ZFS DIRECTORY SCALING

Look up and create files fast

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WHO AM I?

- FreeBSD committer since 2018 (0mp@)
- FreeBSD Core Team member
- Most days I work on cool stuff with folks @ Klara Inc.

- In general, I poke around things like:
  - Documentation
  - Ports
  - rc(8) scripts (script all the things!)
  - Tracing
  - ZFS

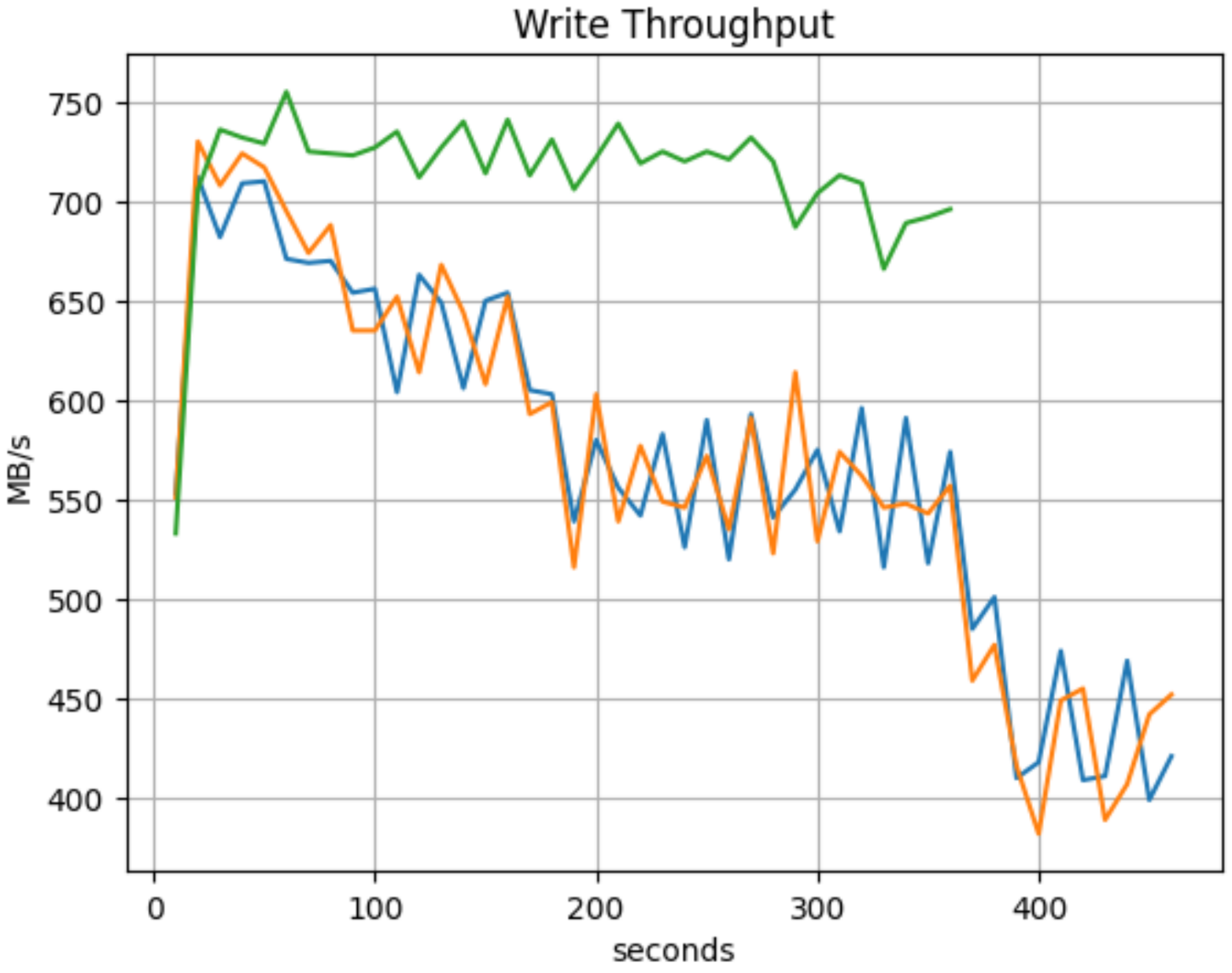
OUTLINE

ZFS

Directories

Scaling

Numbers


Write Throughput
750
700
650
600
550
500
450
400
MB/s
0
100
200
300
400
seconds

ZFS ...

ZFS

What is it?

- Copy-on-write file system
- History
  - Developed at Sun in 2001
  - Imported into FreeBSD in 2008
  - As of 2023, FreeBSD uses OpenZFS
    - Works on both Linux and FreeBSD

ZFS

What does it do?

