP address regardless of which machine issues the request. foo.com can have multiple IPs (eg for load balancing)

Initials: SOLUTIONS

II Operating Systems and Performance

3. [10 points]: A guest OS kernel executes a single process, using the page table shown below on the left (which maps guest-virtual pages to guest-physical pages); this page table is stored in guest-physical page 4. In this table, the 'P' column indicates whether the page in question has been loaded into memory; the 'W' column indicates whether the page is writeable; and the 'U' column indicates whether the page is accessible to non-kernel processes.

The virtual machine monitor (VMM) uses the table shown below on the right to translate the guest-physical pages to host-physical pages.

guest virtual	guest physical	P	W	U
0	5	1	1	1
1	9	0	1	1
2	11	1	0	1
3	4	1	1	0
4	7	1	1	0

Guest OS's page table, stored in guest-physical page 4.

guest physical	host physical
4	2
5	6
6	4
7	3
11	8

VMM's table

To run the VM, the VMM needs to load a *shadow* page table, which maps guest-virtual pages to host-physical pages. The content of that table may differ depending on whether the guest OS has its U/K bit set to U (user) or K (kernel).

Fill in the shadow page table below, which the VMM should load when the guest OS has its U/K bit set to **K**. You can use a dash (—) to indicate values that don't matter or can't be discerned. Assume that the VMM supports virtualization using trap-and-emulate (rather than, e.g., binary translation), and that the VMM runs the guest kernel in user mode. The VMM updates the shadow page table state by tracing writes to the guest OS's page table.

guest virtual	host physical	P	W	U
0	6	1	1	1
1	not present	0	—	—
2	8	1	0	1
3	2	1	0	1
4	3	1	1	1

← Not present; other values can't be discerned / don't matter

← Guest OS in user mode

↑ guest vir → guest phy → host phy

↑ Same as guest OS

↑ Set to 0 so VMM can trace writes

Initials: SOLUTIONS

4. [6 points]: Consider the following bounded buffer code (send and receive), assuming the variables `bb.in` and `bb.out` are 64 bits, never overflow, can be read and written atomically, and neither the compiler nor hardware will ever reorder instructions:

```
send(bb, m):
  // each invocation of send has
  // its own local variables:
  //   my_send_index (64-bit int)
  while True:
    acquire(bb.lock)
    if bb.in - bb.out < N:
      my_send_index = bb.in
      bb.in = bb.in + 1
      release(bb.lock)
      bb.buf[my_send_index mod N] = m
      return
    release(bb.lock)
```

TROUBLE!

```
receive(bb):
  // each invocation of receive
  // has its own local variables:
  //   my_rec_index (64-bit int)
  //   m (message)
  while True:
    acquire(bb.lock)
    if bb.in > bb.out:
      my_rec_index = bb.out
      bb.out = bb.out + 1
      release(bb.lock)
      acquire(bb.rec_lock)
      m = bb.buf[my_rec_index mod N]
      release(bb.rec_lock)
      return m
    release(bb.lock)
```

Circle True or False for each of the following. Recall that a correct bounded-buffer implementation does not allow a sender to overwrite unread messages, and does not allow a receiver to read uninitialized messages.

(a) **True / False** The code is correct if there is one sender and one receiver executing at the same time.

(b) **True / False** The code is correct if there is one sender and many receivers executing at the same time.

(c) **True / False** The code is correct if there are many senders and one receiver executing at the same time.

(d) **True / False** The code is correct if there are many senders and many receivers executing at the same time.

With single sender + single receiver, a concurrent receive can read an uninitialized message from the buffer @ bb.in.

(a) False => (b) – (d) False

Initials: SOLUTIONS

5. [6 points]: Consider the following snippet of code, as part of a larger system in which the variable `x` is modified. The locks `L1` and `L2` are not used anywhere else in the system.

```
Lock L1;
Lock L2;
int x;

function foo() {
  acquire(L1);
  print(x);
  release(L1);
}

function bar(int v) {
  acquire(L2);
  if (v == 0) {
    print(x);
  }
  release(L2);
}
```

(a) False - Eraser does not require race conditions to actually occur in order to flag them

(b) True - If bar() never uses x, Eraser will not think that L2 protects x.

(c) True - Eraser will conclude that L3 protects x

(d) True - Eraser will assume x is a constant and does not need to be protected by locks.

The functions `foo()` and `bar()` are executed from separate threads, but Eraser never flags an error. Which of the following reasons might explain this? Circle **all** that apply.

(a) `foo()` and `bar()` both execute, but never at the same time, so no race condition actually occurs.

(b) `foo()` and `bar()` run concurrently, but `bar()` is always called with 1 as an argument.

