How ZFS Snapshots Really Work

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DELPHIX

What are snapshots?

- Store an old “copy” of the data
- “Oops” recovery
- Malware recovery
- Replication with zfs send/receive

How to use snapshots

```
zfs snapshot pool/fs@snap
zfs snapshot -r pool@snap
zfs destroy pool/fs@snap
zfs send -i @oldsnap pool/fs@newsnap | \
    ssh … zfs receive …
zfs get … pool/fs@snap
```

How to use snapshots

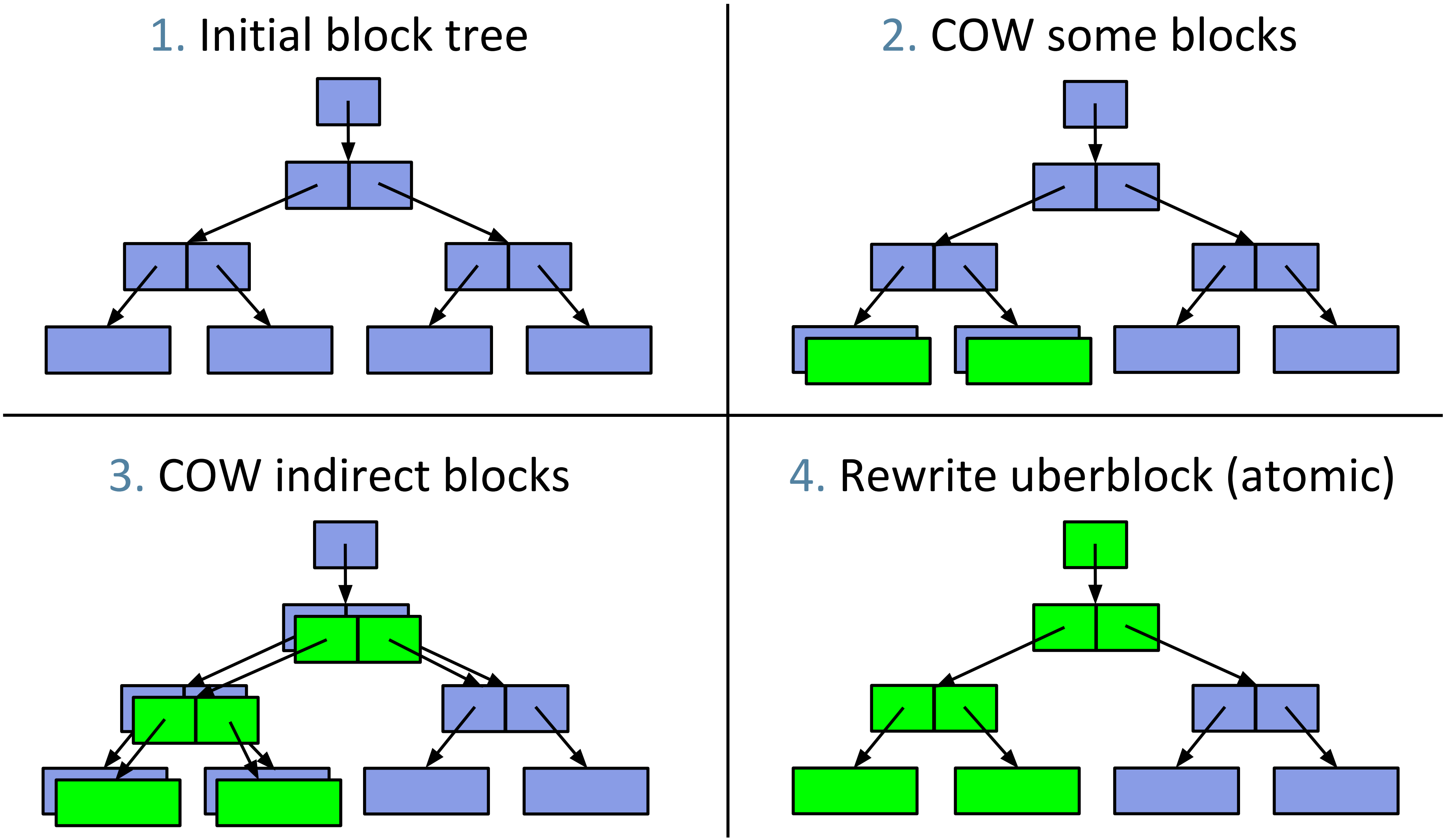
1. Take a snapshot of every filesystem every hour

    (8700 snapshots per filesystem per year)

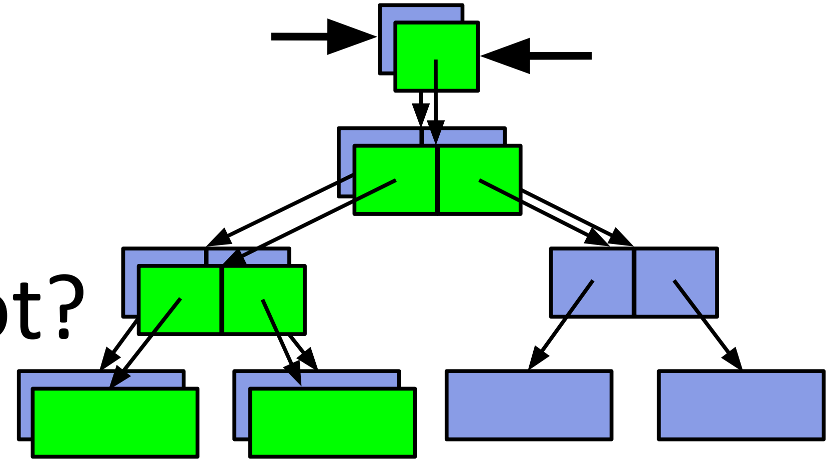
2. …
3. Wonder where all your space went

How do snapshots work?

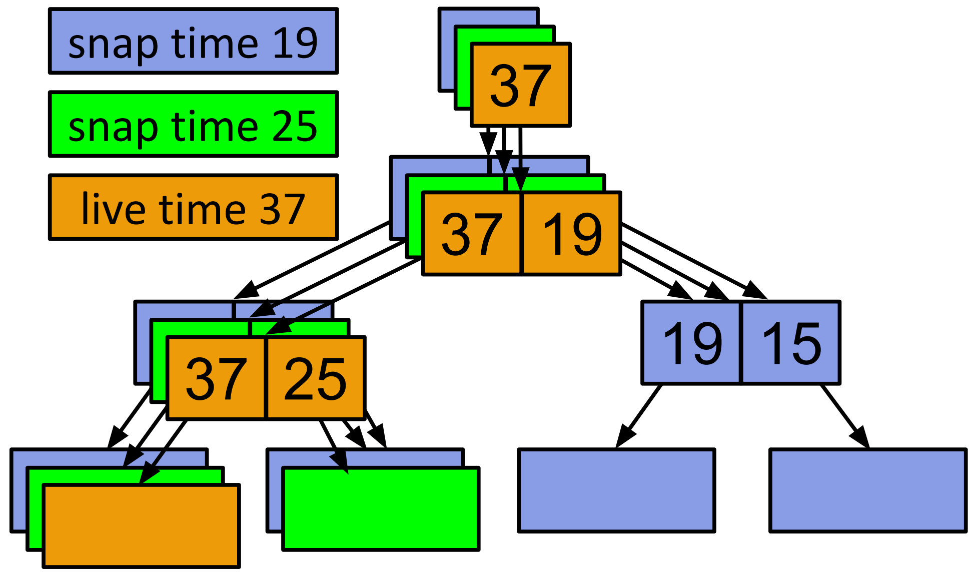
Copy-On-Write Transaction Groups (TXG's)



ZFS Snapshots



- How to create snapshot?
  - Save the root block
- When block is removed, can we free it?
  - Use BP's birth time
  - If birth > prevsnap
    - Free it

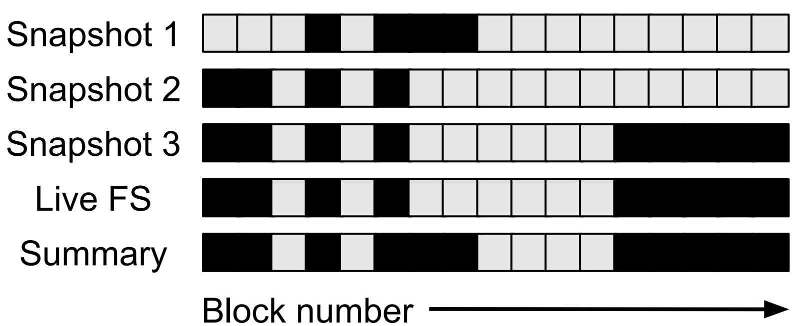


- When delete snapshot, what to free?
  - Find unique blocks - Tricky!

