The ZFS filesystem

One day workshop — SANOG 33

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FreeBSD®

History of ZFS

- 2001: Development started at Sun (now Oracle)
- 2005: ZFS source code released
- 2008: ZFS released in FreeBSD 7.0
- (2019: ZFS still doesn’t work reliably on Linux)

ZFS in a nutshell

End-to-end data integrity

- Detects and corrects silent data corruption

Pooled storage

- The first 128 bit filesystem
- Eliminates the antique notion of volumes

Transactional design

- Data always consistent
- Huge performance wins

Simple administration

- Two commands to manage entire storage configuration

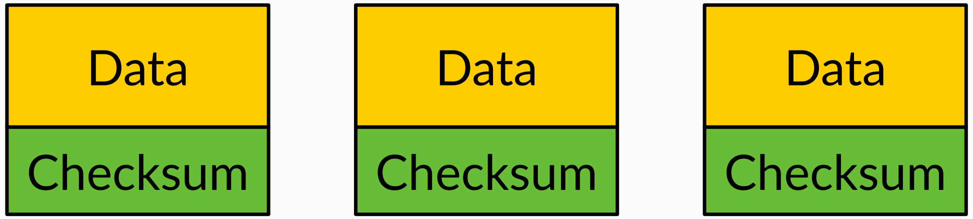
End-to-end data integrity

- Disks
- Controllers
- Cables
- Firmware
- Device drivers
- Non-ECC memory

Disk block checksums

- Checksums are stored with the data blocks
- Any self-consistent block will have a correct checksum
- Can’t even detect stray writes
- Inherently limited to single filesystems or volumes

Disk block checksums only validate media



✓Bit rot

✗Phantom writes

✗Misdirected reads and writes

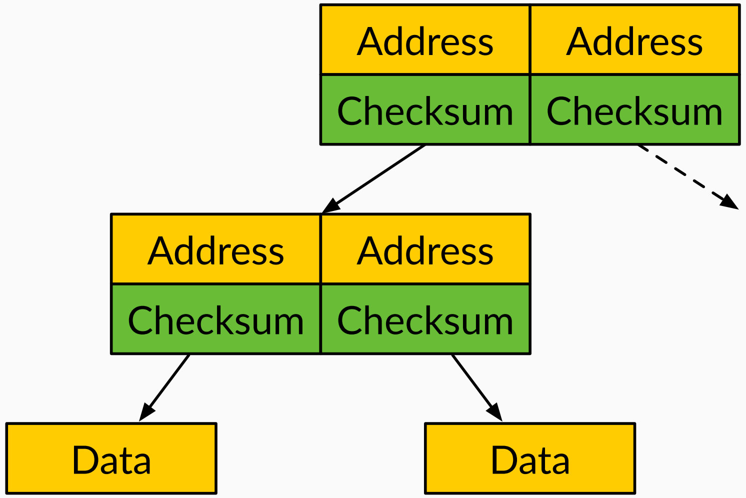
✗DMA parity errors

✗Driver bugs

✗Accidental overwrite

ZFS data authentication

- Checksums are stored in parent block pointers
- Fault isolation between data and checksum
- Entire storage pool is a self-validating Merkle tree



