Name: KUSHAGRA GUPTA Entry number: 2021CS50592

Instructions

- Verify that your exam has pages 1 to 10. Please fill the name and entry number on *every page* front and back. Do this first before starting the exam.
- During the exam, you should not have any electronic equipment including laptop, mobile phone, calculator, tablets, etc.
- The exam is open notes, open book, open slides. You can keep the printouts with you during the exam.
- Please answer each question in the provided space. Rough space is available on Page 5.

Please sign below:

I will not give or receive aid in the examination. I accept that any act of mine that can be considered to be an *IITD Honour Code* violation will invite disciplinary action.

Signature: Kushagra

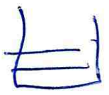
Q1. [4 marks] Assembly program

Let us say that the following recursive function foo is called with arguments 9, 12.

```
foo:
        movl    4(%esp), %eax
        movl    8(%esp), %edx
        cmpl    %edx, %eax
        jne     .L3
        ret
.L11:
        subl    %edx, %eax
        pushl   %edx
        pushl   %eax
        call foo
        ret
.L3:
        cmpl    %eax, %edx
        jl      .L11
        subl    %eax, %edx
        pushl   %edx
        pushl   %eax
        call foo
        ret
```

jump to L3 as ZF is not set

~~eax = 3~~
~~edx = 12~~
~~12, 3~~



$\leftarrow$ $\boxed{9, 3}$

cmpl %edx %eax
compare edx < eax.

Q1.1 [4 marks] What will be the return value (value in register %eax) when the function returns?
Hint: Draw the stack. Track %eip, %esp, %eax, %edx as the program executes.

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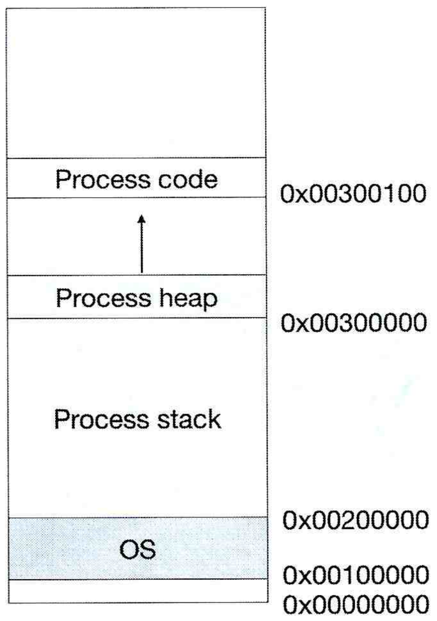
Q2. *[7 marks]* Memory allocator

Let us say that we are running the following program:

```
void* malloc(size_t s) {
  return sbrk(s);
}
void free(void *p){ }

int main(int argc, const char *argv[]) {
  int iter = atoi(argv[1]);
  for(int i = 0; i < iter; i ++) {
    int* ptr = (int*) malloc(sizeof(int));
    *ptr = iter;
    free(ptr);
  }
  return 0;
}
```



Notice that the program is using a custom virtual memory allocator. Assume that the OS is using segmentation hardware to do memory isolation. It has set up the segments for this process as shown in the figure. Initially, the base of the process' heap (data segment) is 0x00300000 and the limit is zero.

Q2.1 [2 marks] For the given layout, what is the smallest positive value of `iter` for which the program will crash? Assume that the OS never relocates segments elsewhere. OS will return a null pointer from sbrk when the segment can no longer grow.

Space between process code & process heap = 256 ~~8~~ B = 256 B
Each ptr malloc takes 4 B on the heap
∴ min iter = ~~[illegible]~~ 65 for the program to crash. (64+1 = 65)
(256/4 = 64 note that memory is byte addressed) byte addressed.
~~(as OS returns null pointer can't dereference)~~

Q2.2 [2 marks] The user observes that the program was working fine for `iter=100`. But, when they run the same program again with `iter=100`, the program crashes. What might be the reason for the crash? Assume the same behaviour of the OS as in the above question.