- Data integrity
  - Checksummed blocks
  - Silent data corruption detection and correction
- Data consistency
  - State gets updated at checkpoints
- Pooled storage
  - No need to partition disks in advance
  - Easier partition creation, growing, and shrinking

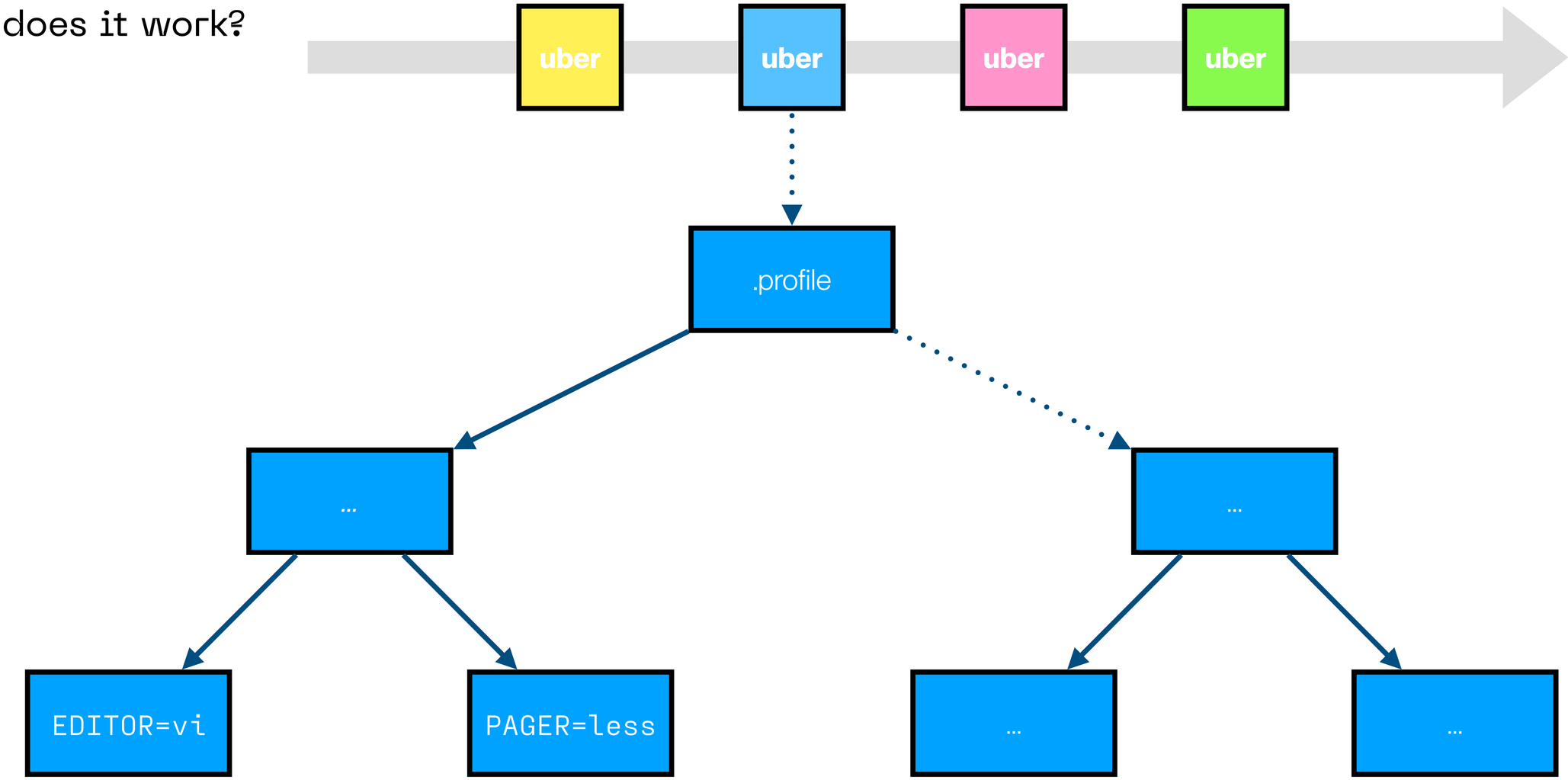
ZFS

What else does it do?