✓Bit rot

✓Phantom writes

✓Misdirected reads and writes

✓DMA parity errors

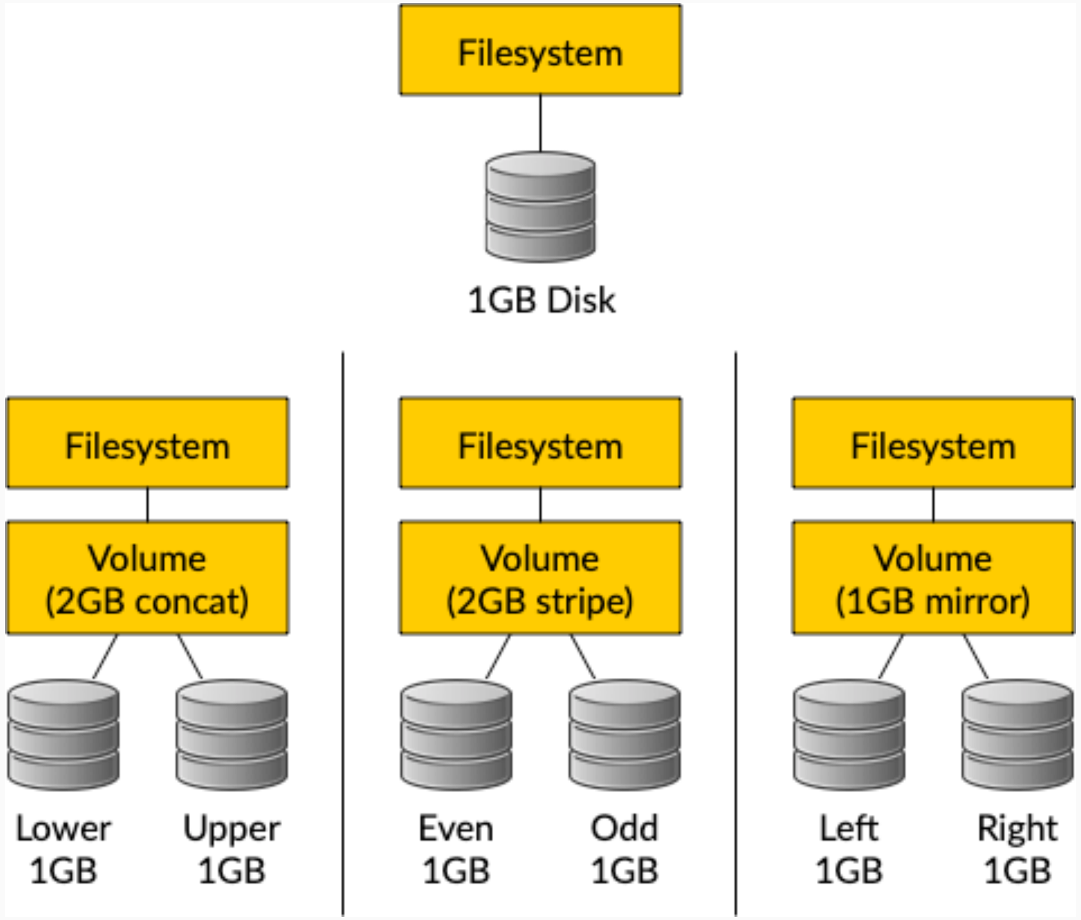
✓Driver bugs

✓Accidental overwrite

ZFS data authentication validates entire I/O path

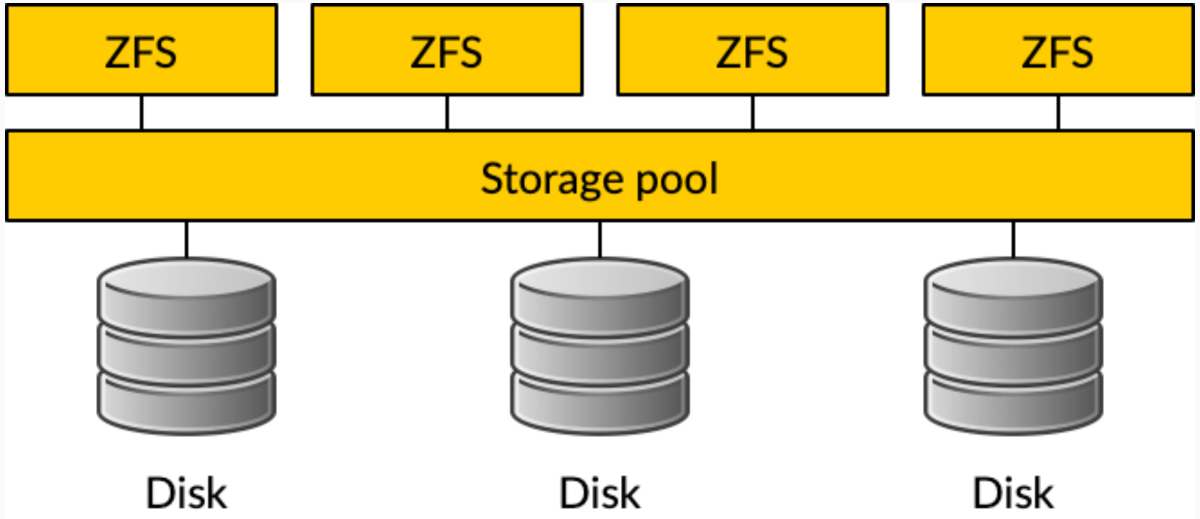
Traditional storage architecture

- Single partition or volume per filesystem
- Each filesystem has limited I/O bandwidth
- Filesystems must be manually resized
- Storage is fragmented

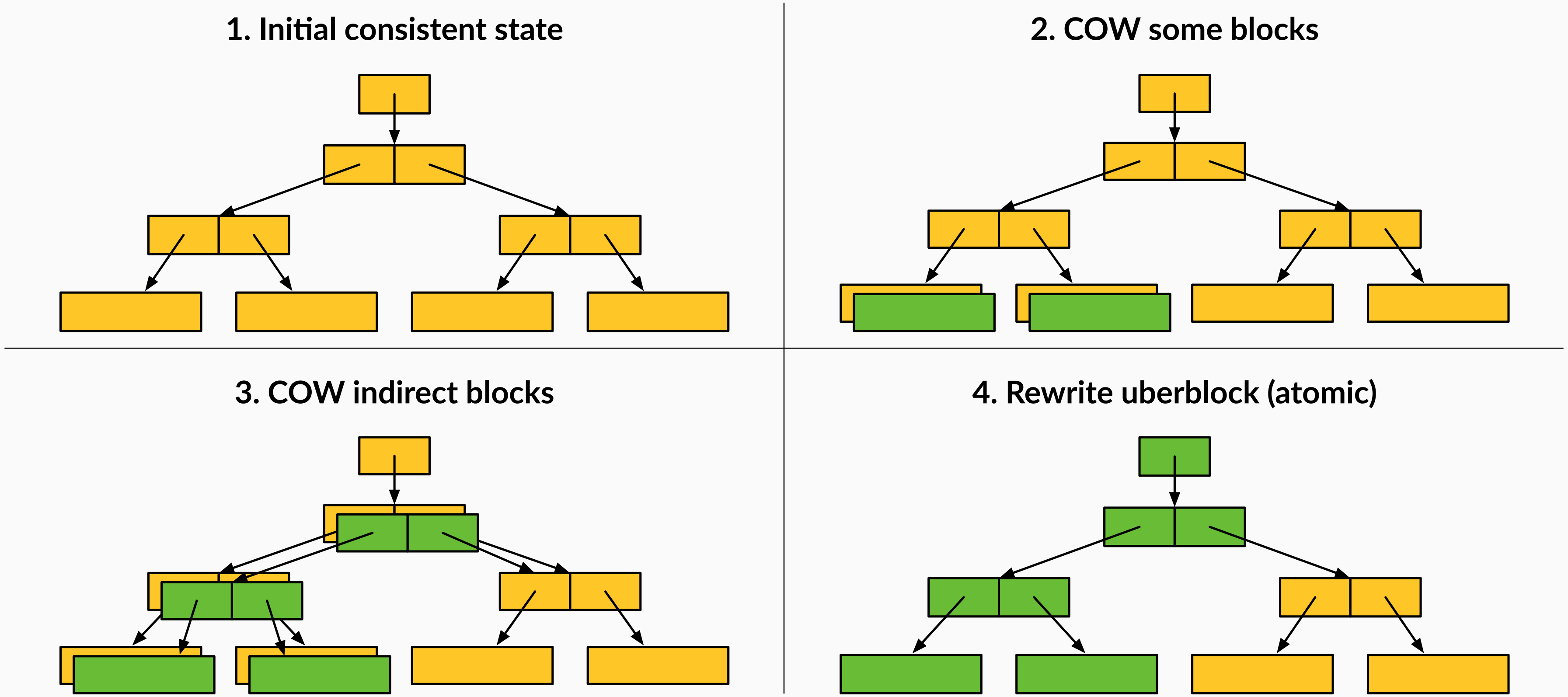


ZFS pooled storage

- No partitions required
- Storage pool grows automatically
- All I/O bandwidth is always available
- All storage in the pool is shared



Copy-on-write transactions



1. Initial consistent state

2. COW some blocks

3. COW indirect blocks

4. Rewrite uberblock (atomic)

Simple administration

Only two commands:

1. Storage pools: `zpool`
   - Add and replace disks
   - Resize pools

2. Filesystems: `zfs`
   - Quotas, reservations, etc.
   - Compression and deduplication
   - Snapshots and clones
   - atime, readonly, etc.

Storage pools

Storage pools

Creating storage pools (1/2)

To create a storage pool named “tank” from a single disk:

```
# zpool create tank /dev/md0
```

ZFS can use disks directly. There is no need to create partitions or volumes.

After creating a storage pool, ZFS will automatically:

- Create a filesystem with the same name (e.g. `tank`)
- Mount the filesystem under that name (e.g. `/tank`)

The storage is immediately available

Storage pools

Creating storage pools (2/2)

All configuration is stored with the storage pool and persists across reboots.