Even though with iter = 100, the program worked fine once ~~as presumably it wrote (overwrote) some bytes &~~ as after iter = 64, it may ~~not~~ or may ~~may not~~ return the null pointer from sbrk. ~~able to dereference~~ ~~the end~~
In some of the scenarios, it is able to overflow the process code space safely and not receive a null ptr
~~Also~~ Due to the dereferencing of null ptr, the program crashes in general. (sometimes like strlen(), we miss the '\0' but still we are able to write, maybe similar case here)

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Q2.3 [3 marks] Please modify malloc/free implementations to fix this program such that it works for all iter values. You may assume that the OS can, regardless of other processes in the system, grow the process' heap (data segment) to a size of 0x100 bytes.

Hint: You only need to make sure that the given program does not crash. You need not make arbitrary programs work. You are not allowed to modify the main function.

We need to write the free command by appropriately decrementy/ incrementy sbrk.
by -ve value

```
void free (void * p) {
    return sbrk (- sizeof(* p));
}
```

↑ decrement

So free works.

Q3. [5 marks] Hard disk drives

Let us say we are using a RAID-5 setup with 8 identical HDDs. The HDD mentions the following specifications in its datasheet:

Capacity: 1TB; Max. Sustained Transfer Rate (MB/s): 200MB/s; Bytes per sector: 4096; Rotational speed (RPM): 6,000; Average seek delay: 5ms

Q3.1 [1 mark] How many disk failures can the setup tolerate before we lose data? 1
Q3.2 [1 mark] What is the capacity of the setup? 7TB
Q3.3 [1 mark] What sequential read throughput can we expect? 7S = 1400MB/s
Q3.4 [1 mark] What random read throughput can we expect? 8R = 3.2 MB/s
Q3.5 [1 mark] What random write throughput can we expect? 2R = 0.8 MB/s

S = 200MB/s
R = 0.4 MB/s

4KB sector random read latency
$= \frac{4096}{200} \approx 20\ \mu s + 5\text{ ms (seek)} + \overset{5\text{ ms}}{\frac{60\times1000}{6000\times2}}$ (rotate)
$= 0.01 s$

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Q4. *[7 marks]* Metadata journaling

Let us say our disk has 512 byte blocks. There is a file which is spread over three data blocks (file size = 1536 bytes). The file contains 1536 'A's. A program opens the file, seeks to the start of the file, makes one write operation to write 1536 'B's, and closes the file. All the working of the program is in a single file system transaction. After the program ends, the computer abruptly restarts. When the file system becomes available, the user sees that the file has 512 'A's, then 512 'B's, and then 512 'A's.

Q4.1 [4 mark] Precisely explain the sequence of events which led to this outcome. The file system was using metadata journaling.

* In Metadata journalling, we make the write atomic partially due to log size constraints and only write metadata (inode, bitmaps etc) to the log.
* The first step followed in it is writing the data blocks (in metadata journalling the first step is writing data blocks, then update tail, txn descriptor, contents etc -)
* So, when we write the data blocks, the disk schedules the writes and hence it becomes the case that the first block written (based on SSTF or other scheduling algorithm & posn of disk head) is the middle of the file. [The 3 blocks may be on different tracks]
* After that is written, the system crashes. (before writing log) Since the writes were only partially atomic, we cannot recover back to the disk state, so the user finds 512 A's 512 B's, 512 A's in the file even after recovery step.

Q4.2 [3 mark] Can the same outcome be observed if the file system was instead using full journaling, i.e, logging both the data and the metadata blocks? Justify your answer.

* No, if the user logged both the data and metadata blocks, the file will be written in the log log (and not the disk). Unless the transaction is committed, the txn contents would not be sent to home locations (on disk) after recovery. (from buffer)
* So, despite of a crash, the txn commit is either not written or all the data / metadata is logged and then commit is written.
* So, after recovery, either the file has 1536 'A's or 1536 'B's so atomicity is preserved. Hence, such an outcome is not observed.

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Q5 [3 marks]: Protection

Let us say that the value of the code segment (cs) register is 0x001B and the data segment (ds) register is 0x0012.

Q5.1 [1 mark] What is the current privilege level? CPL = 3 , RPL = 2
Q5.2 [1 mark] Which index of the GDT is going to be used to do address translation for eip? ~~000~~ 0000 0000 0001 1 (binary) (first 13 of CS)
Q5.3 [1 mark] What value should the descriptor privilege level be set to, in the segment descriptor, such that it can be referred by the program? DPL = 3

This area is intentionally left blank. You can use it for rough work.