(c) Every time `foo()` or `bar()` is called, an additional lock `L3` is also held.

(d) The value of `x` is changed for the last time before either `foo()` or `bar()` are called for the first time.

6. [6 points]: Circle True or False for each of the following questions about MapReduce.

(a) **True** / **False** If there are m map tasks, using more than m workers in the map phase may still improve performance beyond that achieved with m workers.

(b) **True** / **False** To achieve locality, map workers always execute on the same machine as the input data that they consume.

(c) **True** / **False** Intermediate data passed between the map workers and reduce workers is stored in the Google File System (GFS).

(a) Master will ~~restart~~ restart stragglers

(b) Master tries to place map workers w/ the input data, but if it can't it places them elsewhere (preferably nearby)

(c) Intermediate data stored on local disk

Initials: SOLUTIONS

7. [8 points]: Consider the following pseudocode. The starting process (P1) forks, creating a child process (P2), which also calls fork, creating a child process of its own (P3).

```
int main()
{
  int f1 = open("file1.txt")
  int f2 = 0;
  int f3 = open("file3.txt")
  int f4 = open("file4.txt")

  // P1
  if (fork() != 0) {
    f2 = open("file2.txt");
  }

  else {
    // P2
    close(f3);
    if (fork() != 0) {
      close(f4);
    } else {
      // P3
    }
  }
}
```

Inherited by ~~P2~~

f2 opened after fork(), so not inherited by P2 (or P3). (b) is false

f3 closed before fork(), so not inherited by P2. (c) is false.

closed after fork(). P3 still has it opened.

P3 inherits open file descriptors: f1, f4

What type of communication is available between P1 and P3?

(a) **True** / **False** P1 and P3 can communicate via writing to/reading from the file descriptor f1.

(b) **True** / **False** P1 and P3 can communicate via writing to/reading from the file descriptor f2.

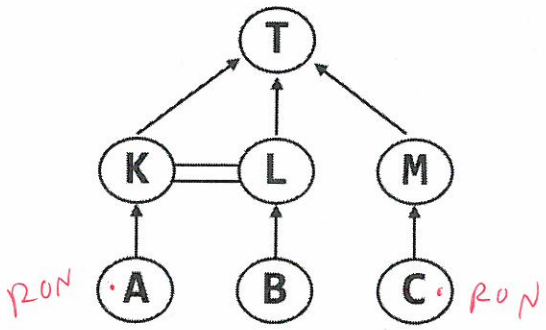
(c) **True** / **False** P1 and P3 can communicate via writing to/reading from the file descriptor f3.

(d) **True** / **False** P1 and P3 can communicate via writing to/reading from the file descriptor f4.

Initials: SOLUTIONS

III Routing

8. [6 points]: Consider the following AS graph. Arrows in the graph indicate the relationships between ASes: An arrow from X to Y ($X \rightarrow Y$) means that X is a **customer** of Y. Two lines between X and Y ($X = Y$) means that X and Y are **peers**.



There are two distinct paths between AS A and AS C:

- **Path 1:** $A \rightarrow K \rightarrow T \rightarrow M \rightarrow C$
- **Path 2:** $A \rightarrow K \rightarrow L \rightarrow T \rightarrow M \rightarrow C$

Suppose that two RON nodes exist: one in AS A, and one in AS C. Is it possible that, via RON, a machine in AS A could route data to a machine in AS C via Path 2? Circle the **best** answer.

(a) Yes, but RON is not needed; Path 2 is the path that BGP exposes between A and C.

(b) Yes, and no additional RON nodes are needed.

(c) Yes, but there must exist a RON node in AS L.

(d) Yes, but there must exist a RON node in AS L and a RON node in AS K.