Trickiness will be worth it!

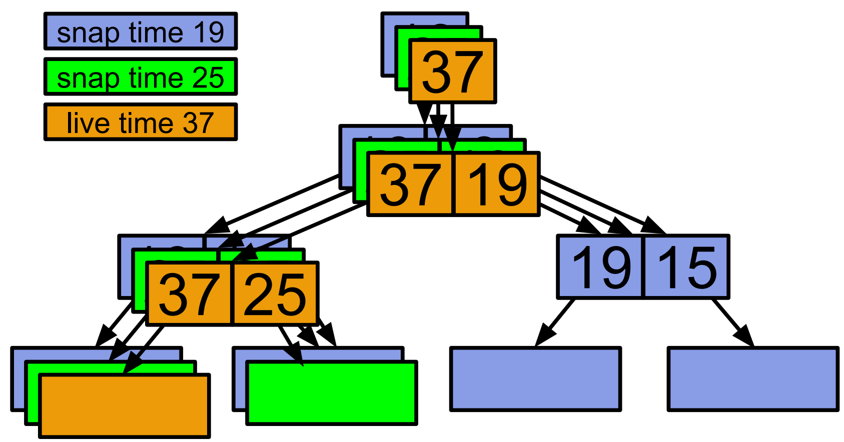
Per-Snapshot Bitmaps

- Block allocation bitmap for every snapshot
  - O(N) per-snapshot space overhead
  - Limits number of snapshots
- O(N) create, O(N) delete, O(N) incremental
  - Snapshot bitmap comparison is O(N)
  - Generates unstructured block delta
  - Requires some prior snapshot to exist



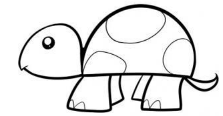
ZFS Birth Times

- Each block pointer contains child's birth time
  - O(1) per-snapshot space overhead
  - Unlimited snapshots
- O(1) create, O(Δ) delete, O(Δ) incremental
  - Birth-time-pruned tree walk is O(Δ)
  - Generates semantically rich object delta
  - Can generate delta since any point in time

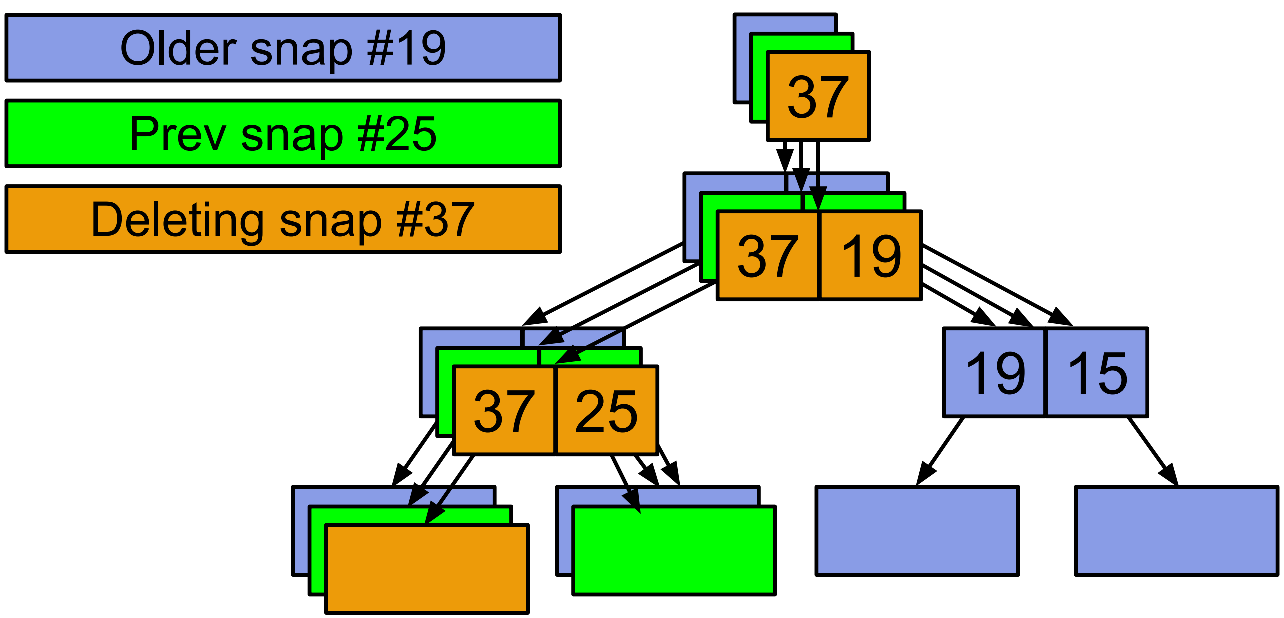


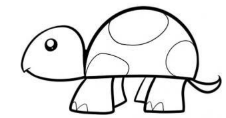
Snapshot Deletion

- Free unique blocks (ref'd only by this snap)
- Optimal algo: O(# blocks to free)
  - And # blocks to read from disk << # blocks to free
- Block lifetimes are contiguous
  - AKA "there is no afterlife"
  - Unique = not ref'd by prev or next (ignore others)

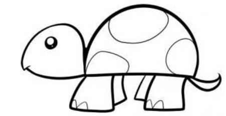
Snapshot Deletion ()

- Traverse tree of blocks
- Birth time <= prev snap?
  - Ref'd by prev snap; do not free.
  - Do not examine children; they are also <= prev



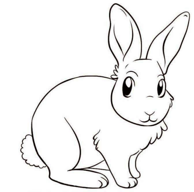
Snapshot Deletion ()

- Traverse tree of blocks
- Birth time <= prev snap?
  - Ref’d by prev snap; do not free.
  - Do not examine children; they are also <= prev
- Find BP of same file/offset in next snap
  - If same, ref’d by next snap; do not free.
- O(# blocks written since prev snap)
- How many blocks to read?
  - Could be 2x # blocks written since prev snap

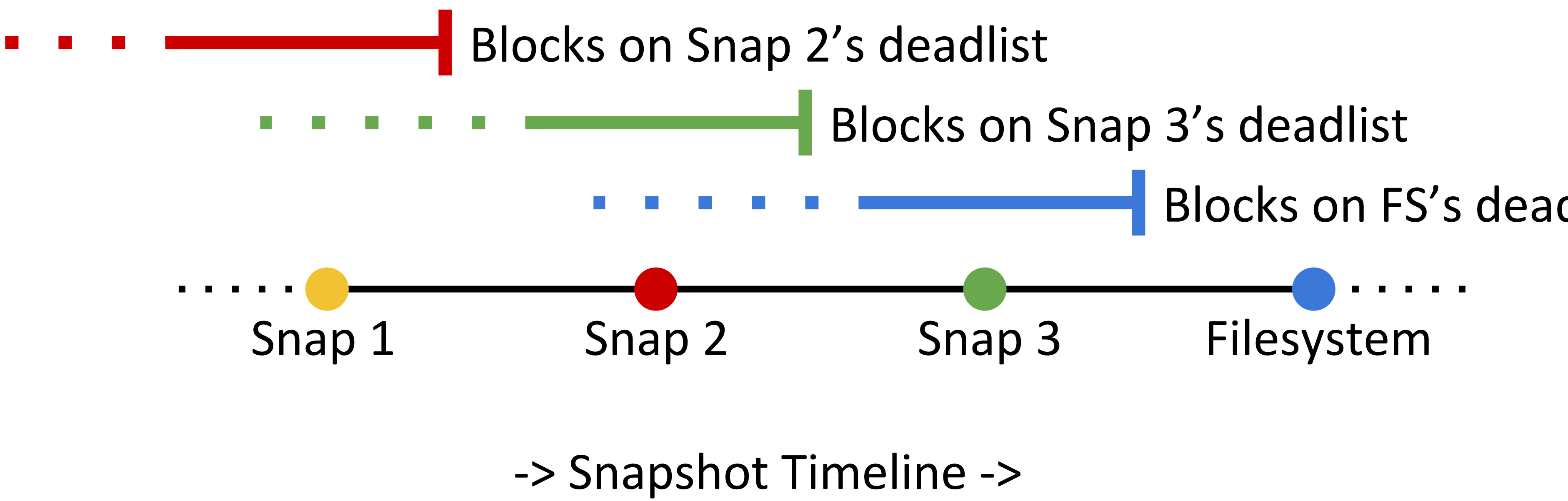
Snapshot Deletion ()