Cs = 001B

first 13 bits

B

9

A = 10

B = 11 = ~~0~~ 10~~11~~

$\boxed{0000\ 0000\ 0001\ 1}011$

0010.

0010

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Q6 [24 marks]. Snapshotting

One disk block = 512 bytes

In this problem, we are interested in extending the indexed file system studied in class to support *hourly snapshotting*. A snapshot is a consistent state of the file system. Snapshots can be used to recover old versions of files and folders. For example, let us say a user accidentally deleted a file named `/exam.md` and wants to recover it. The following example shows how to list all the versions of `/exam.md` saved in snapshots.

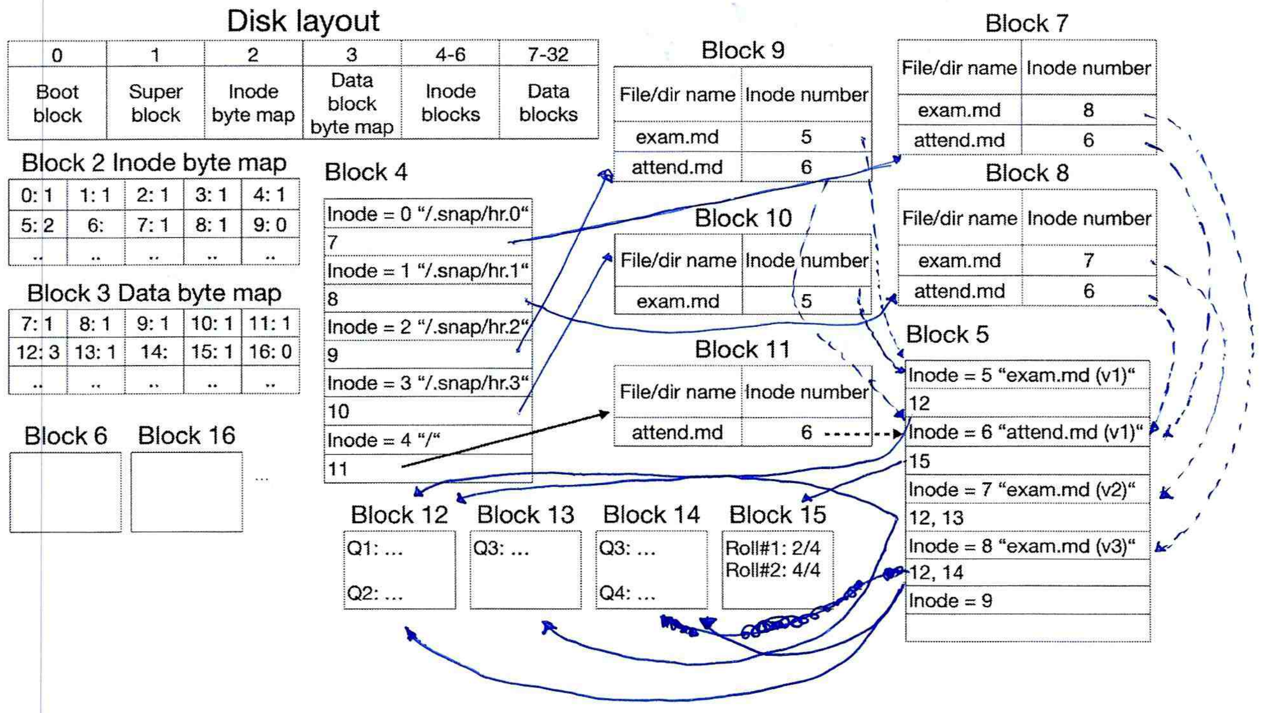
```
$ ls -lh /.snap/*/exam.md
-rw-r--r--@ 1 user  group  1002 Feb 24 11:00 /.snap/hr.0/exam.md
-rw-r--r--@ 1 user  group   958 Feb 24 10:00 /.snap/hr.1/exam.md
-rw-r--r--@ 1 user  group   512 Feb 24 09:00 /.snap/hr.2/exam.md
-rw-r--r--@ 1 user  group   512 Feb 24 08:00 /.snap/hr.3/exam.md
```

The user can recover the most recent version by copying it:

```
$ cp /.snap/hr.0/exam.md /
```

One naive approach to implement snapshotting would be to copy the entire file system every hour. But this approach will be very slow. It also wastes disk space: if most files are not changed across snapshots, we are unnecessarily creating copies of it.