No need to edit `/etc/fstab`.

```
# mount | grep tank
# ls -al /tank
ls: /tank: No such file or directory
# zpool create tank /dev/md0
# mount | grep tank
tank on /tank (zfs, local, nfsv4acls)
# ls -al /tank
total 9
drwxr-xr-x   2 root  wheel   2 Oct 12 12:17 .
drwxr-xr-x  23 root  wheel  28 Oct 12 12:17 ..
# reboot
[...]

# mount | grep tank
tank on /tank (zfs, local, nfsv4acls)
```

Storage pools

Displaying pool status

```
# zpool list
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  1016G    83K  1016G        -         -     0%     0%  1.00x  ONLINE  -

# zpool status
  pool: tank
 state: ONLINE
  scan: none requested
config:

        NAME        STATE     READ WRITE CKSUM
        tank        ONLINE       0     0     0
          md0       ONLINE       0     0     0

errors: No known data errors
```

Storage pools

Displaying I/O statistics

ZFS contains a built-in tool to display I/O statistics.

Given an interval in seconds, statistics will be displayed continuously until the user interrupts with `Ctrl+C`.

Use `-v` (verbose) to display more detailed statistics.

```
# zpool iostat 5
               capacity     operations    bandwidth
pool        alloc   free   read  write   read  write
----------  -----  -----  -----  -----  -----  -----
tank          83K  1016G      0      0    234    841
tank          83K  1016G      0      0      0      0


# zpool iostat -v
               capacity     operations    bandwidth
pool        alloc   free   read  write   read  write
----------  -----  -----  -----  -----  -----  -----
tank          83K  1016G      0      0    206    739
  md0         83K  1016G      0      0    206    739
----------  -----  -----  -----  -----  -----  -----
```

Storage pools

Destroying storage pools

Destroying storage pools is a constant time operation. If you want to get rid of your data, ZFS will help you do it very quickly!

All data on a destroyed pool will be **irretrievably lost**.

```
# time zpool create tank /dev/md0
    0.06 real   0.00 user   0.02 sys

# time zpool destroy tank
    0.09 real   0.00 user   0.00 sys
```

Storage pools

Creating stripes

A pool with just one disk does not provide any redundancy, capacity or even adequate performance.

Stripes offer higher capacity and better performance (reading will be parallelised) but they provide **no redundancy**.

```
# zpool create tank /dev/md0 /dev/md1
# zpool status
  pool: tank
 state: ONLINE
  scan: none requested
config:

       NAME        STATE     READ WRITE CKSUM
       tank        ONLINE       0     0     0
         md0       ONLINE       0     0     0
         md1       ONLINE       0     0     0

errors: No known data errors

# zpool list
NAME   SIZE  ALLOC   FREE CAP  DEDUP  HEALTH
tank  1.98T    86K  1.98T  0%  1.00x  ONLINE
```

Storage pools

Creating mirrors (RAID-1)

Mirrored storage pools provide **redundancy** against disk failures and better read performance than single-disk pools.

However, mirrors only have **50% of the capacity** of the underlying disks.

```
# zpool create tank mirror /dev/md0 /dev/md1
# zpool status
  pool: tank
 state: ONLINE
  scan: none requested
config:

       NAME        STATE     READ WRITE CKSUM
       tank        ONLINE       0     0     0
         mirror-0  ONLINE       0     0     0
           md0     ONLINE       0     0     0
           md1     ONLINE       0     0     0

errors: No known data errors
# zpool list
NAME   SIZE  ALLOC   FREE  CAP  DEDUP  HEALTH
tank  1016G    93K  1016G  0%  1.00x  ONLINE
```

Storage pools

Creating raidz groups

raidz is a variation on RAID-5 with single-, double-, or triple parity.

A raidz group with N disks of size X with P parity disks can hold approximately $(N - P) * X$ bytes and can withstand P device(s) failing before data integrity is compromised.

```
# zpool create tank \
> raidz1 /dev/md0 /dev/md1 /dev/md2 /dev/md3
# zpool status
 pool: tank
 state: ONLINE
  scan: none requested
config:

       NAME        STATE     READ WRITE CKSUM
       tank        ONLINE       0     0     0
         raidz1-0  ONLINE       0     0     0
           md0     ONLINE       0     0     0
           md1     ONLINE       0     0     0
           md2     ONLINE       0     0     0
           md3     ONLINE       0     0     0

errors: No known data errors
```

Storage pools

Combining vdev types

Single disks, stripes, mirrors and raidz groups can be combined in a single storage pool

ZFS will complain when adding devices would make the pool less redundant

```
# zpool create tank mirror /dev/md0 /dev/md1
# zpool add tank /dev/md2
invalid vdev specification
use '-f' to override the following errors:
mismatched replication level:
pool uses mirror and new vdev is disk

# zpool create tank \
> raidz2 /dev/md0 /dev/md1 /dev/md2 /dev/md3
# zpool add tank \
> raidz /dev/md4 /dev/md5 /dev/md6
invalid vdev specification
use '-f' to override the following errors:
mismatched replication level:
pool uses 2 device parity and new vdev uses 1
```

Storage pools

Increasing storage pool capacity

More devices can be added to a storage pool to increase capacity without downtime.

Data will be striped across the disks, increasing performance, but there will be **no redundancy**.

If *any* disk fails, **all data is lost!**

```
# zpool create tank /dev/md0
# zpool add tank /dev/md1
# zpool list
NAME   SIZE  ALLOC   FREE  CAP  DEDUP  HEALTH
tank  1.98T   233K  1.98T   0%  1.00x  ONLINE
# zpool status
  pool: tank
 state: ONLINE
  scan: none requested
config:

      NAME        STATE     READ WRITE CKSUM
      tank        ONLINE       0     0     0
        md0       ONLINE       0     0     0
        md1       ONLINE       0     0     0

errors: No known data errors
```

Storage pools

Creating a mirror from a single-disk pool (1/4)

A storage pool consisting of only one device can be converted to a mirror.

In order for the new device to mirror the data of the already existing device, the pool needs to be “resilvered”.

This means that the pool synchronises both devices to contain the same data at the end of the resilver operation.

During resilvering, access to the pool will be slower, but there will be no downtime.