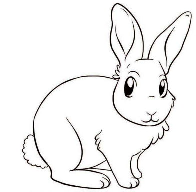
- Read Up to 2x # blocks written since prev snap
- Maybe you read a million blocks and free nothing
  - (next snap is identical to this one)
- Maybe you have to read 2 blocks to free one
  - (only one block modified under each indirect)
- RANDOM READS!
  - 200 IOPS, 8K block size -> free 0.8 MB/s
  - Can write at ~200MB/s

FIGURE 131. Hourglass

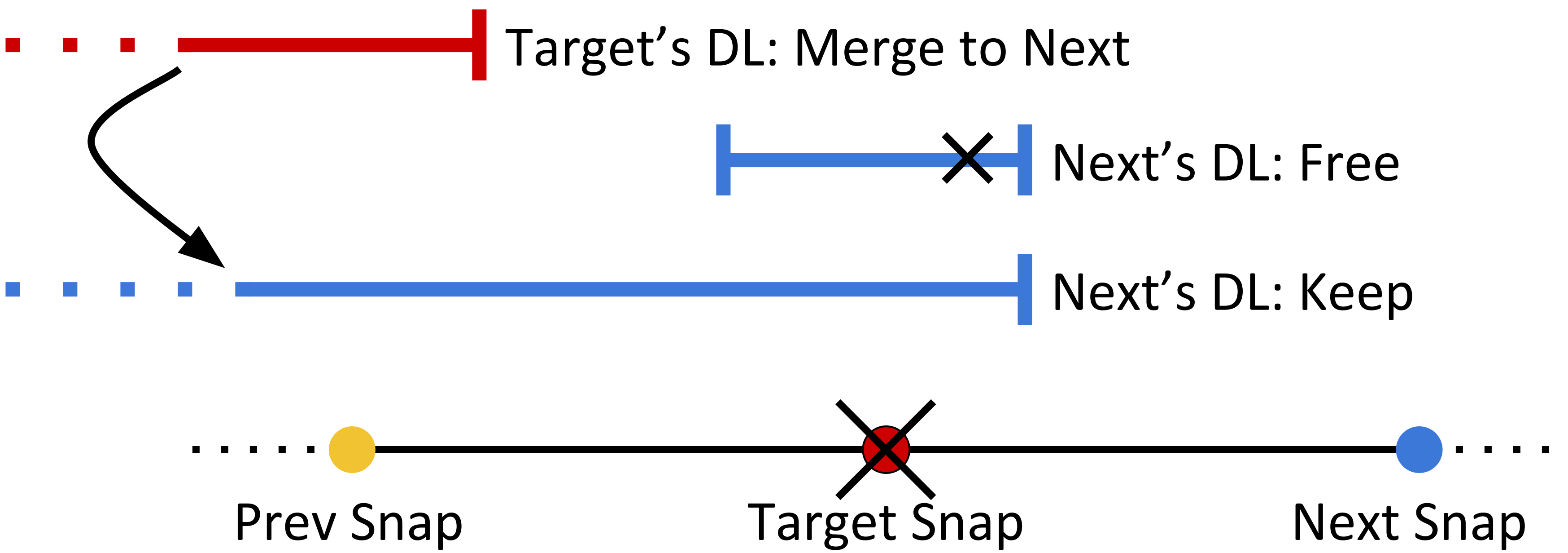
Snapshot Deletion ()

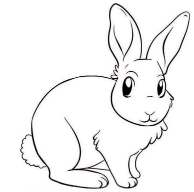
- Keep track of no-longer-referenced ("dead") blocks
- Each dataset (snapshot & filesystem) has "dead list"
  - On-disk array of block pointers (BP's)
  - blocks ref'd by prev snap, not ref'd by me



Snapshot Deletion ()

- Traverse next snap's deadlist
- Free blocks with birth > prev snap



Snapshot Deletion ()

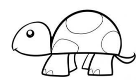
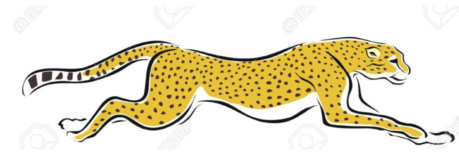
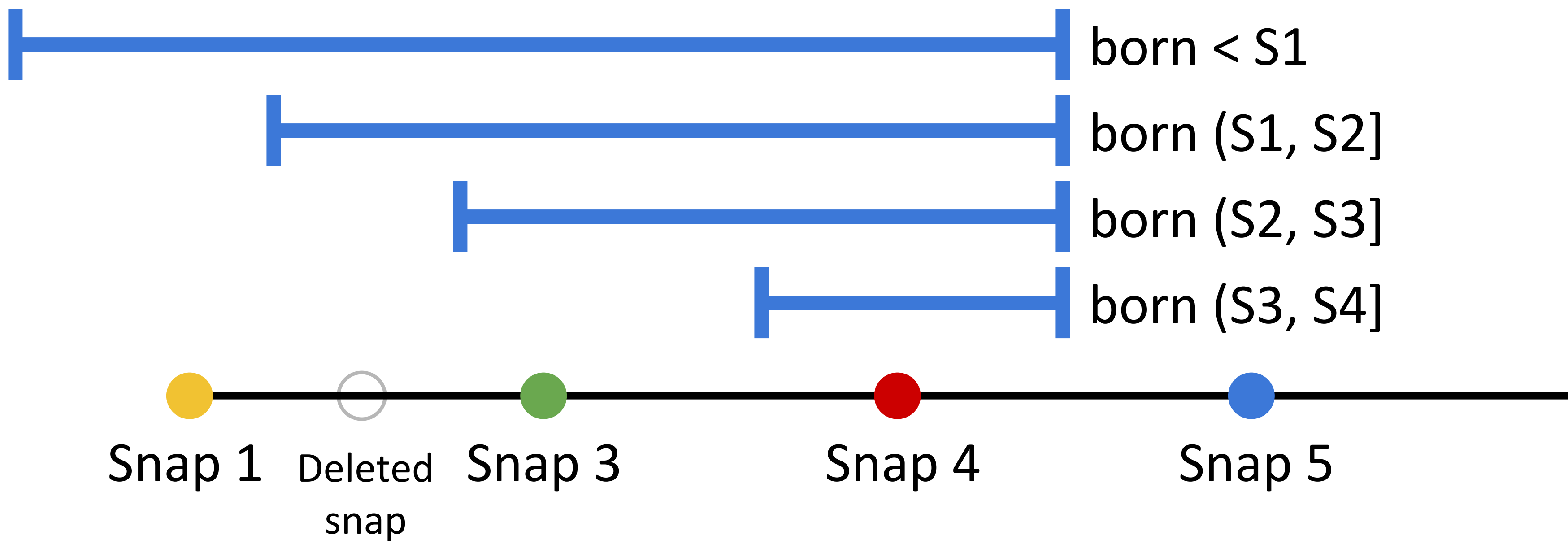
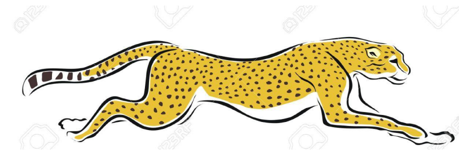
- O(size of next's deadlist)
  - = O(# blocks deleted before next snap)
  - Similar to  (# deleted ~= # created)
- Deadlist is compact!
  - 1 read = process 1024 BP's
  - Up to 2048x faster than Algo 1!
- Could still take a long time to free nothing