Therefore, we try to use a *copy-on-write* approach to share blocks across the current file system and the snapshots. The following shows the state of our file system with four hourly snapshots. We assume that each inode block contains 5 inodes each. Inodes 0, 1, 2, 3, and 4 are in block 4. Inodes 0, 1, 2, and 3 contain hourly snapshots and inode 4 contains the current file system.



0	1	2	3	4-6	7-32
Boot block	Super block	Inode byte map	Data block byte map	Inode blocks	Data blocks

Block 2 Inode byte map

0: 1	1: 1	2: 1	3: 1	4: 1
5: 2	6:	7: 1	8: 1	9: 0
..	..	..	..	..

Block 3 Data byte map

7: 1	8: 1	9: 1	10: 1	11: 1
12: 3	13: 1	14:	15: 1	16: 0
..	..	..	..	..

Block 4

Inode = 0 "/.snap/hr.0"
7
Inode = 1 "/.snap/hr.1"
8
Inode = 2 "/.snap/hr.2"
9
Inode = 3 "/.snap/hr.3"
10
Inode = 4 "/"
11

Block 9

File/dir name	Inode number
exam.md	5
attend.md	6

Block 10

File/dir name	Inode number
exam.md	5

Block 11

File/dir name	Inode number
attend.md	6

Block 7

File/dir name	Inode number
exam.md	8
attend.md	6

Block 8

File/dir name	Inode number
exam.md	7
attend.md	6

Block 5

Inode = 5 "exam.md (v1)"
12
Inode = 6 "attend.md (v1)"
15
Inode = 7 "exam.md (v2)"
12, 13
Inode = 8 "exam.md (v3)"
12, 14
Inode = 9

Block 12	Block 13	Block 14	Block 15
Q1: ... Q2: ...	Q3: ...	Q3: ... Q4: ...	Roll#1: 2/4 Roll#2: 4/4

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Q6.1 [2 marks]: Draw solid arrows from inodes to data blocks and dotted arrows from directory entries to inodes. Two examples are already drawn in the figure.

The file system described above is as follows. The (v1), (v2), etc. annotations in block 5 are only shown for clarity.

```
/
├── .snap
│   ├── hr.0
│   │   ├── attend.md
│   │   └── exam.md
│   ├── hr.1
│   │   ├── attend.md
│   │   └── exam.md
│   ├── hr.2
│   │   ├── attend.md
│   │   └── exam.md
│   └── hr.3
│       └── exam.md
└── attend.md
```

Byte maps to track reference counts: In the indexed file system, we kept inode (data block) bitmaps where we stored 0 if the inode (data block) is free. We modify this slightly for our snapshotting file system. The inode byte map (block 2) and the data block byte map (block 3) now store 1 byte for each inode and data block respectively. For each inode (data block), inode byte map (data block byte map) stores the number of incoming arrows to the inode (data block).

Q6.2 [1 mark]: What will be the byte map values for inode 6 and for data block 14 in the file system shown above.

Inode 6 : 4 Data Block ~~Inode~~ 14 : 1

Q6.3 [1 mark]: How many inode byte map blocks are required if this file system had 1000 inode blocks. Each inode byte map entry = 1 byte (

So we require $\lceil 1000/512 \rceil = 2$ inode byte map blocks)

Deduplication: Notice that this file system design is de-duplicating inodes and data blocks across snapshots. For example, `/.snap/hr.2/exam.md` and `/.snap/hr.3/exam.md` were identical. Therefore, their directory entries for `exam.md` point to the same inode number 5. Similarly, the first data block of `exam.md` was the same for all versions. Therefore, all `exam.md` inodes have the same first data block as 12.

Q6.4 [1 mark]: `/.snap/hr.1/exam.md` has more contents than `/.snap/hr.2/exam.md`.