Storage pools

Creating a mirror from a single-disk pool (2/4)

```
# zpool create tank /dev/md0
# zpool status
  pool: tank
 state: ONLINE
  scan: none requested
config:

       NAME        STATE     READ WRITE CKSUM
       tank        ONLINE       0     0     0
         md0       ONLINE       0     0     0

errors: No known data errors

# zpool list
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  1016G    93K  1016G        -         -     0%     0%  1.00x  ONLINE  -
```

Storage pools

Creating a mirror from a single-disk pool (3/4)

```
# zpool attach tank /dev/md0 /dev/md1
# zpool status tank
  pool: tank
 state: ONLINE
status: One or more devices is currently being resilvered.  The pool
        will continue to function, possibly in a degraded state.
action: Wait for the resilver to complete.
  scan: resilver in progress since Fri Oct 12 13:55:56 2018
        5.03M scanned out of 44.1M at 396K/s, 0h1m to go
        5.03M resilvered, 11.39% done
config:

        NAME        STATE     READ WRITE CKSUM
        tank        ONLINE       0     0     0
          mirror-0  ONLINE       0     0     0
            md0     ONLINE       0     0     0
            md1     ONLINE       0     0     0 (resilvering)

errors: No known data errors
```

Storage pools

Creating a mirror from a single-disk pool (4/4)

```
# zpool status
  pool: tank
 state: ONLINE
  scan: resilvered 44.2M in 0h1m with 0 errors on Fri Oct 12 13:56:29 2018
config:

       NAME        STATE     READ WRITE CKSUM
       tank        ONLINE       0     0     0
         mirror-0  ONLINE       0     0     0
           md0     ONLINE       0     0     0
           md1     ONLINE       0     0     0

errors: No known data errors

# zpool list
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  1016G  99.5K  1016G        -         -     0%     0%  1.00x  ONLINE  -
```

Datasets

Datasets

Creating datasets

- ZFS uses the term *dataset* to refer to filesystems
- Datasets are mounted automatically by default
  - Can be disabled for individual datasets (or entire hierarchies)
  - Mountpoint defaults to the name of the pool
- Can be used like directories with many useful properties

```
# zfs create tank/users
# zfs list
NAME            USED  AVAIL  REFER  MOUNTPOINT
tank            150K   984G    23K  /tank
tank/users       23K   984G    23K  /tank/users

# zfs create tank/users/a
# zfs list
NAME            USED  AVAIL  REFER  MOUNTPOINT
tank            180K   984G    23K  /tank
tank/users       46K   984G    23K  /tank/users
tank/users/a     23K   984G    23K  /tank/users/a
```

Datasets

Properties (1/2)

- Configuration and statistics are kept in dozens of properties
  - Use `zfs get all` for a list
  - All documented in the `zfs(8)` Unix manual page
- Datasets inherit properties from their parents
- Inherited properties can be overridden

```
# zfs set atime=off tank
# zfs get atime
NAME            PROPERTY  VALUE  SOURCE
tank            atime     off    local
tank/users      atime     off    inherited from tank
tank/users/a    atime     off    inherited from tank

# zfs set atime=on tank/users/a
# zfs get atime
NAME            PROPERTY  VALUE  SOURCE
tank            atime     off    local
tank/users      atime     off    inherited from tank
tank/users/a    atime     on     local
```

Datasets

Properties (2/2)

- Read-only properties have their SOURCE set to –, e.g.:
  - `creation` dataset creation time
  - `used` currently used space
- Changed properties take effect immediately; there is no need to remount
- Overrides can be restored with the `zfs inherit` command.

```
# zfs get creation,used,atime,readonly tank
NAME  PROPERTY  VALUE                  SOURCE
tank  creation  Fri Oct 12 15:15 2018  -
tank  used      180K                   -
tank  atime     off                    local
tank  readonly  off                    default

# mount | grep tank
tank on /tank (zfs, local, noatime, nfsv4acls)

# zfs inherit atime tank
# mount | grep tank
tank on /tank (zfs, local, nfsv4acls)
```

Datasets

Mounting (1/2)

- By default, ZFS mounts datasets at the name of the pool that contain them
- The `mountpoint` property changes this behaviour
- Note: mountpoints must have a leading / (as usual in Unix) but the ZFS path in the pool must not have a leading /.

```
# zfs get mountpoint
NAME          PROPERTY    VALUE          SOURCE
tank          mountpoint  /tank          default
tank/users    mountpoint  /tank/users    default

# mount | grep tank
tank on /tank (zfs, local, nfsv4acls)
tank/users on /tank/users (zfs, local, nfsv4acls)

# zfs set mountpoint=/usr/home tank/users
# mount | grep tank
tank on /tank (zfs, local, nfsv4acls)
tank/users on /usr/home (zfs, local, nfsv4acls)
```

Datasets

Mounting (2/2)

- The `canmount` property determines whether datasets are mounted automatically
  - Datasets are mounted by default
  - Set `canmount=noauto` to not mount the dataset by default
  - Set `canmount=off` to make the dataset unmountable

```
# mount | grep tank
tank on /tank (zfs, local, nfsv4acls)
tank/users on /tank/users (zfs, local, nfsv4acls)

# zfs set canmount=off tank/users
# mount | grep tank
tank on /tank (zfs, local, nfsv4acls)
```

Datasets

Commonly used properties: readonly

- Datasets are mounted for reading and writing by default
- The `readonly` property changes this behaviour
- Remember: properties persist across reboots; there is no need to edit `/etc/fstab`

```
# zfs create -p tank/projects/current
# zfs create tank/projects/finished
# zfs set mountpoint=/projects tank/projects

# cp -a /home/alice/projects /projects/current

# zfs get readonly tank/projects/finished
NAME                    PROPERTY  VALUE   SOURCE
tank/projects/finished  readonly  off     default

# cp /projects/current/homework.tex \
> /projects/finished

# zfs set readonly=on tank/projects/finished
# cp -a /projects/current/thesis.tex \
> /projects/finished
cp: /projects/finished: Read-only file system
```

Datasets

Commonly used properties: exec (1/3)

- The `exec` property determines whether or not files can be executed on a dataset
- Useful on e.g. `/var/log` where executing files would do more harm than good
- Can also be used to protect the system from untrustworthy users…

```
# zfs create tank/logfiles
# zfs set mountpoint=/var/log tank/logfiles
# zfs set exec=off tank/logfiles

# zfs get exec
NAME                  PROPERTY  VALUE  SOURCE
tank                  exec      on     default
tank/logfiles         exec      off    local

# mount | grep logfiles
tank/logfiles on /var/log (zfs, local, noexec)
```

Dataset

Commonly used properties: exec (2/3)

```
# zfs create tank/users
# zfs set mountpoint=/home tank/users
# zfs set exec=off tank/users
# zfs create tank/users/alice
# zfs get exec
NAME              PROPERTY  VALUE  SOURCE
tank              exec      on     default
tank/users        exec      off    local
tank/users/alice  exec      off    inherited

# ls -al /home/alice/
total 2
drwxr-xr-x  2 alice  alice   3 Oct 12 16:54 .
drwxr-xr-x  3 alice  alice   3 Oct 12 16:52 ..
-rwxr-xr-x  1 alice  alice  27 Oct 12 16:54 evil.sh
```

Dataset

Commonly used properties: exec (3/3)

```
% cat /home/alice/evil.sh
#!/bin/sh
rm -fr /projects

% cd /home/alice
% ./evil.sh
sh: ./evil.sh: Permission denied

% su
# ./evil.sh
./evil.sh: Permission denied.
```