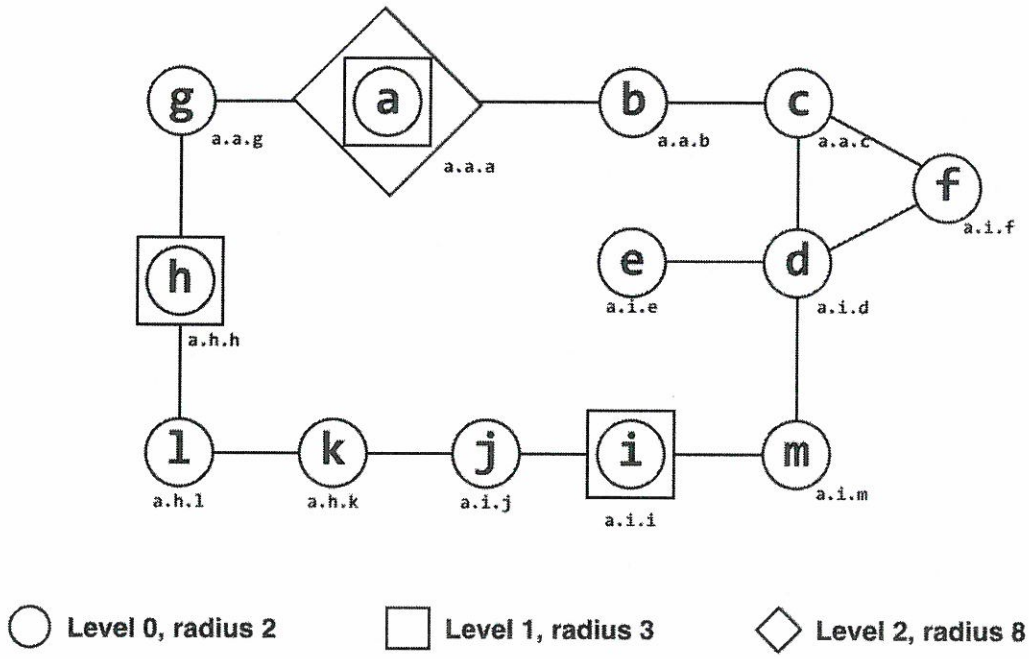
(e) No.

BGP will not expose Path 2; K will only use the peering link to send data to L or B.

To expose the path, we need a RON node in L. Then, packets can take the BGP ~~path~~ path from A to L (A → K → L) and then the BGP path from L to C (L → T → M → C).

Initials: SOLUTIONS

9. [9 points]: Consider the following network, which uses landmark routing.



A. Which of the following routers know about $\texttt{LM}_1\texttt{[i]}$? Circle **all** that apply.

(a) a ←
(b) e > 3 hops away
(c) h ←
(d) m

B. Which of the following routers know about $\texttt{LM}_2\texttt{[a]}$? Circle **all** that apply.

(a) e
(b) h
(c) i
(d) m

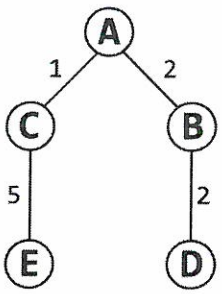
All nodes know about $LM_2[a]$

C. What path will packets from `a.i.d.` to `a.h.l.` take?

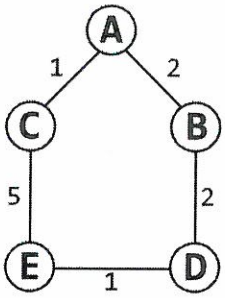
(a) $d \to m \to i \to j \to k \to \ell$
(b) $d \to c \to b \to a \to g \to h \to \ell$
(c) $d \to f \to c \to b \to a \to g \to h \to \ell$
(d) None of the above

Initials: SOLUTIONS

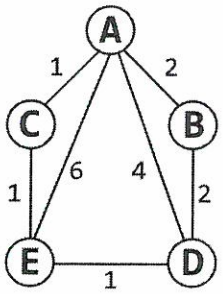
10. [8 points]: Consider the four topologies below. The number near each link is the link's cost.



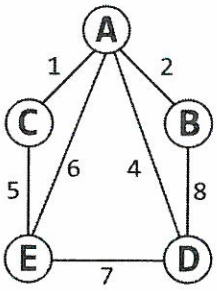
Topology I



Topology II



Topology III



Topology IV

For all parts of this problem, assume that the routing protocol has converged, and that there are no losses or failures in the network.

A. Assume that the network is running a **distance-vector** routing protocol. Node A sends the following advertisement.

$$[(A, 0), (B, 2), (C, 1), (D, 4), (E, 6)]$$

Which of the topologies are consistent with the above advertisement? Circle **all** that apply.

(a) Topology I
(b) Topology II
(c) Topology III
(d) Topology IV
(e) None

Advertisements in DV reflect the shortest path costs to nodes.

B. Assume that the network is running a **link-state** routing protocol. Node A sends the following advertisement.

$$[542 : (A, 0), (B, 2), (C, 1), (D, 4), (E, 6)]$$

Which of the topologies are consistent with the above advertisement? Circle **all** that apply.

(a) Topology I
(b) Topology II
(c) Topology III
(d) Topology IV
(e) None

Advertisements in LS reflect the links to neighbors

Initials: SOLUTIONS

IV Transport, Queues, and New Architectures

11. [6 points]: Consider a reliable sender and receiver. The sender sends a stream of new data packets—i.e., none of the packets are retransmissions—and in response receives the following (cumulative) ACKs from the receiver:

packet 5 — and perhaps others — was dropped.