[True/False] False

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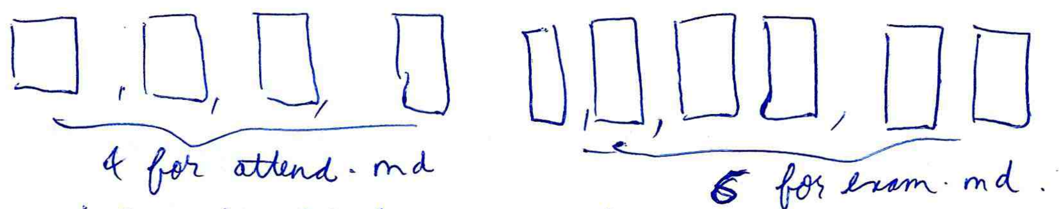
Q6.5 *[1 mark]:* `attend.md` has not changed in the last 2 hours.

[True/False] True

Q6.6 *[4 marks]*: With deduplication, we are able to store 4 snapshots and the current file system in 2 inode blocks (4, 5) and 9 data blocks (7-15). Calculate how many inode blocks and how many data blocks would be required for storing the same information if we were simply copying the file system for creating snapshots i.e, without any deduplication.

Hint: Redraw the disk blocks when there is no deduplication.

Disk blocks without deduplication -



10 disk blocks instead of 4.

We will have 8 entries in inode instead of 4 (for each of the 4 attend.md & 6 exam.md disk blocks)

So we would require $\lceil 8/5 \rceil = 2$ inode blocks now instead of 1 for files. We already have 1 for directory inode

3 inode blocks

10+5 data blocks
= 15 data blocks (disk file + directory)

Copy on write.

Now, whenever we are modifying an inode (or a data block), we first check if the corresponding byte map value is greater than 1. If it is, that means the inode (data block) is also being referenced from earlier snapshots. In such cases, we instead copy the inode (data block). For example, at hr.0, the user appended "Q4" to the exam.md file. At that point, instead of directly changing inode 7 and data block 13, the file system created a new inode 8 and data block 14.

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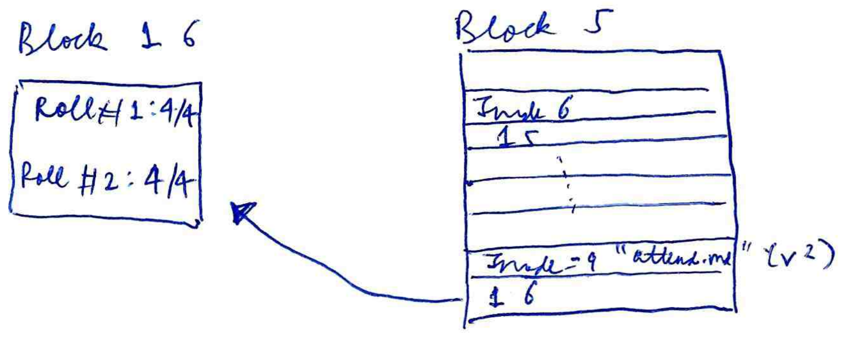
Q6.7 [3 marks]: Let us say the user wants to update the attendance of Roll#1 to 4/4 from 2/4 in `attend.md`. Redraw only the changed blocks below.



Snapshotting. At each hour, we want to snapshot the current file system state. In particular,