Datasets

User-defined properties

- User-defined properties can store locally relevant metadata with the dataset, e.g.:
    - Last backup time
    - Cost centre paying for the disks
    - Anything you want them to store!
- A namespace (e.g. `acme`) distinguishes user-defined properties from built-in ones

```
# zfs set acme:lastbackup=20181012030000 tank
# zfs get acme:lastbackup tank
NAME  PROPERTY         VALUE            SOURCE
tank  acme:lastbackup  20181012030000   local

# zfs set acme:disksource=vendorname
# zfs set acme:diskbought=2018-10-01
# zfs set acme:diskprice=100EUR
```

Datasets

Quotas (1/3)

- By default, datasets can use all the space provided by the underlying storage pool

- Quotas set an upper limit on how much data can be stored in a dataset

```
# zfs get quota
NAME                 PROPERTY  VALUE  SOURCE
tank                 quota     none   default
tank/users           quota     none   default
tank/users/alice     quota     none   default
tank/users/bob       quota     none   default

# zfs set quota=10GB tank/users
# zfs set quota=50GB tank/users/alice

# zfs get quota
NAME                 PROPERTY  VALUE  SOURCE
tank                 quota     none   local
tank/users           quota     10G    local
tank/users/alice     quota     50G    local
tank/users/bob       quota     none   default
```

Datasets

Quotas (2/3)

```
# zfs get quota
NAME                PROPERTY  VALUE  SOURCE
tank                quota     none   default
tank/users/alice    quota     none   default
tank/users/bob      quota     none   default

# df -h
Filesystem            Size    Used   Avail Capacity  Mounted on
tank                  984G     23K    984G     0%    /tank
tank/users/alice      984G     23K    984G     0%    /tank/users/alice
tank/users/bob        984G     23K    984G     0%    /tank/users/bob

# zfs set quota=500M tank/users/alice
# df -h
Filesystem            Size    Used   Avail Capacity  Mounted on
tank                  984G     23K    984G     0%    /tank
tank/users/alice      500M     23K    500M     0%    /tank/users/alice
tank/users/bob        984G     23K    984G     0%    /tank/users/bob
```

Datasets

Quotas (3/3)

```
# dd if=/dev/urandom of=/tank/users/alice/bigfile.dat
dd: /tank/users/alice/bigfile.dat: Disc quota exceeded

# ls -alh /tank/users/alice/bigfile.dat
-rw-r--r--  1 root  wheel   500M Oct 12 18:21 /tank/users/alice/bigfile.dat

# df -h
Filesystem          Size    Used   Avail Capacity  Mounted on
tank                984G     23K    984G     0%    /tank
tank/users/alice    500M    500M      0B   100%    /tank/users/alice
tank/users/bob      984G     23K    984G     0%    /tank/users/bob
```

Datasets

Reservations (1/3)

- Reservations ensure that there is always a certain amount of free space available to a dataset
- This is in contrast with quotas, which ensure that no more than a certain amount of data can be written

```
# zfs get reservation
NAME                PROPERTY     VALUE    SOURCE
tank                reservation  none     default
tank/users          reservation  none     default
tank/users/alice    reservation  none     default
tank/users/bob      reservation  none     default

# zfs set reservation=500M tank/users/bob
```

Datasets

Reservations (2/3)

```
# zfs get reservation
NAME              PROPERTY     VALUE   SOURCE
tank              reservation  none    default
tank/users/alice  reservation  none    default
tank/users/bob    reservation  none    default

# df -h
Filesystem          Size    Used   Avail Capacity  Mounted on
tank                1.2G     23K    1.2G     0%    /tank
tank/users/alice    1.2G     23K    1.2G     0%    /tank/users/alice
tank/users/bob      1.2G     23K    1.2G     0%    /tank/users/bob

# zfs set reservation=500M tank/users/bob
# df -h
Filesystem          Size    Used   Avail Capacity  Mounted on
tank                780M     23K    780M     0%    /tank
tank/users/alice    780M     23K    780M     0%    /tank/users/alice
tank/users/bob      1.2G     23K    1.2G     0%    /tank/users/bob
```

Datasets

Reservations (3/3)

```
# dd if=/dev/urandom of=/tank/users/alice/bigfile.dat bs=850M
dd: /tank/users/alice/bigfile.dat: No space left on device

# ls -alh /tank/users/alice/bigfile.dat
-rw-r--r--  1 root  wheel   780M Oct 12 18:21 /tank/users/alice/bigfile.dat

# df -h /tank /tank/users /tank/users/alice /tank/users/bob
Filesystem          Size    Used   Avail Capacity  Mounted on
tank                 23K     23K      0B   100%    /tank
tank/users/alice    780M    780M      0B   100%    /tank/users/alice
tank/users/bob      500M     23K    500M     0%    /tank/users/bob
```

Datasets

Compression (1/2)

- ZFS can transparently compress data written to datasets and decompress it automatically when reading
- Several algorithms are available
  - Default: lz4
  - gzip, gzip-N, zle, lzjb,…
- Only newly written data is compressed. ZFS does not recompress existing data!

```
# zfs create \
> -o mountpoint=/usr/ports \
> -p tank/ports/uncompressed
# portsnap fetch extract
# zfs list tank/ports
NAME            USED   AVAIL   REFER  MOUNTPOINT
tank/ports      437M    984G     23K  /usr/ports

# zfs create tank/ports/compressed
# zfs set compression=on tank/ports/compressed
# cp -a /usr/ports/ /tank/ports/compressed/

# zfs list -r tank/ports
NAME                           USED   AVAIL   REFER
tank/ports                     636M    983G     23K
tank/ports/compressed          196M    983G    196M
tank/ports/uncompressed        440M    983G    440M
```

Datasets

Compression (2/2)

- The `compressratio` property can be checked to evaluate how effective compression is
- It’s very easy to experiment!
- Bonus: compression also improves read performance on systems where the CPU is faster than the disks (i.e.: most systems)