FIGURE 131. Hourglass

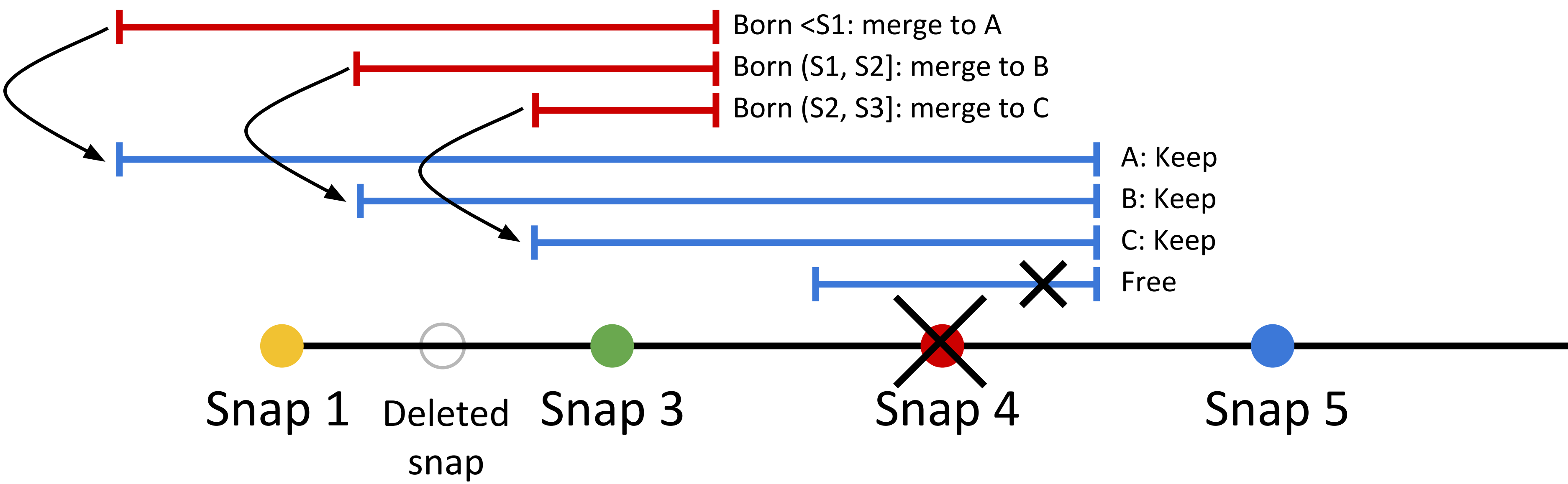
Snapshot Deletion ()

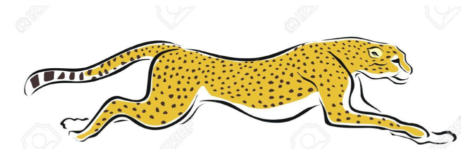
- Divide deadlist into sub-lists based on birth time
- One sub-list per earlier snapshot
  - Delete snapshot: merge FS's sublists



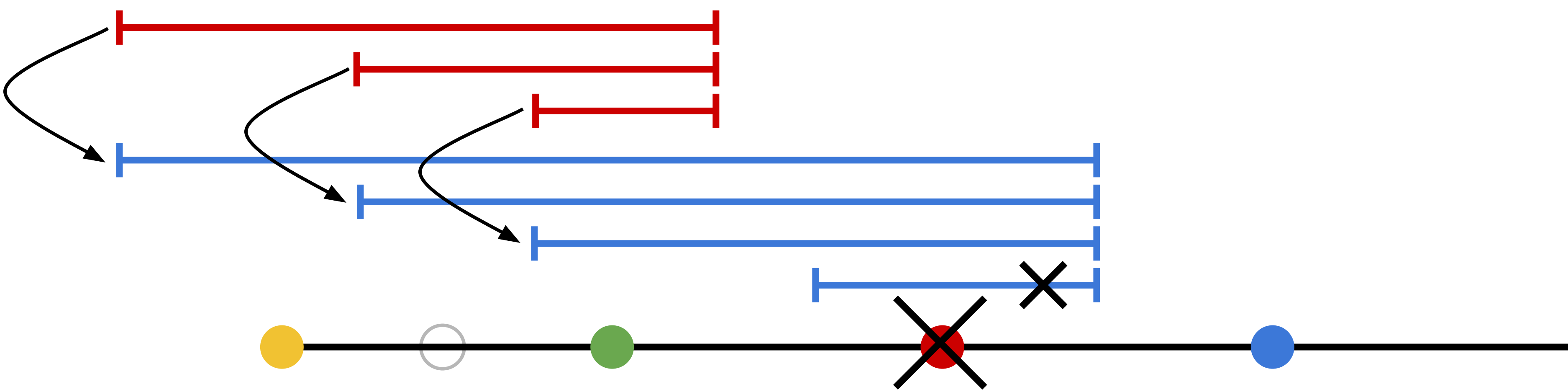
Snapshot Deletion ()

- Iterate over sublists
- If mintxg > prev, free all BP’s in sublist
- Merge target’s deadlist into next’s
  - Append sublist by reference -> O(1)



Snapshot Deletion ()

- Deletion: O(# sublists + # blocks to free)
  - 200 IOPS, 8K block size -> free 1500MB/sec
- Optimal: O(# blocks to free)
- # sublists = # snapshots present when snap created
- # sublists << # blocks to free



Where did all the space go?

How much space are the snapshots using?

```
$ zfs list
NAME                    USED  AVAIL  REFER  MOUNTPOINT
rpool                   1000G  100G    50K  /rpool
rpool/fs                1000G  100G   700G  /rpool/fs

$ zfs get usedbysnapshots pool/fs
300G
```

How much space would be recovered if all of this fs's snapshots were destroyed.

I.e. How much storage am I paying for all these snapshots?

How much space are the snapshots using?

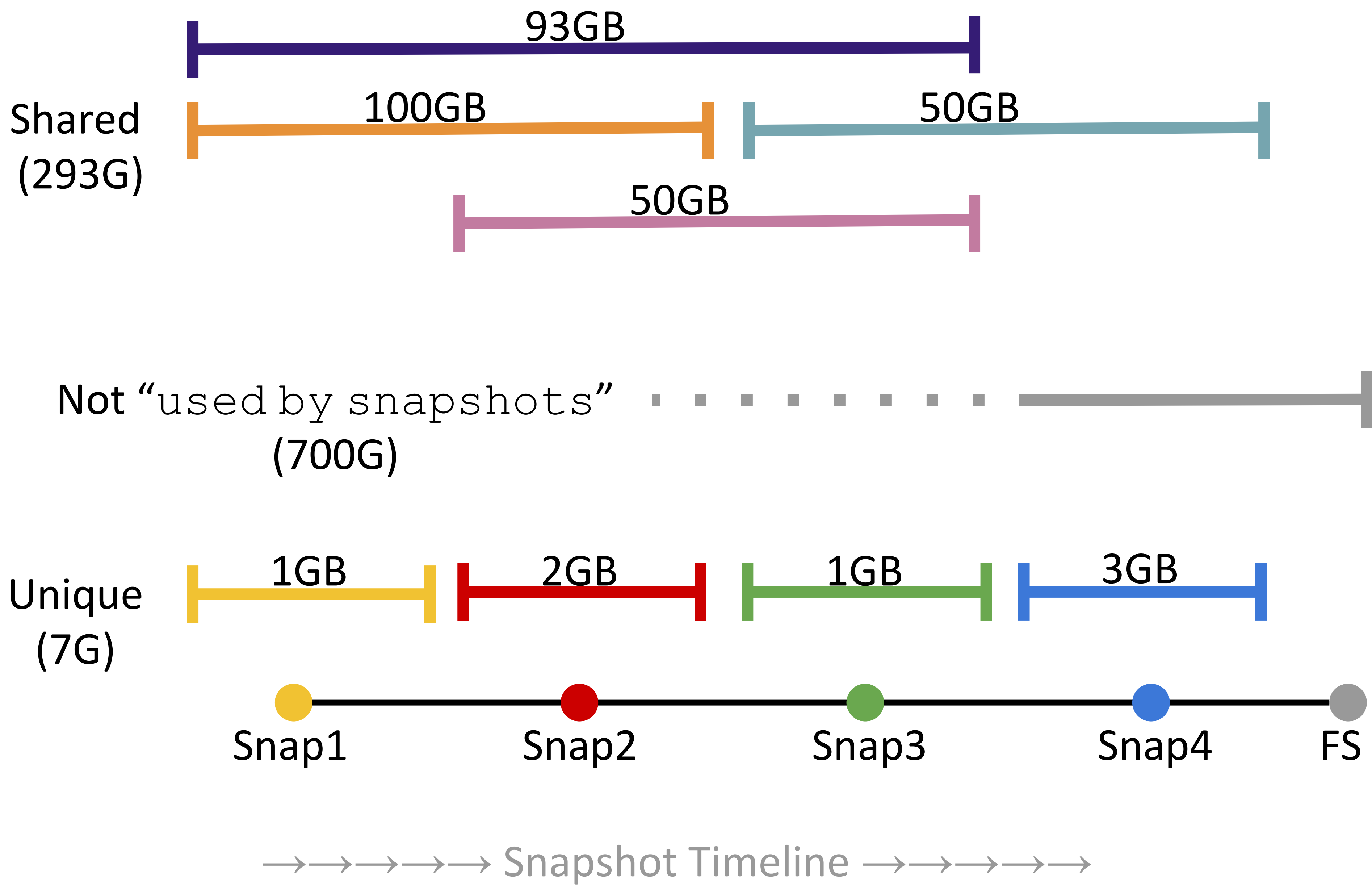
```
$ zfs list -t all
NAME                    USED  AVAIL  REFER  MOUNTPOINT
rpool                  1000G   100G    50K  /rpool
rpool/fs               1000G   100G   700G  /rpool/fs
rpool/fs@snap1            1G      -   699G  -
rpool/fs@snap2            2G      -   699G  -
rpool/fs@snap3            1G      -   700G  -
rpool/fs@snap4            3G      -   700G  -

$ zfs get usedbysnapshots pool/fs
300G
```