1 2 3 4 4 4 4 4 4 4

Now, suppose that the sender times out and retransmits the first unacknowledged data packet. When the receiver gets that retransmitted data packet, what can you say about the ACK, a, that it sends? Circle the **best** answer.

(a) $a = 5$
(b) $a \geq 5$
(c) $5 \leq a \leq 11$
(d) $a = 11$
(e) $a \leq 11$

It's tempting to imagine that only packet 5 was lost, i.e., the ACKs reflect:

1	2	3	4	5	6	7	8	9	10	11	← received
1	2	3	4	X	4	4	4	4	4	4	← ACK

In which case, when 5 is retransmitted, $a = 11$. However

- It's possible that another packet — say 6 — was lost. So a may be < 11.
- It's possible that some ACKs have been lost, in which case, $a > 11$

12. [4 points]: Consider two senders, S_1 and S_2, sending to two receivers, R_1 and R_2 respectively. The paths from S_1 to R_1 and from S_2 to R_2 share a bottleneck link. The round-trip-time between S_1 and R_1 is RTT_1; between S_2 and R_2 it is RTT_2.

S_1 and S_2 are both using TCP's AIMD congestion control; however, only S_2 is using the slow-start optimization. For the purposes of this problem, you can assume that the queue at the bottleneck link is infinite; packets will not be dropped.

Assume that S_1 and S_2 start sending data at the exact same time, each with an initial window size of 1. Both S_1 and S_2 each need to send 30 packets, all of the same size. What must be true about RTT_1 and RTT_2 in order for S_1's transfer to finish before S_2's? Circle the **best** answer.

(a) $RTT_1 < RTT_2$
(b) $RTT_1 < \frac{5}{8} RTT_2$
(c) $RTT_1 < \frac{1}{5} RTT_2$
(d) S_1's transfer will complete before S_2's regardless of the values of RTT_1 and RTT_2

round trip

		1	2	3	4	5	6	7	8
S_1	window	1	2	3	4	5	6	7	8
	total # packets sent	1	3	6	10	15	21	28	30
S_2	window	1	2	4	8	16			
	total # packets sent	1	3	7	15	30			

S_1 takes 8 round trips.
S_2 takes 5 round trips.
$\therefore 8RTT_1 < 5RTT_2$
$\Rightarrow RTT_1 < 5/8\, RTT_2$

Initials:

SOLUTIONS

13. [4 points]: Which of the following best describe DCTCP? (Circle the **best** answer.)

decreases in proportion to congestion

(a) A DCTCP sender will decrease its window-size by half as soon as it sees a single packet mark.

(b) A DCTCP sender will decrease its window-size by at most half as soon as it sees a single packet mark.

(c) A DCTCP sender will decrease its window-size by at most half as soon as it sees a single packet drop.

~~Does it use both marks~~ Uses marks

(d) None of the above.

14. [8 points]: Consider a switch with two queues. Q_1 contains only 10-byte packets, and Q_2 contains only 20-byte packets. You can assume that each queue has infinitely many packets in it.

Muriel is trying to decide whether to use weighted-round-robin (WRR) or deficit-round-robin (DRR) to schedule packets from these queues. Regardless of the protocol she chooses, a single packet (of any size) takes one second to send (and so 10 packets will take 10 seconds to send). If a round of the protocol proceeds without sending any packets, that round will also take 1 second.

Muriel has two requirements:

- **Efficiency:** Every second, a packet should be transmitted (i.e., there should be no "wasted" seconds).
- **Short-term Fairness:** In each two-second window, Q_2 should transmit twice as many bits as Q_1.

Which of the schemes below satisfy both of Muriel's requirements? Circle **all** that apply.

(a) DRR with the quantum for Q_1 set to 1 and the quantum for Q_2 set to 2. ← Wasted slots

(b) DRR with the quantum for Q_1 set to 10 and the quantum for Q_2 set to 20.

(c) DRR with the quantum for Q_1 set to 100 and the quantum for Q_2 set to 200. ← multiple packets per round

(d) WRR with the weight for Q_1 set to $\frac{1}{3}$ and the weight for Q_2 set to $\frac{2}{3}$.

Both of these result in one packet per queue per round which satisfies Muriel's goals

15. [5 points]: For each of the characteristics below, decide whether it better describes a P2P network, such as BitTorrent, or a CDN, such as Akamai. If a characteristic describes both a P2P network and a CDN, circle "Both".

(a) **P2P / CDN / Both** Uses an overlay network

(b) **P2P / CDN / Both** Better for streaming content

(c) **P2P / CDN / Both** Uses DNS rewrites

(d) **P2P / CDN / Both** Has a hierarchical organization

(e) **P2P / CDN / Both** Tolerates individual machine failures

Initials: SOLUTIONS