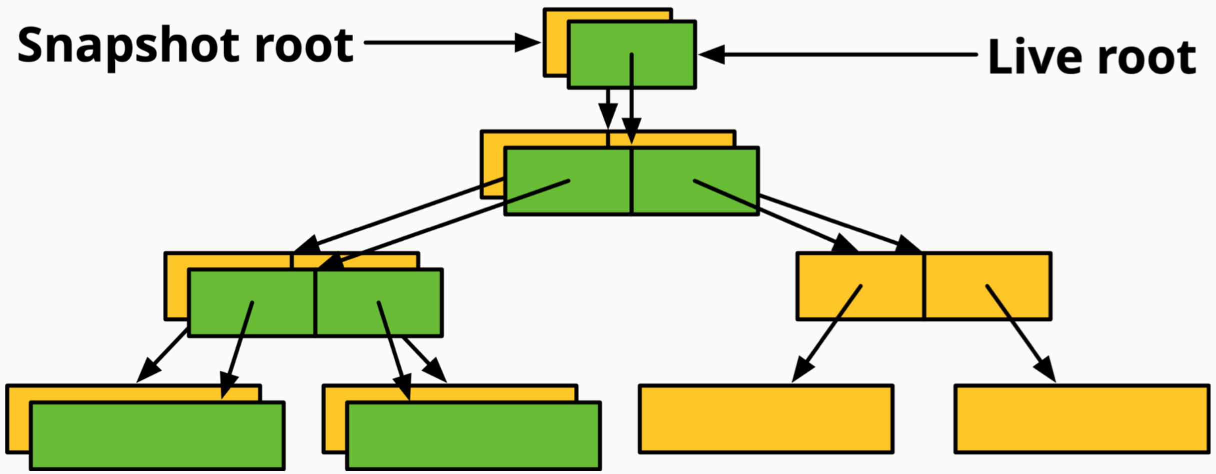
```
# zfs get compression,compressratio
NAME                   PROPERTY       VALUE
tank/ports/compressed  compression    on
tank/ports/compressed  compressratio  2.47x

# zfs create tank/ports/gzipped
# zfs set compression=gzip-9 tank/ports/gzipped
# cp -a /tank/ports/compressed/
> /tank/ports/gzipped/

# zfs get -r compressratio,used tank/ports
NAME                     PROPERTY       VALUE
tank/ports/compressed    compressratio  2.47x
tank/ports/compressed    used           197M
tank/ports/gzipped       compressratio  3.10x
tank/ports/gzipped       used           163M
tank/ports/uncompressed  compressratio  1.00x
tank/ports/uncompressed  used           440M
```

Snapshots

Snapshots

Overview

- A snapshot is a read-only copy of a dataset or volume
- ZFS snapshots are extremely fast
  - Side-effect of the underlying copy-on-write transaction model
  - Faster than deleting data!
- Snapshots occupy no space until the original data starts to diverge



Snapshots

Creating and listing snapshots (1/2)

- A snapshot only needs an identifier
  - Can be anything you like!
  - A timestamp is traditional
  - But you can use more memorable identifiers too…

```
# zfs snapshot tank/users/alice@myfirstbackup
# zfs list -t snapshot
NAME                              USED  AVAIL  REFER  MOUNTPOINT
tank/users/alice@myfirstbackup       0      -    23K  -

# zfs list -rt all tank/users/alice
NAME                              USED  AVAIL  REFER  MOUNTPOINT
tank/users/alice                   23K   984G    23K  /tank/users/alice
tank/users/alice@myfirstbackup       0      -    23K  -
```

Snapshots

Creating and listing snapshots (2/2)

- Snapshots save only the changes between the time they were created and the previous (if any) snapshot
- If data doesn’t change, snapshots occupy zero space

```
# echo hello world > /tank/users/alice/important_data.txt
# zfs snapshot tank/users/alice@mysecondbackup
# zfs list -rt all tank/users/alice
NAME                              USED  AVAIL  REFER  MOUNTPOINT
tank/users/alice                 36.5K   984G  23.5K  /tank/users/alice
tank/users/alice@myfirstbackup     13K      -    23K  -
tank/users/alice@mysecondbackup      0      -  23.5K  -
```

Snapshots

Differences between snapshots

- ZFS can display the differences between snapshots

Character	Type of change
+	File was added
-	File was deleted
M	File was modified
R	File was renamed

```
# touch /tank/users/alice/empty
# rm /tank/users/alice/important_data.txt
# zfs diff tank/users/alice@mysecondbackup
M       /tank/users/alice/
-       /tank/users/alice/important_data.txt
+       /tank/users/alice/empty
```

Snapshots

Rolling back snapshots (1/2)

- Snapshots can be rolled back to undo changes
- All files changed since the snapshot was created will be discarded

```
# echo hello_world > important_file.txt
# echo goodbye_cruel_world > also_important.txt
# zfs snapshot tank/users/alice@myfirstbackup
# rm *

# ls

# zfs rollback tank/users/alice@myfirstbackup

# ls
also_important.txt   important_file.txt
```

Snapshots

Rolling back snapshots (2/2)

- By default, the latest snapshot is rolled back. To roll back an older snapshot, use `-r`
- Note that intermediate snapshots will be destroyed
- ZFS will warn about this

```
# touch not_very_important.txt
# touch also_not_important.txt
# ls
also_important.txt   important_file.txt
also_not_important.txt      not_very_important.txt
# zfs snapshot tank/users/alice@mysecondbackup
# zfs diff tank/users/alice@myfirstbackup \
> tank/users/alice@mysecondbackup
M       /tank/users/alice/
+       /tank/users/alice/not_very_important.txt
+       /tank/users/alice/also_not_important.txt
# zfs rollback tank/users/alice@myfirstbackup
# zfs rollback -r tank/users/alice@myfirstbackup
# ls
also_important.txt   important_file.txt
```

Snapshots

Restoring individual files

- Sometimes, we only want to restore a single file, rather than rolling back an entire snapshot
- ZFS keeps snapshots in a very hidden `.zfs/snapshots` directory
  - It’s like magic :-)
  - Set `snapdir=visible` to unhide it
- Remember: snaphots are read-only. Copying data to the magic directory won’t work!

```
# ls
also_important.txt  important_file.txt

# rm *
# ls

# ls .zfs/snapshot/myfirstbackup
also_important.txt  important_file.txt

# cp .zfs/snapshot/myfirstbackup/* .

# ls
also_important.txt  important_file.txt
```

Snapshots

Cloning snapshots

- Clones represent a *writeable* copy of a read-only snapshot
- Like snapshots, they occupy no space until they start to diverge

```
# zfs list -rt all tank/users/alice
NAME                              USED  AVAIL  REFER  MOUNTPOINT
tank/users/alice                  189M   984G   105M  /tank/users/alice
tank/users/alice@mysecondbackup      0      -   105M  -

# zfs clone tank/users/alice@mysecondbackup tank/users/eve

# zfs list tank/users/eve
NAME               USED  AVAIL  REFER  MOUNTPOINT
tank/users/eve        0   984G   105M  /tank/users/eve
```

Snapshots

Promoting clones

- Snapshots cannot be deleted while clones exist
- To remove this dependency, clones can be *promoted* to ”ordinary” datasets
- Note that by promoting the clone, it immediately starts occupying space