How much space would be recovered if each snapshot was destroyed?

1+2+1+3 = 7G ≠ 300G

What about the other 293GB?

Snapshots' "`used`" is "`unique`"


93GB
Shared
(293G)
100GB
50GB
50GB
Not "used by snapshots"
(700G)
Unique
(7G)
1GB
2GB
1GB
3GB
Snap1
Snap2
Snap3
Snap4
FS
→→→→→ Snapshot Timeline →→→→→

How much space is being used?

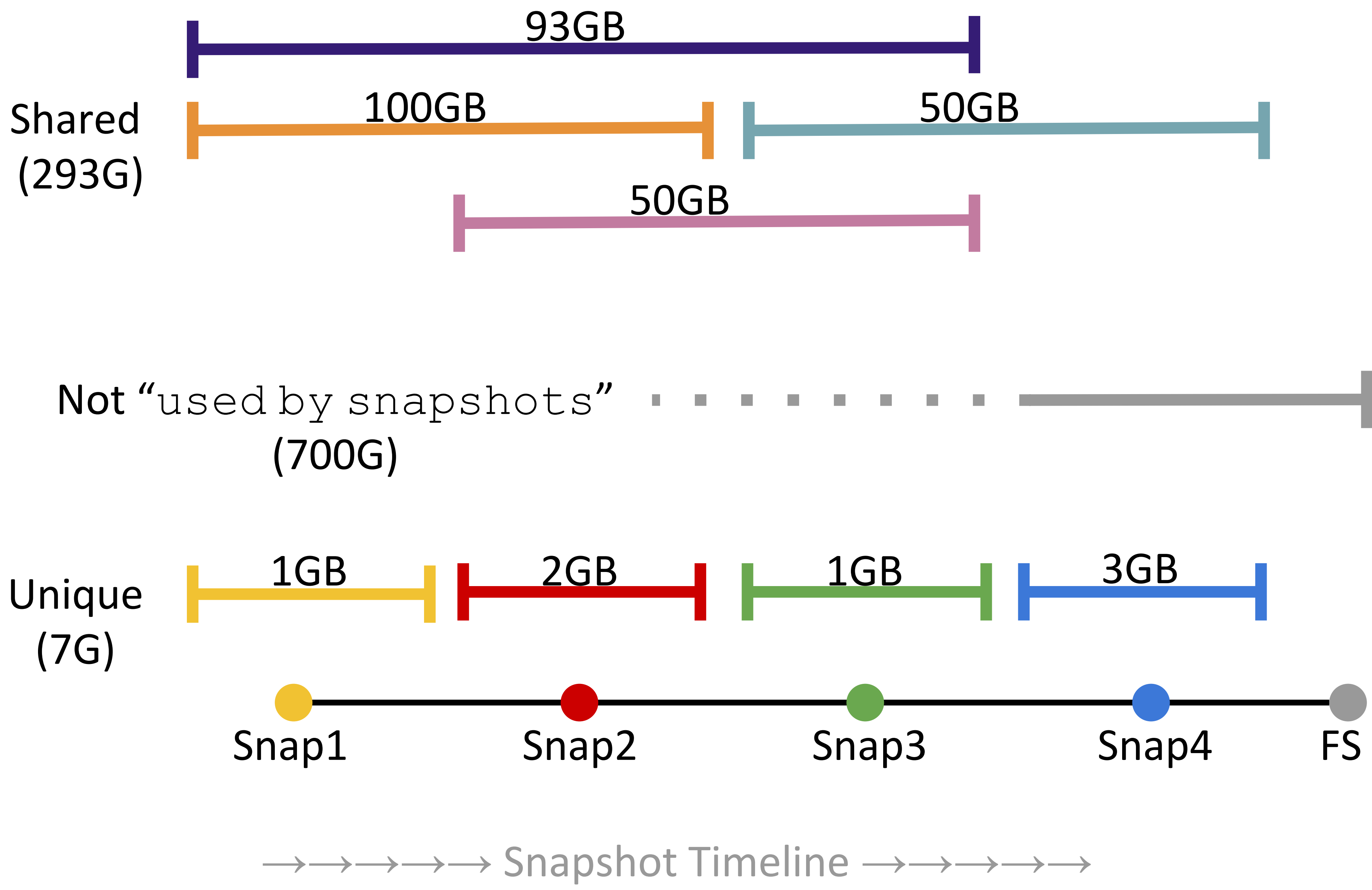
```
$ zfs list -t all -o name,written,used,refer rpool/fs
NAME                    WRITTEN   USED   REFER
rpool/fs                      0  1000G    700G
rpool/fs@snap1             894G     1G    699G
rpool/fs@snap2              52G     2G    699G
rpool/fs@snap3              51G     1G    700G
rpool/fs@snap4               3G     3G    700G

$ zfs get usedbysnapshots pool/fs
300G
```