- Snapshots
- Efficient remote replication
- Compression
- Encryption
- Deduplication
- RAIDZ
- Quotas
- Boot environments
- …

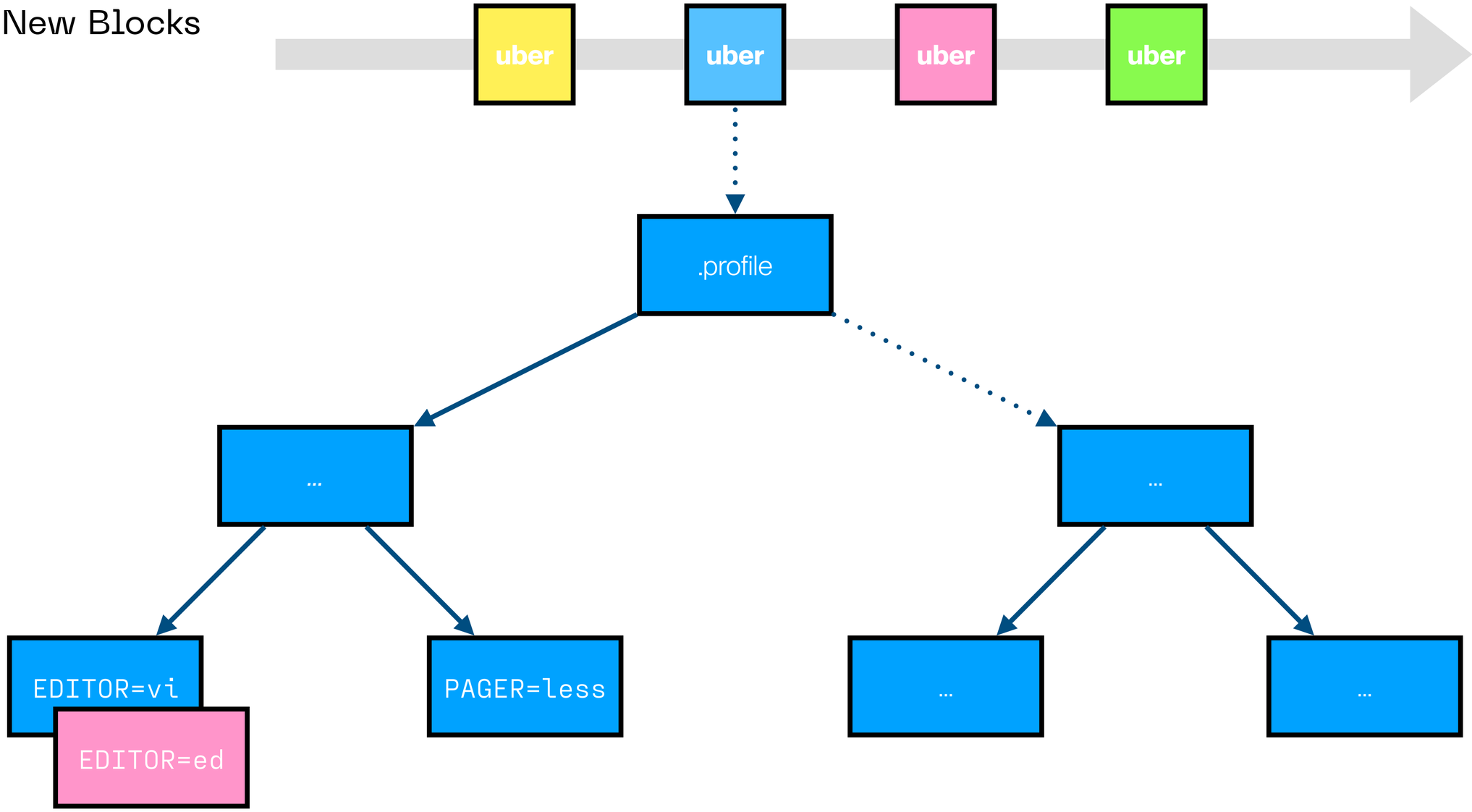
ZFS

How does it work?