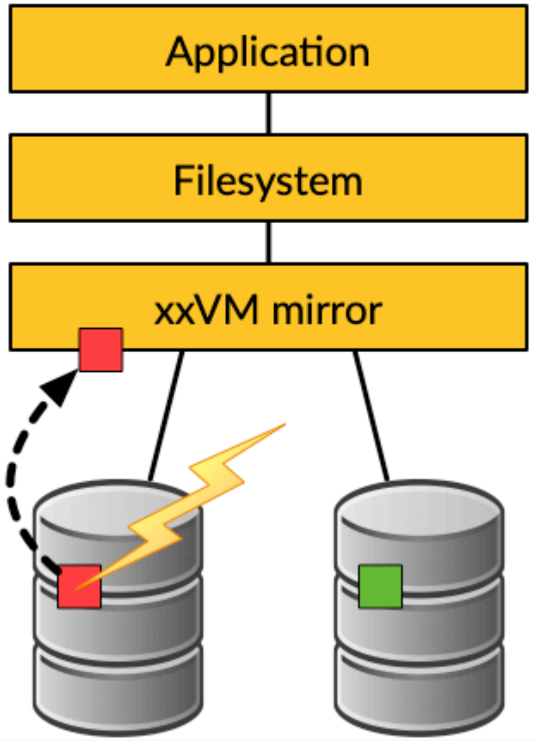
```
# zfs destroy tank/users/alice@mysecondbackup
cannot destroy 'tank/users/alice@mysecondbackup’:
snapshot has dependent clones
use '-R' to destroy the following datasets:
tank/users/eve

# zfs list tank/users/eve
NAME             USED  AVAIL  REFER  MOUNTPOINT
tank/users/eve      0   984G   105M  /tank/users/eve

# zfs promote tank/users/eve

# zfs list tank/users/eve
NAME             USED  AVAIL  REFER  MOUNTPOINT
tank/users/eve   189M   984G   105M  /tank/users/eve
```

Self-healing data

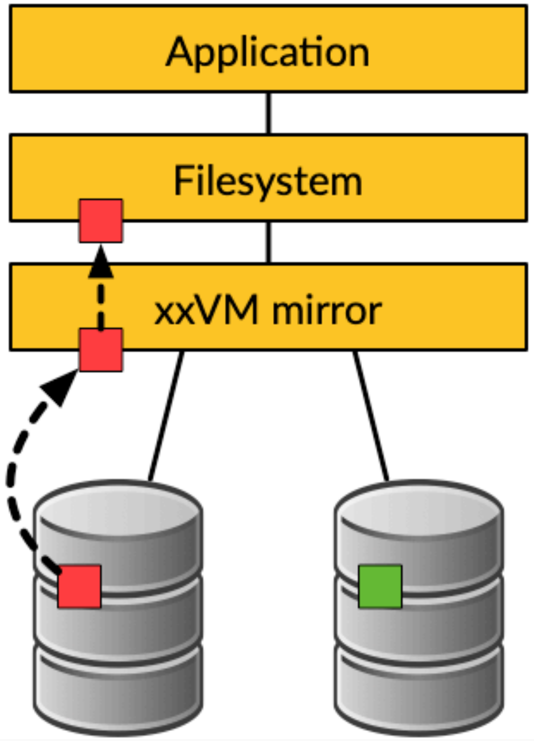
Demo

Traditional mirroring

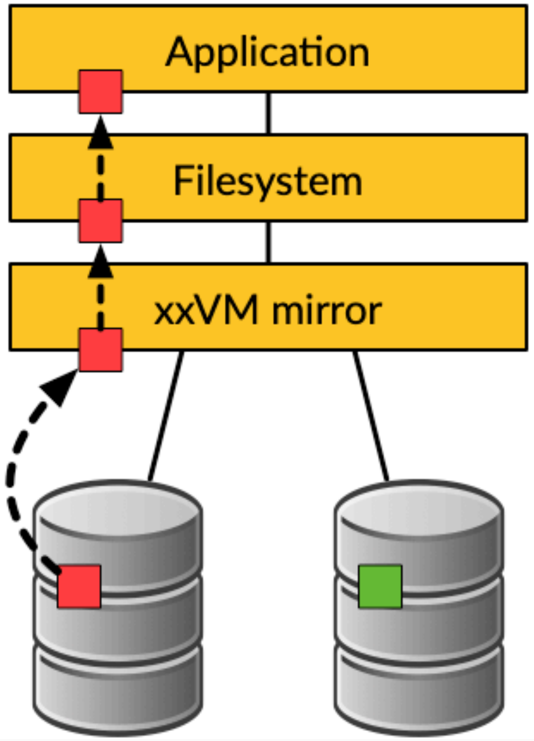
1. Application issues a read.
Mirror reads the first disk,
which has a corrupt block.
It can't tell.