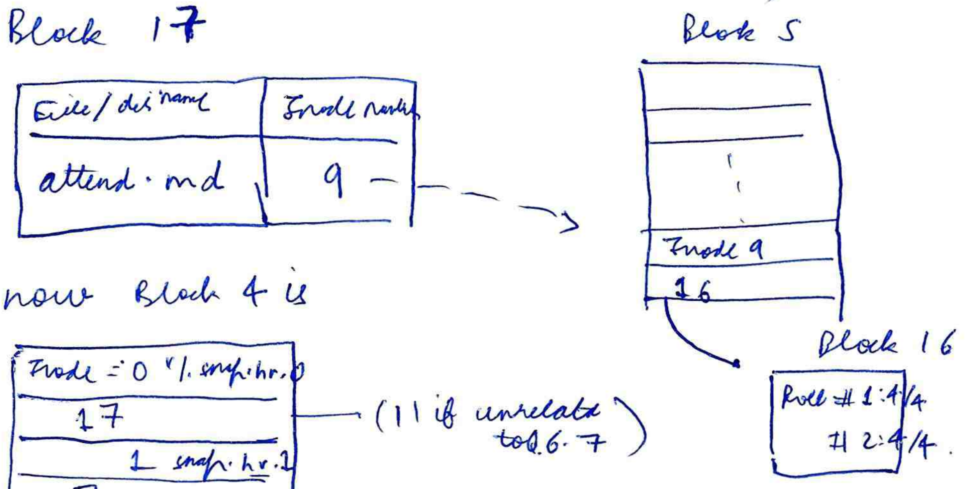
- `/.snap/hr.0` should contain what `/` contained before the snapshot,
- `/.snap/hr.1` should contain what `/.snap/hr.0` contained before the snapshot,
- `/.snap/hr.2` should contain what `/.snap/hr.1` contained before the snapshot,
- `/.snap/hr.3` should contain what `/.snap/hr.2` contained before the snapshot.

Q6.8 [3 marks]: Modify and redraw the state of the disk blocks after a new snapshot has been created. Try to change the least number of blocks.

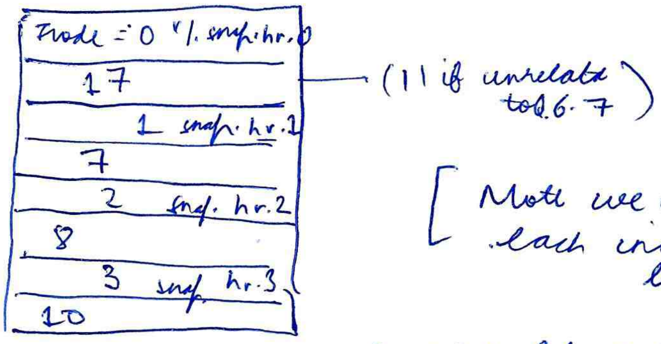
Based on state ~~[illegible]~~ changed after Q6.7 (attend.md changed) (unrelated to Q6.7)

A new disk block pointed ~~[illegible]~~ by (Inode 0) is created.

Block 17



So, now Block 4 is



[Note we can just shift each inode entries block by 1]

Added only 1 disk block (17) → no add if unrelated to 6.7

(Rest blocks, 7, 8, 9, 10, 11, 12, 13, 14, 15 are same)

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Crash consistency. Let us say that we "recover" the file system after a crash by simply reverting to the last snapshot. Therefore, we are not doing any kind of write ahead logging.

Q6.9 [3 marks]: Describe an ordering based approach to create a new snapshot which also cleans up the oldest snapshot. For simplicity, assume we are blocking all other file system operations while we are creating the snapshot. Argue why this ordering cannot lead to dangling pointers.

So similar to previous ~~quest~~ answer, we assign inode pointers by shifting the old hr. 0 to hr. 1 pointers and so on. Note that the old "oldest" snapshot is cleaned because we don't assign its pointer to any "new" snapshot. Therefore, we simply remove it from the inode block (block 4 in this case). Since we never cleared memory yet, we can't have dangling pointers. Once this is done, we unlink the dir block, clear ~~it~~ from file inode block, and unlink them in order to avoid dangling ptrs & memory leaks (clear the old snapshot file) (Child then parent approach)

Q6.10 [3 marks]: Is creating a snapshot a fast or a slow operation? Justify your answer.

Creating a snapshoft is a fast operation because we do not need to change all directory disk blocks but rather shift the pointers to inodes (such as assign old hr. 0 to hr. 1's inode and so on) Since we maintain only limited snapshots, this is a constant time operation (O(#snapshots)) Also note we might need to add a new disk block (only 1) reflecting changes in "/" but it is also const time, so fast operation.

Q6.11 [2 marks]: Contrast this file system with the ext3 file system studied in the class. What are the pros and cons?

Pros: It allows very fast ~~recovery~~ snapshot creation due to copy on write and helps in version control (maintaining multiple versions of the file) compared to the ext3 file system

Cons: It may lead to space/memory leaks because it involves a lot of disk blocks maintenance if we do not appropriately perform the operations.