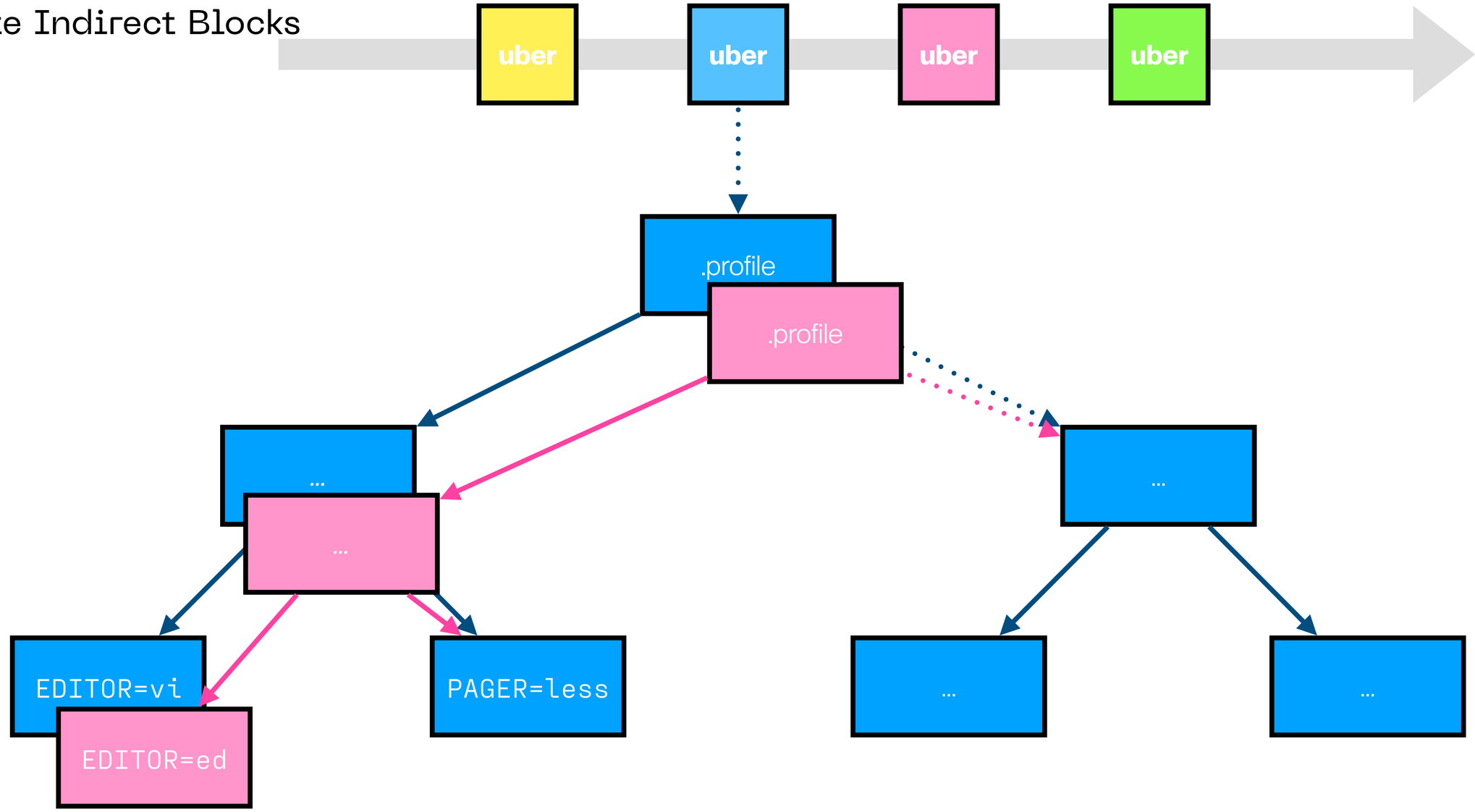
ZFS

Write New Blocks