Sum of `written` = FS's `used`

0 + 894 + 52 + 51 + 3 = **1000G**

FS's `referenced` + `usedbysnapshots` = `used`

700 + 300 = **1000G**


93GB
Shared
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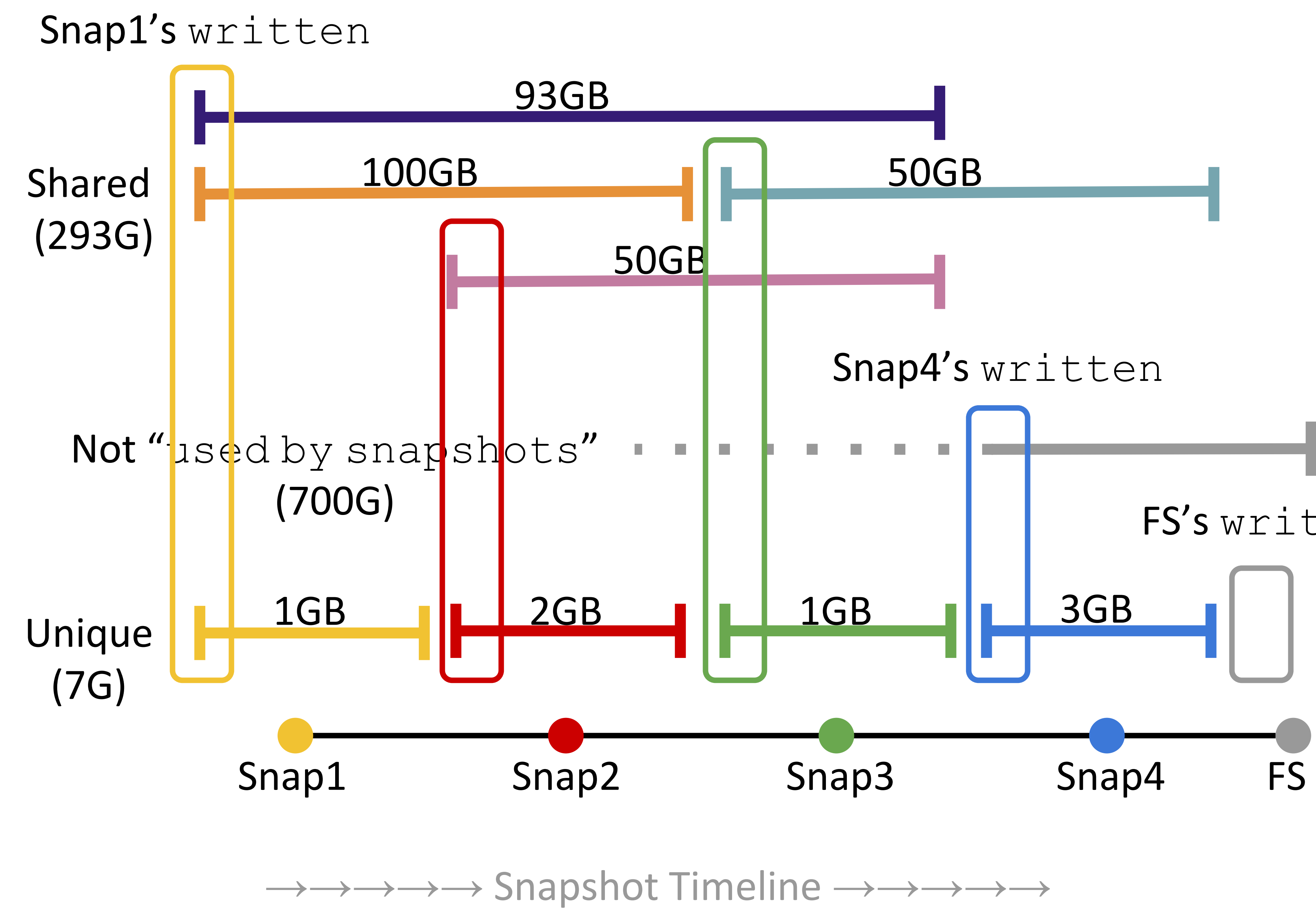
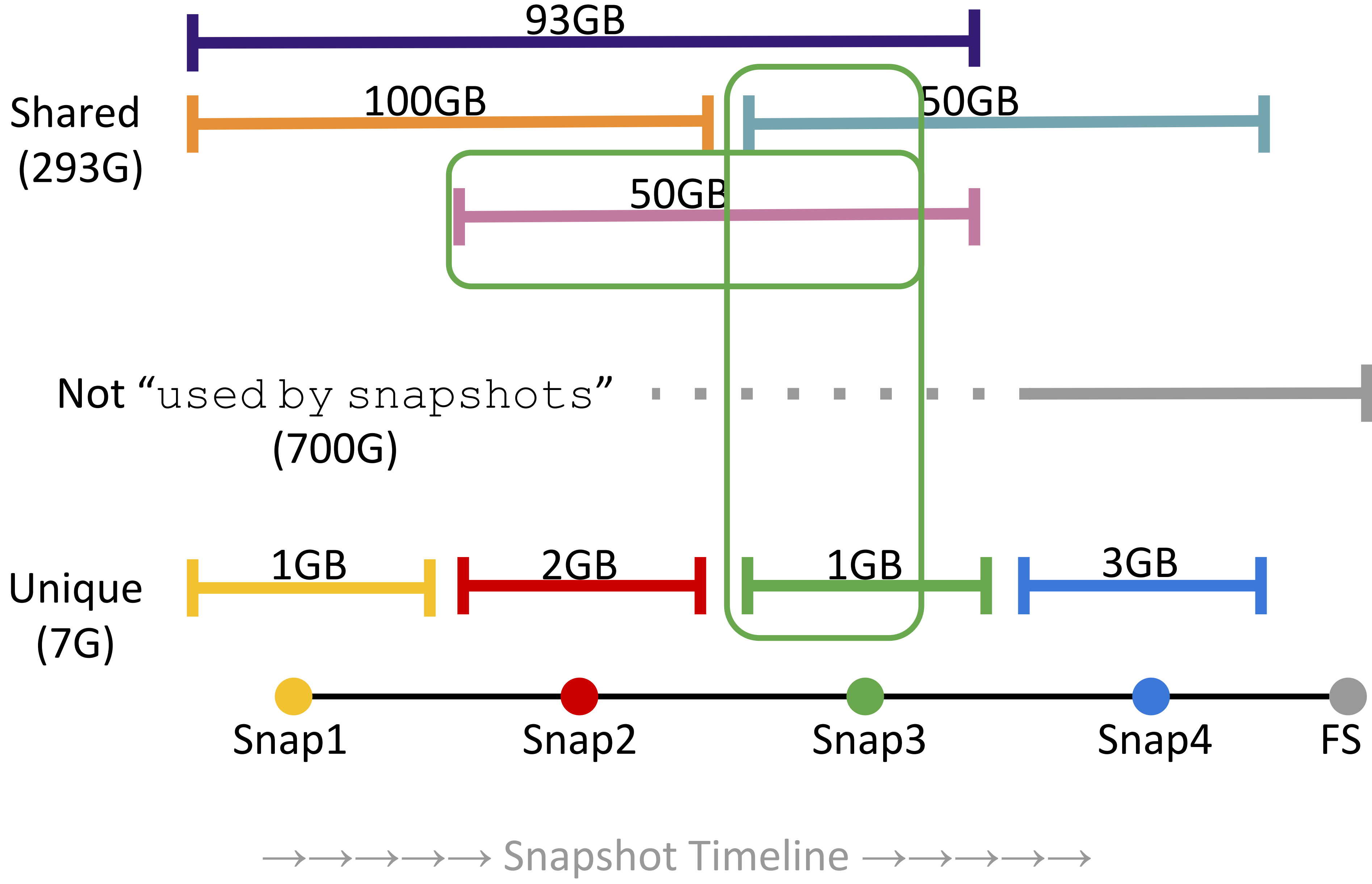
Snap3
Snap4
FS
→→→→→ Snapshot Timeline →→→→→



Snap1's written
93GB
Shared (293G)
100GB
50GB
50GB
Snap4's written
Not "used by snapshots" (700G)
FS's writ
Unique (7G)
1GB
2GB
1GB
3GB
Snap1
Snap2
Snap3
Snap4
FS
→→→→→ Snapshot Timeline →→→→→

Snap3's `written@snap1 = 50+50+1 = 101GB`



How does `written@old` work?

- Can’t quickly find “blocks born in this txg range that exist in this snapshot”
  - Deadlists store blocks that were killed
  - We are interested in some blocks that are still alive
- New’s `refer` - old’s `refer` + space freed in between
- Deadlists tell us what was freed
- Written
  - Examine one sublist
  - O(1)
- written@...
  - Examine all snapshots in between
    - Examine their sublists for births < old
  - O(num_snaps_between_old_and_new * num_snaps_before_old)

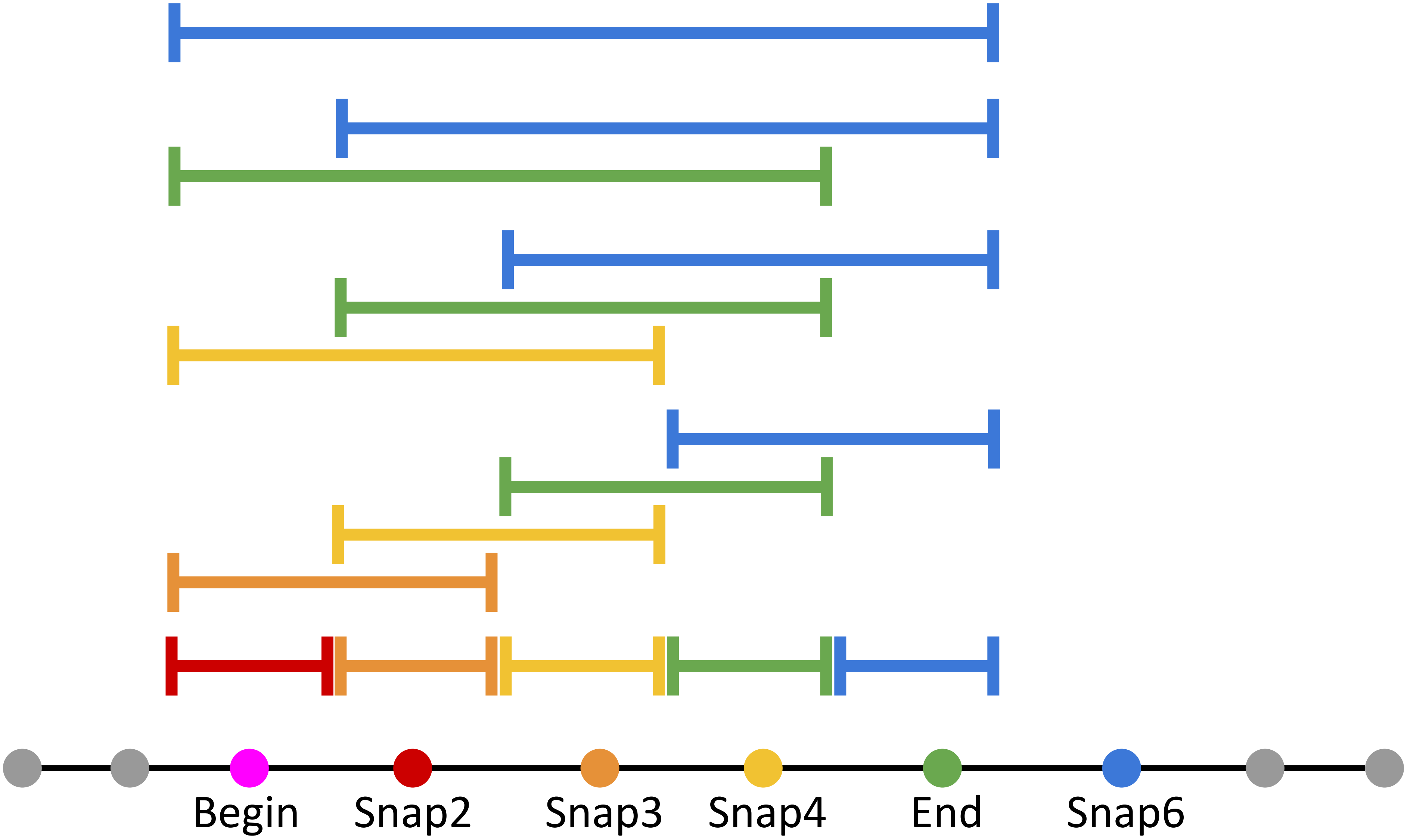
How to understand shared snapshot space?

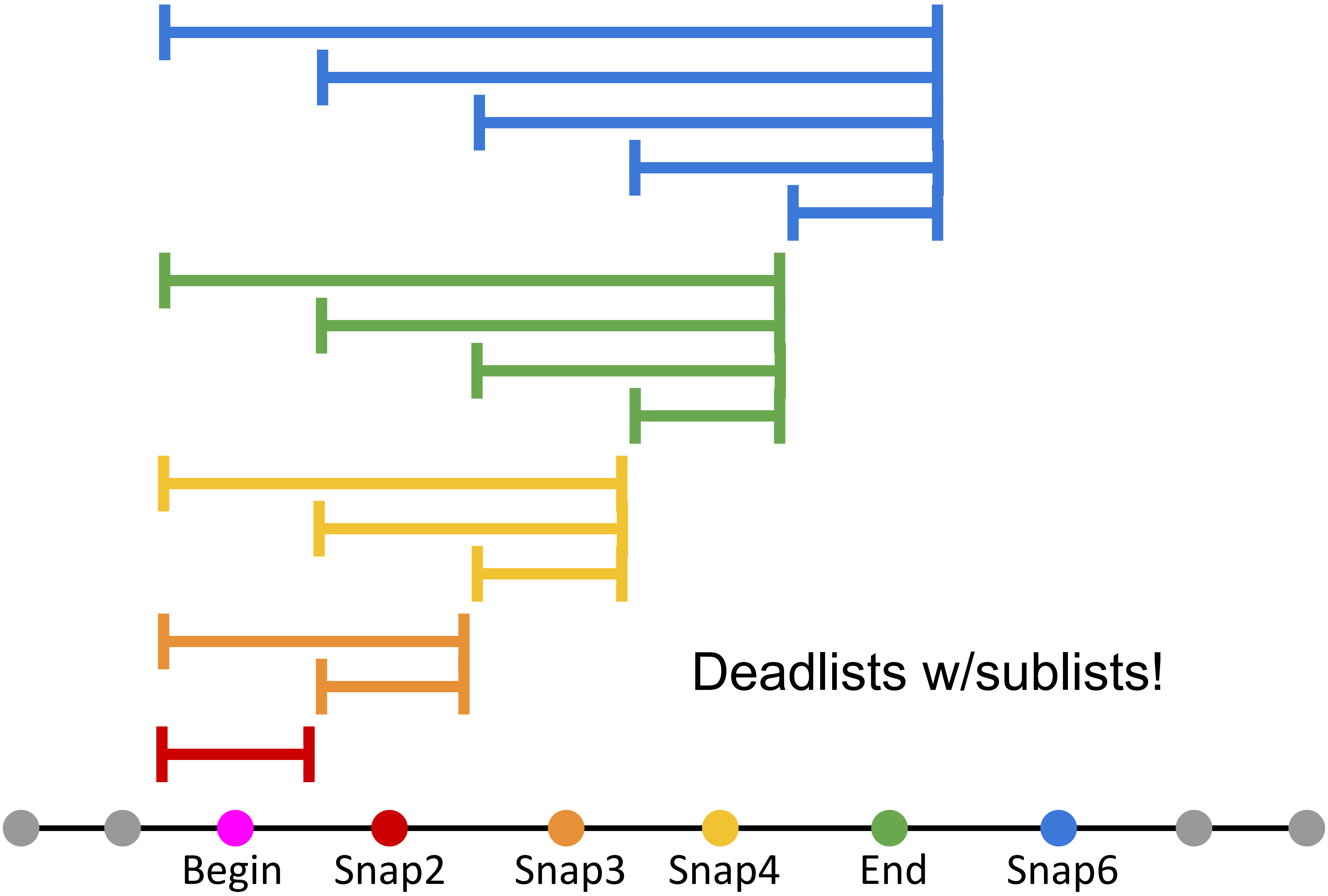
- What if we delete some of the snapshots?
  - `zfs destroy -nv pool/fs@begin%end`
  - `zfs destroy -nv pool/fs@a,b,j,k,z`
- How to use
  - Categorize snap space into different (application-defined) classes
  - E.g. space for periodic snapshots vs user-requested snaps (but some space will be shared between classes too)