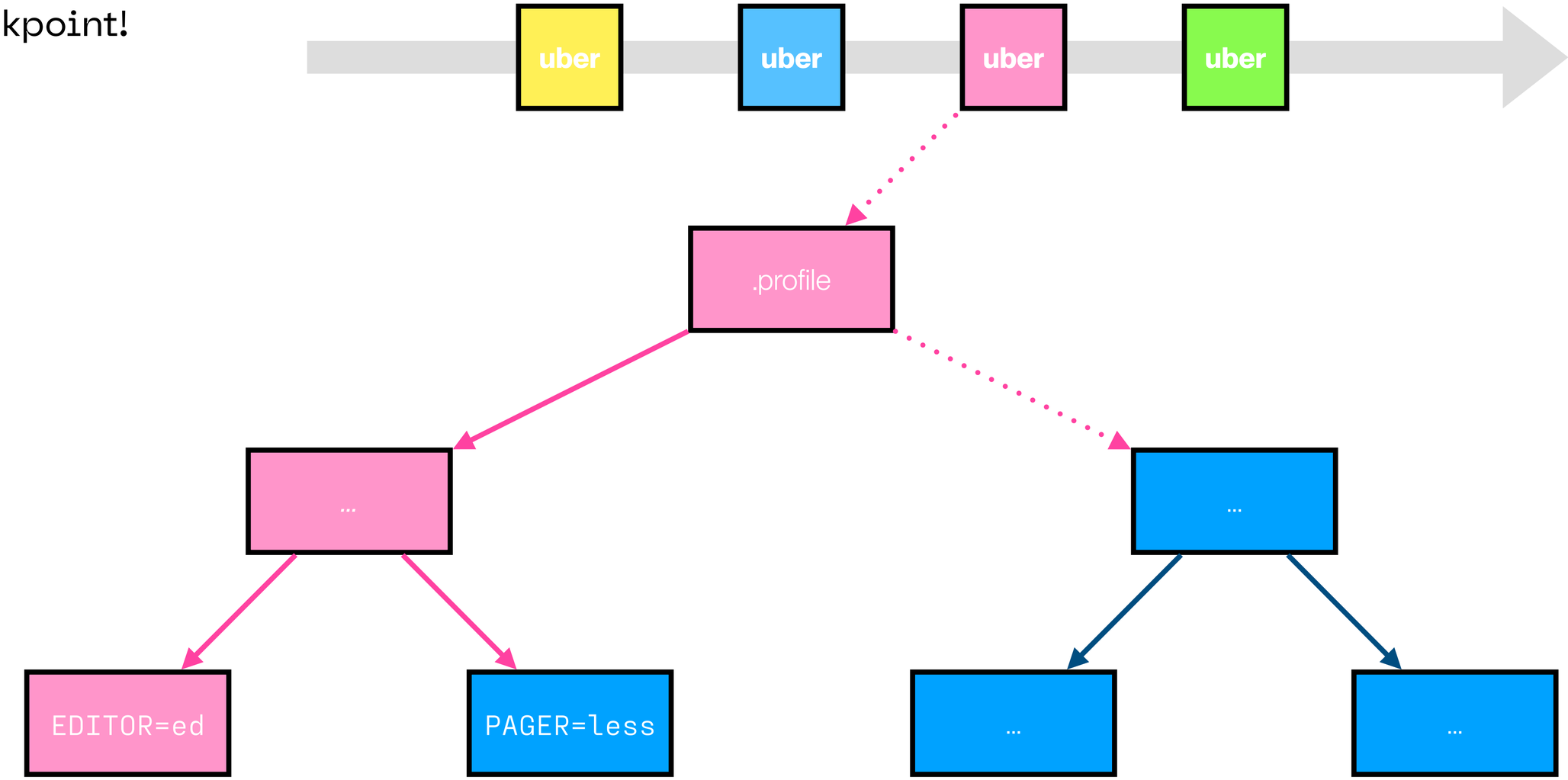
ZFS

Update Indirect Blocks



ZFS

Checkpoint!

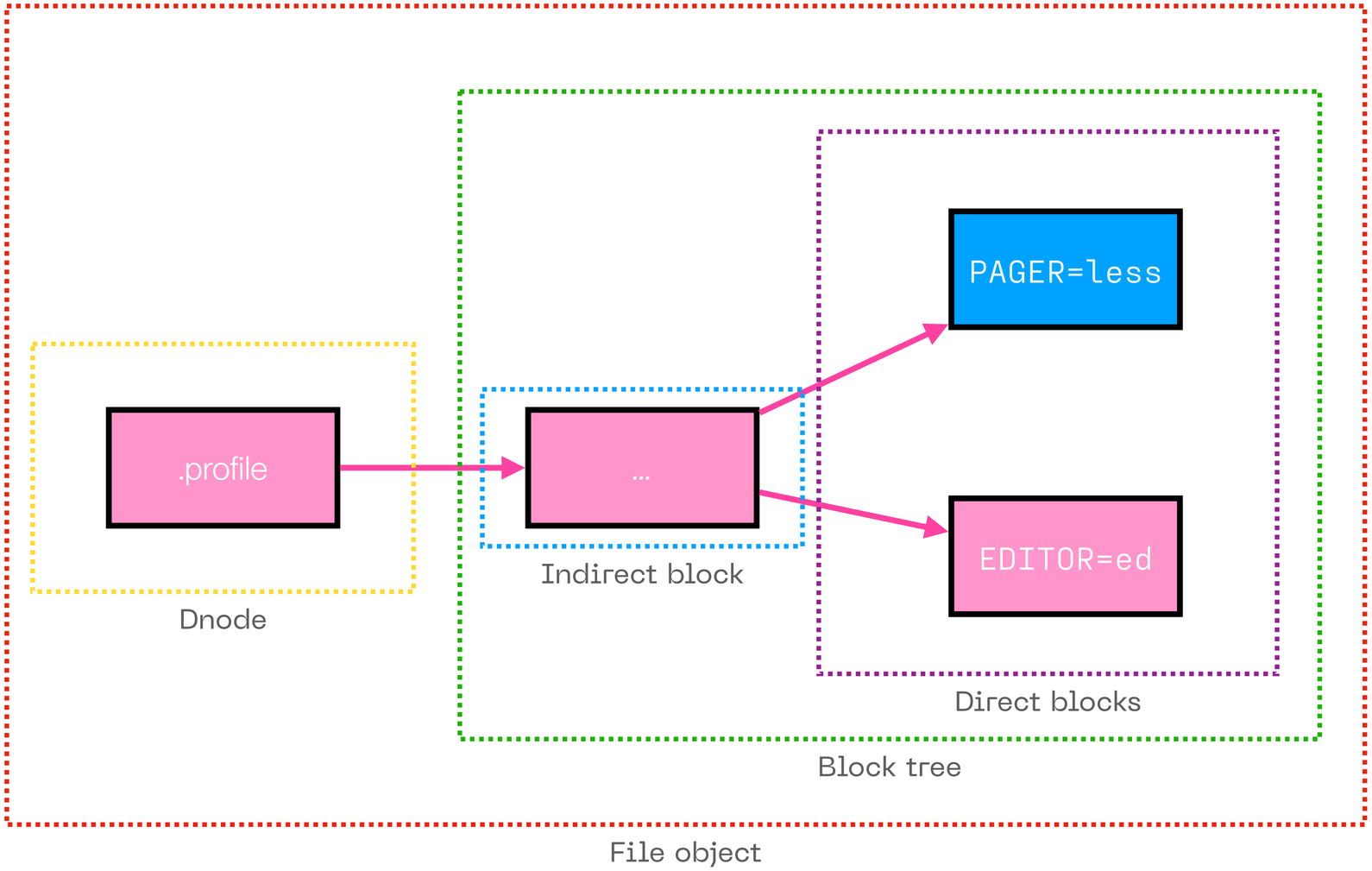


ZFS

What is a file?

- What is a file?
  - File is an object
- What is an object?
  - Group of blocks
  - Organized by a dnode
- Almost everything is an object
  - Files, directories, datasets, …

- Let's take a closer look!



ZFS

Inspecting a File with zdb(8)

```
# dd bs=512M count=1 if=/dev/random of=/tank/ds/bigfile && zdb -ddddd tank/ds "$(stat -f %i /tank/ds/bigfile)"

Dataset tank/ds [ZPL], ID 67, cr_txg 7, 512M, 9 objects, rootbp DVA[0]=<0:1000c600:200> DVA[1]=<0:1800c600:200> [L0 DMU objset]
fletcher4 lz4 unencrypted LE contiguous unique double size=1000L/200P birth=78L/78P fill=9 cksum=0000000c7663135c:[…]

    Object  lvl   iblk   dblk  dsize  dnsize  lsize   %full  type
       128    3   128K   128K   512M     512   512M  100.00  ZFS plain file (K=inherit) (Z=inherit=lz4)
                                            168   bonus  System attributes
[…]
        path    /bigfile
[…]
        size    536870912
        parent  34
[…]
Indirect blocks:
               0 L2   0:20025a00:400 0:28025a00:400 20000L/400P F=4096 B=78/78 cksum=000000942cf061fb:[…]
               0  L1  0:4fcea00:a400 0:8027e00:a400 20000L/a400P F=1024 B=72/72 cksum=000010db03b46137:[…]
               0   L0 0:5a00bc00:20000 20000L/20000P F=1 B=71/71 cksum=00003fec43129f47:[…]
[…]
        1ffe0000   L0 0:6202aa00:20000 20000L/20000P F=1 B=78/78 cksum=00003fec5b2a0425:[…]

               segment [0000000000000000, 0000000020000000) size  512M
```

ZFS

zdb(8) Example: /usr/share/misc/flowers (1/2)

```
# ls -lah /usr/share/misc/flowers
-r--r--r--  1 root wheel  1.4K Sep  1 08:21 /usr/share/misc/flowers

# zfs set recordsize=512B tank/ds

# cat /usr/share/misc/flowers > /tank/ds/flowers

# zdb -ddddd tank/ds $(stat -f %i /tank/ds/flowers)
[…]
                0 L1  0:3800f800:400 20000L/400P F=3 B=1007/1007 cksum=0000008b56b724f9:[…]
                0  L0 0:28032c00:200 200L/200P F=1 B=1007/1007 cksum=0000002d1f3a62b8:[…]
              200  L0 0:28032e00:200 200L/200P F=1 B=1007/1007 cksum=0000002e5c3bc058:[…]
              400  L0 0:28033000:200 200L/200P F=1 B=1007/1007 cksum=00000020e7272cab:[…]

                segment [0000000000000000, 0000000000000600) size 1.50K

# zdb -ddddd tank/ds $(stat -f %i /tank/ds/flowers)  | awk '/  L0 /{print $3; exit}'
0:28032c00:200
```