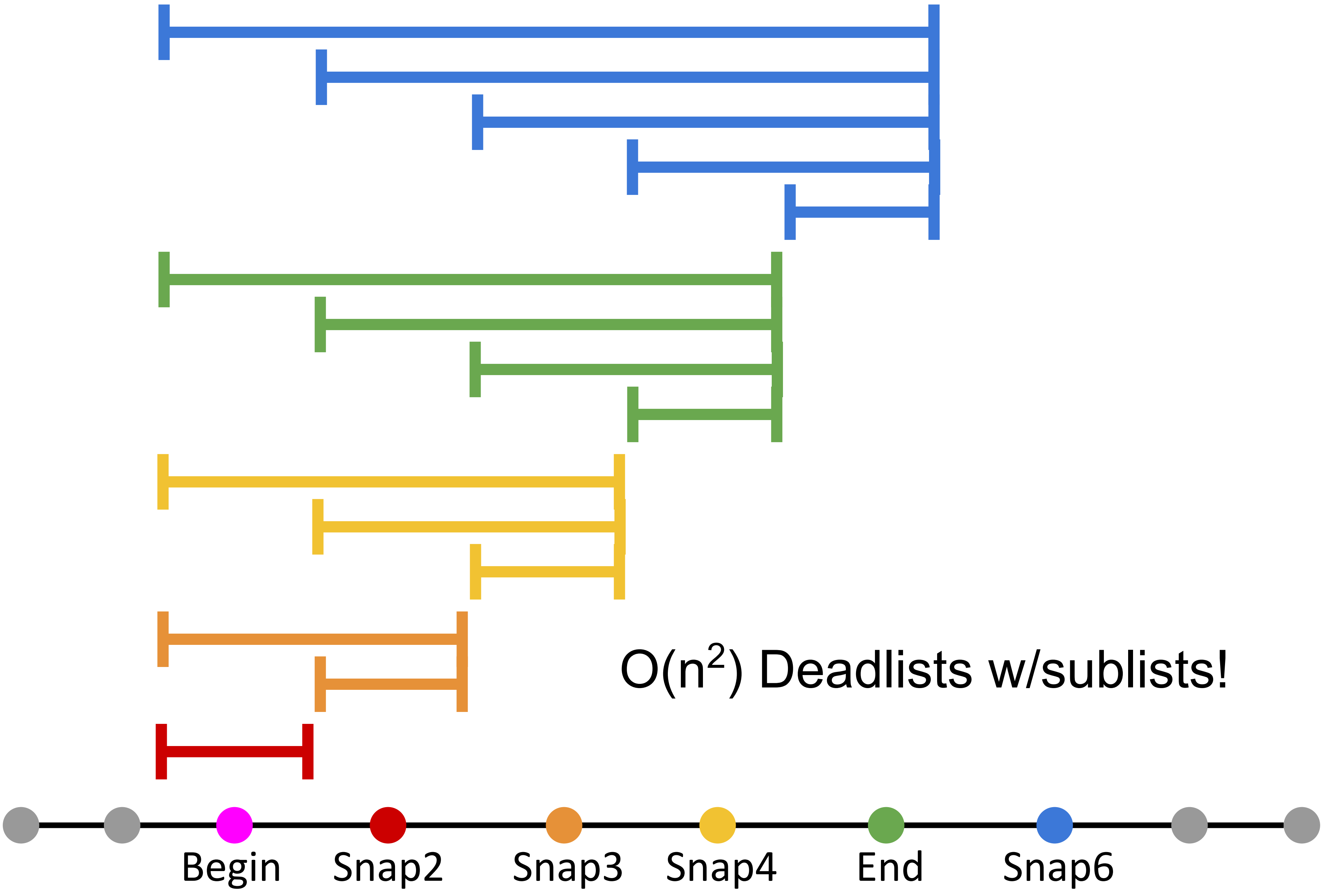
How to implement shared snapshot space?

- Corner cases:
  - One snapshot: same as `used` and `unique` properties
  - All snapshots: same as `used by snapshots` property
- General case:
  - Blocks born after begin->prev, died before end->next
  - Deadlist breakdown

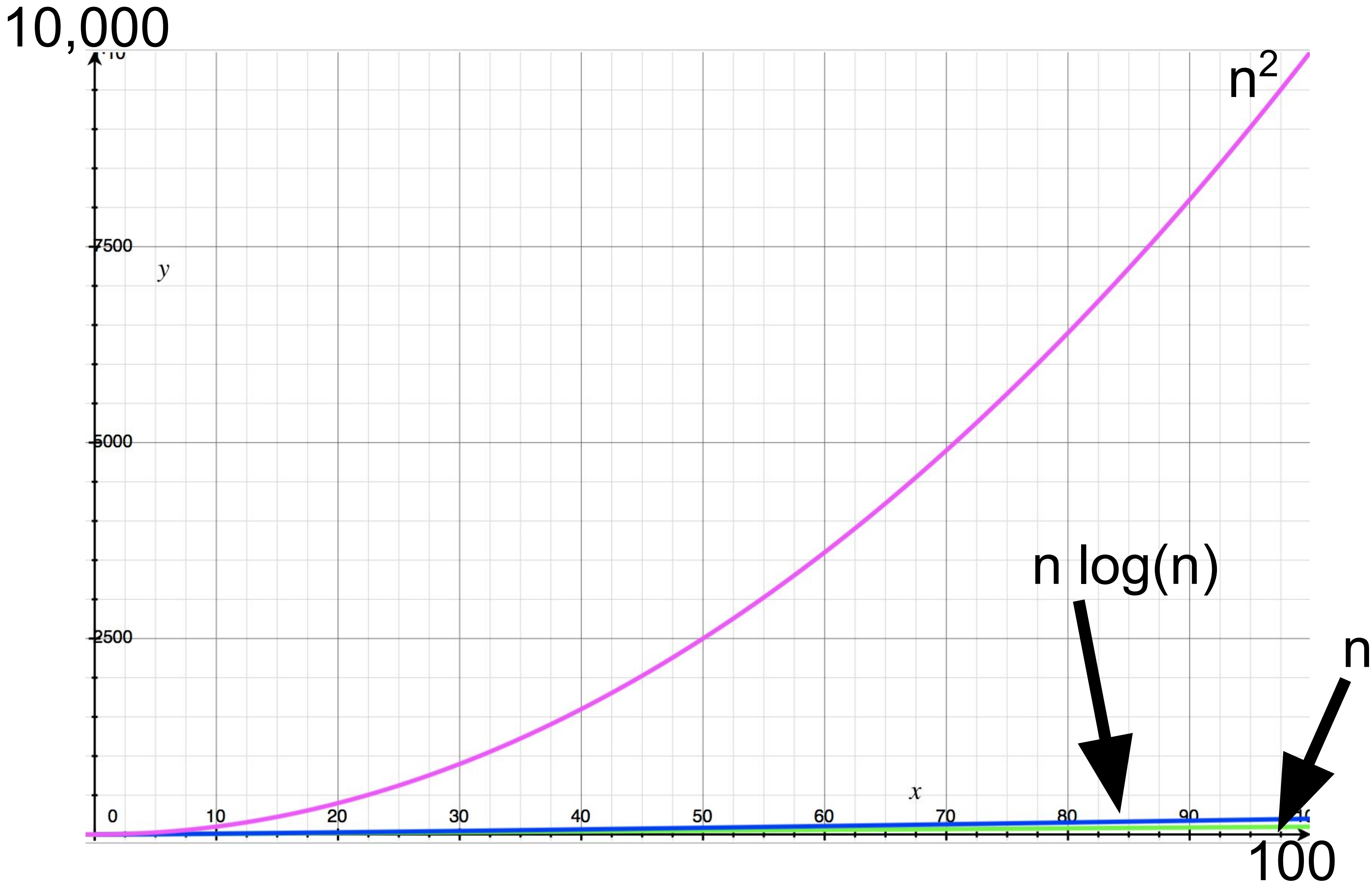
What if we delete Begin...End (5 snaps)?




Deadlists w/sublists!
Begin
Snap2
Snap3
Snap4
End
Snap6


O(n²) Deadlists w/sublists!
Begin
Snap2
Snap3
Snap4
End
Snap6

Fear $O(n^2)$



Fear $O(n^2)$

- About those 8700 snaps per year (per fs)...
- 75 Million lists!
  - Imagine each one is 1 sector (4K)
  - 288GB on disk (per fs)
- `zfs destroy -nv pool/fs@snap10%snap8690`
  - Read them all (at 10,000 iops) in 2 hours
  - While holding locks that prevent TXG sync

Fear $O(n^2)$?

Nearly all lists are empty

- Don't store them on disk (`empty_bpobj` feature, 2012)
  - 60 seconds (when ARC-cached)
- Partial deadlist load (ignore empty bpobj's)
  - 5x speed up → 12 sec
  - Review out
- Cache (partial) deadlist
  - Additional 70x speed up (350x from base) → 0.2 sec
  - Prototyped
- Still $O(n^2)$!

Confused by snapshot space usage?
You're not alone :-)

1. Look at `usedbysnapshots` first
2. Ignore snapshots' `used` (it's really `unique`)
3. `written` can help understand space growth
4. "What if" with `zfs destroy -nv pool/fs@<snaps>`

7th annual OZDS!
November 4-5, 2019
Talk proposals due Aug 19
Sponsorship opportunities