ZFS

zdb(8) Example: /usr/share/misc/flowers (2/2)

```
# zdb -R tank 0:28032c00:200 | tail -n 3
0001d0:  0a486f6e65797375  636b6c653a426f6e  .Honeysuckle:Bon
0001e0:  6473206f66206c6f  76652e0a4976793a  ds of love..Ivy:
0001f0:  467269656e647368  69702c2066696465  Friendship, fide

# head -c 512 /usr/share/misc/flowers | tail -n 2
Honeysuckle:Bonds of love.
Ivy:Friendship, fide
```

... Directory ...

DIRECTORIES

Definition

- From dir(5):
  - Directories provide a convenient hierarchical method of grouping files while obscuring the underlying details of the storage medium.
  - It consists of records (directory entries) each of which contains information about a file and a pointer to the file itself.

DIRECTORIES

Hierarchical File System Operations

- From *The Design and Implementation of The FreeBSD Operating System, Table 9.1*:
  - **pathname searching (e.g., lookup)**
  - **name creation (e.g., create)**
  - name change/deletion (e.g., rename)
  - attribute manipulation (e.g., getattr)
  - object interpretation (e.g., open)
  - process control (e.g., ioctl)
  - object management (e.g., lock)

ZFS DIRECTORIES

What Is a Directory in ZFS?

- An object
  - Just like a file
- Contains a tree of ZAP blocks
  - Instead of data blocks (as file objects do)

ZFS DIRECTORIES

ZFS Attribute Processor (ZAP)

- Key-value store
- Keys can be strings and values can be, e.g., strings, numbers, or arrays of numbers
- Primarily used for directories
- Extensible hash table
- Scales nicely up to hundreds of millions of entries in a single directory

- Also called a FatZAP

ZFS DIRECTORIES

MicroZAP

- Single directory block
- Stores the mapping of file names to objects directly in the directory block
- Max 2047 entries
  - Keys: 50 bytes (due to max MicroZAP size of 128 KiB)
  - Values limited to integers.
- Automatically promoted to FatZAP
  - A FatZAP never shrinks back into a MicroZAP
    - OpenZFS#8420
    - OpenZFS#14088

... Scaling

ZFS TUNING

Different Ways of Tuning ZFS

- `zfs set atime=off tank`
- `zfs create -o recordsize=16m tank/bigfiles`
- `sysctl vfs.zfs.zap_micro_max_size="1048576"`
- `echo 'vfs.zfs.zio.taskq_batch_pct="20"' >> /boot/loader.conf`

ZFS TUNING

Popular Tunables

- ZFS properties:
  - **atime** (e.g., off)
    - Usually not necessary
  - **recordsize** (e.g., 16m)
    - Good when aligns with the workload
  - **primarycache** (e.g., metadata)
    - Beneficial, if applications do their own caching
  - **compression** (e.g., lz4)
    - Different algorithms offer different tradeoffs

ZFS DIRECTORY TUNING

Maximum size of a MicroZAP

- Control the maximum size of a MicroZAP with **vfs.zfs.zap_micro_max_size**
  - Changes the moment of the switch to a FatZAP
  - Default: 128 KiB (2047 files)
    - 1 MiB (16383 files)
- Introduced in OpenZFS#14292 (2023-01-10)

- Advantages and disadvantages of a larger MicroZAP:
  - Directory object has less indirect blocks
  - More bytes to process during write operations

ZFS DIRECTORY TUNING

Size of Indirect Blocks

- Control the size of indirect blocks with **vfs.zfs.default_ibs**
  - Default: 17 (2^{17}, 128 KiB)
- Available on FreeBSD for a long time (since 2023-01-11 also on Linux, OpenZFS#14293)

- Advantages and disadvantages of a smaller indirect block size:
  - Less bytes per block to process when reading or writing
  - More blocks to traverse

Numbers

NUMBERS

Overview

- Two benchmarks
  - Lookup (read-only)
  - Create (read & write)
- Benchmarking harness
  - hyperfine
- Tunables
  - `vfs.zfs.zap_micro_max_size`
  - `vfs.zfs.default_ibs`

BENCHMARK 1

Lookup

BENCHMARK 1: LOOKUP

Overview

- Measuring:
  - Time to list files of all subdirectories (with ftw(3))
- Parameters:
  - Files per subdirectory
  - Maximum MicroZAP size:
    - 131072 (128 KiB, default)
    - 1048576 (1 MiB)
  - Indirect block size:
    - 15 (2^{15}, 32 KiB)
    - 17 (2^{17}, 128 KiB, default)

BENCHMARK 1: LOOKUP

16000 Files (Exceeds 128-KiB MicroZAP & Fits 1-MiB MicroZAP)

```
                                                    fpd     microzap   ibs
                                                
                                          'lookup 16000   1048576    15' ran
1.00 ± 0.01 times faster than 'lookup 16000   1048576    17'
1.06 ± 0.01 times faster than 'lookup 16000   131072     15'
1.06 ± 0.01 times faster than 'lookup 16000   131072     17'
```

- Larger MicroZAPs increase performance
- Indirect block size does not matter that much

BENCHMARK 1: LOOKUP

64000 Files (Exceeds 128-KiB & 1-MiB MicroZAPs)

```
                                                fpd    microzap  ibs

                                     'lookup 64000  131072    15' ran
1.00 ± 0.01 times faster than 'lookup 64000  131072    17'
1.01 ± 0.01 times faster than 'lookup 64000  1048576   15'
1.01 ± 0.01 times faster than 'lookup 64000  1048576   17'
```

- Once FatZAPs kick in, the benefits of MicroZAPs disappear

BENCHMARK 1: LOOKUP

16500 Files (Exceeds 128-KiB & 1-MiB MicroZAPs) & primarycache=none

```
                                                fpd    microzap   ibs

                                      'lookup 16500   1048576    15' ran
1.01 ± 0.00 times faster than 'lookup 16500   131072     15'
1.42 ± 0.00 times faster than 'lookup 16500   1048576    17'
1.42 ± 0.01 times faster than 'lookup 16500   131072     17'
```

- When blocks read from disk…
  - 🖐️ MicroZAP size does not matter
  - 👉 indirect block size matters

BENCHMARK 2

Create

NUMBERS

Benchmark 2: Create

- Measuring:
  - Time to create files in a directory (with open(2))
- Parameters:
  - Files per subdirectory
  - Indirect block size:
    - 15 (2^{15}, 32 KiB)
    - 17 (2^{17}, 128 KiB, default)
  - Maximum MicroZAP size:
    - 131072 (128 KiB, default)
    - 1048576 (1 MiB)

BENCHMARK 2: CREATE

2047 Files (Fits 128-KiB & 1-MiB MicroZAPs)

```
                                                fpd    microzap  ibs

                                     'create 2047   131072    17' ran
1.00 ± 0.04 times faster than 'create 2047   1048576   15'
1.00 ± 0.03 times faster than 'create 2047   1048576   17'
1.02 ± 0.05 times faster than 'create 2047   131072    15'
```

- No observable difference for small directories

BENCHMARK 2: CREATE

16838 Files (Exceeds 128-KiB MicroZAP & Fits 1-MiB MicroZAP)

```
                                                    fpd    microzap   ibs

                                          'create 2047   131072     17' ran
  7.20 ± 0.21 times faster than 'create 16838   131072     15'
  7.23 ± 0.20 times faster than 'create 16838   131072     17'
 14.98 ± 0.41 times faster than 'create 16838   1048576    17'
 15.03 ± 0.42 times faster than 'create 16838   1048576    15'
```

- Larger MicroZAPs are more expensive when writing
- 128-KiB MicroZAPs are x2 faster than 1-MiB MicroZAPs

BENCHMARK 2: CREATE

64000 Files (Exceeds 128-KiB & 1-MiB MicroZAPs)

```
                                                    fpd    microzap   ibs
                                                'create 2047   131072    17' ran
27.82 ± 0.76 times faster than 'create 64000   131072    15'
27.88 ± 0.76 times faster than 'create 64000   131072    17'
35.53 ± 0.98 times faster than 'create 64000   1048576   15'
35.57 ± 0.97 times faster than 'create 64000   1048576   17'
```

- Larger MicroZAPs are more expensive when writing
- Smaller performance gap between 128-KiB MicroZAPs and 1-MiB MicroZAPs

Summary

SUMMARY

- Two important tunables for directory scaling:
  - Maximum MicroZAP size: **vfs.zfs.zap_micro_max_size**
  - Indirect block size: **vfs.zfs.default_ibs**
- Tuning takeaways:
  - **Reads** are faster with larger MicroZAPs and smaller indirect blocks
  - **Writes** may slow down when using larger MicroZAPs
  - Tuning depends on the system. Measure the system before tuning it.

Questions?

Thanks!