2. Volume manager passes bad
block up to filesystem.
If it's a metadata block, the
filesystem panics. If not…

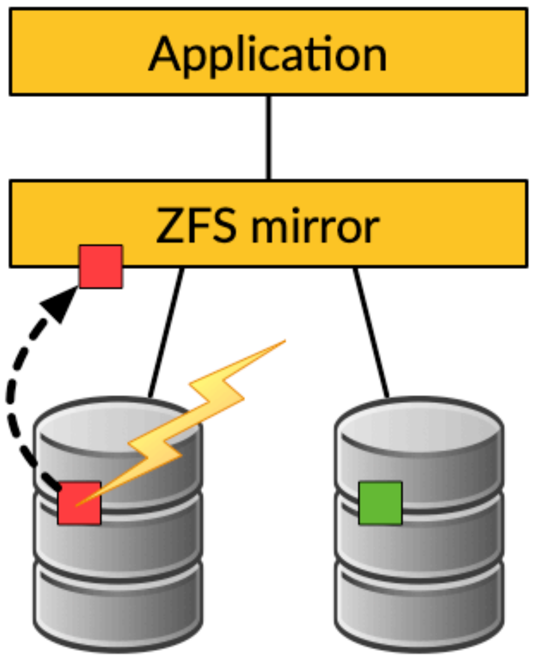


3. Filesystem returns bad data
to the application.

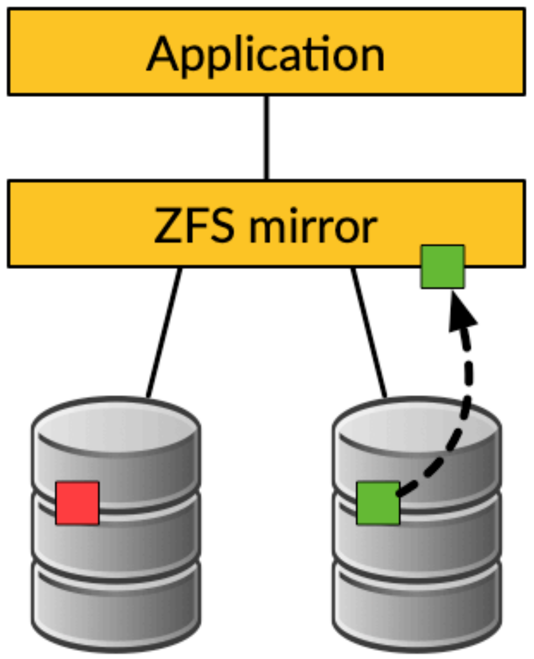


Self-healing data in ZFS

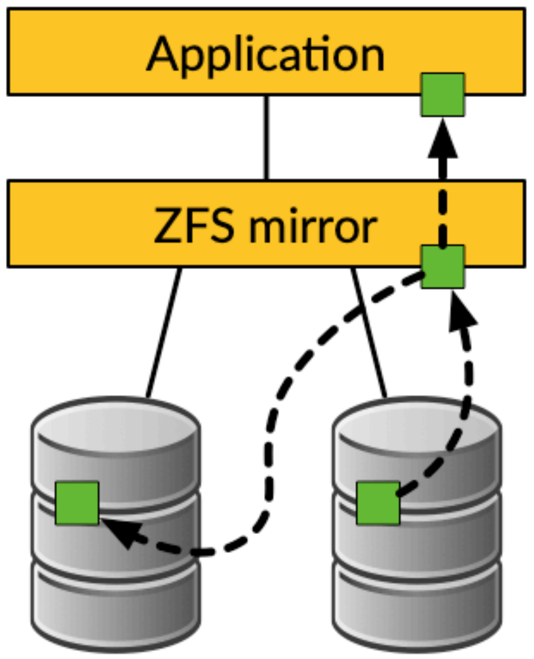
1. Application issues a read. ZFS mirror tries the first disk. Checksum reveals that the block is corrupt on disk.



2. ZFS tries the second disk. Checksum indicates that the block is good.



3. ZFS returns good data to the application **and repairs the damaged block** on the first disk.



Self-healing data demo

Store some important data (1/2)

- We have created a redundant pool with two mirrored disks and stored some important data on it

- We will be very sad if the data gets lost! :-(

```
# zfs list tank
NAME    USED  AVAIL  REFER  MOUNTPOINT
tank     74K   984G    23K  /tank

# cp -a /some/important/data/ /tank/

# zfs list tank
NAME    USED  AVAIL  REFER  MOUNTPOINT
tank   3.23G   981G  3.23G  /tank
```

Self-healing data demo

Store some important data (2/2)

```
# zpool status tank
  pool: tank
 state: ONLINE
  scan: none requested
config:

        NAME          STATE     READ WRITE CKSUM
        tank          ONLINE       0     0     0
          mirror-0    ONLINE       0     0     0
            md0       ONLINE       0     0     0
            md1       ONLINE       0     0     0

errors: No known data errors

# zpool list tank
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  1016G  3.51G  1012G        -         -     0%     0%  1.00x  ONLINE  -
```

Self-healing data demo

Destroy one of the disks (1/2)

Caution!

This example can destroy data when used on the wrong device or a non-ZFS filesystem!

Always check your backups!

```
# zpool export tank

# dd if=/dev/random of=/dev/md1 bs=1m count=200

# zpool import tank
```

Self-healing data demo

Destroy one of the disks (2/2)

```
# zpool status tank
  pool: tank
 state: ONLINE
status: One or more devices has experienced an unrecoverable error.  An
        attempt was made to correct the error.  Applications are unaffected.
action: Determine if the device needs to be replaced, and clear the errors
        using 'zpool clear' or replace the device with 'zpool replace'.
   see: http://illumos.org/msg/ZFS-8000-9P
  scan: none requested
config:

        NAME        STATE     READ WRITE CKSUM
        tank        ONLINE       0     0     0
          mirror-0  ONLINE       0     0     0
            md0     ONLINE       0     0     5
            md1     ONLINE       0     0     0

errors: No known data errors
```

Self-healing data demo

Make sure everything is okay (1/3)

```
# zpool scrub tank
# zpool status tank
  pool: tank
 state: ONLINE
status: One or more devices has experienced an unrecoverable error.  An
        attempt was made to correct the error.  Applications are unaffected.
action: Determine if the device needs to be replaced, and clear the errors
        using 'zpool clear' or replace the device with 'zpool replace'.
   see: http://illumos.org/msg/ZFS-8000-9P
  scan: scrub in progress since Fri Oct 12 22:57:36 2018
        191M scanned out of 3.51G at 23.9M/s, 0h2m to go
        186M repaired, 5.32% done
config:

        NAME          STATE     READ WRITE CKSUM
        tank          ONLINE       0     0     0
          mirror-0    ONLINE       0     0     0
            md0       ONLINE       0     0 1.49K  (repairing)
            md1       ONLINE       0     0     0

errors: No known data errors
```

Self-healing data demo

Make sure everything is okay (2/3)

```
# zpool status tank
  pool: tank
 state: ONLINE
status: One or more devices has experienced an unrecoverable error.  An
        attempt was made to correct the error.  Applications are unaffected.
action: Determine if the device needs to be replaced, and clear the errors
        using 'zpool clear' or replace the device with 'zpool replace'.
   see: http://illumos.org/msg/ZFS-8000-9P
  scan: scrub repaired 196M in 0h0m with 0 errors on Fri Oct 12 22:58:14 2018
config:

        NAME        STATE     READ WRITE CKSUM
        tank        ONLINE       0     0     0
          mirror-0  ONLINE       0     0     0
            md0     ONLINE       0     0 1.54K
            md1     ONLINE       0     0     0

errors: No known data errors
```

Self-healing data demo

Make sure everything is okay (3/3)

```
# zpool clear tank

# zpool status tank
  pool: tank
 state: ONLINE
  scan: scrub repaired 196M in 0h0m with 0 errors on Fri Oct 12 22:58:14 2018
config:

        NAME        STATE     READ WRITE CKSUM
        tank        ONLINE       0     0     0
          mirror-0  ONLINE       0     0     0
            md0     ONLINE       0     0     0
            md1     ONLINE       0     0     0

errors: No known data errors
```

Self-healing data demo

But what if it goes very wrong? (1/2)

```
# zpool status
  pool: tank
 state: ONLINE
status: One or more devices has experienced an error resulting in data
        corruption.  Applications may be affected.
action: Restore the file in question if possible.  Otherwise restore the
        entire pool from backup.
   see: http://illumos.org/msg/ZFS-8000-8A
  scan: scrub in progress since Fri Oct 12 22:46:01 2018
        498M scanned out of 3.51G at 99.6M/s, 0h0m to go
        19K repaired, 13.87% done
config:

        NAME          STATE     READ WRITE CKSUM
        tank          ONLINE       0     0 1.48K
          mirror-0    ONLINE       0     0 2.97K
            md0       ONLINE       0     0 2.97K
            md1       ONLINE       0     0 2.97K

errors: 1515 data errors, use '-v' for a list
```

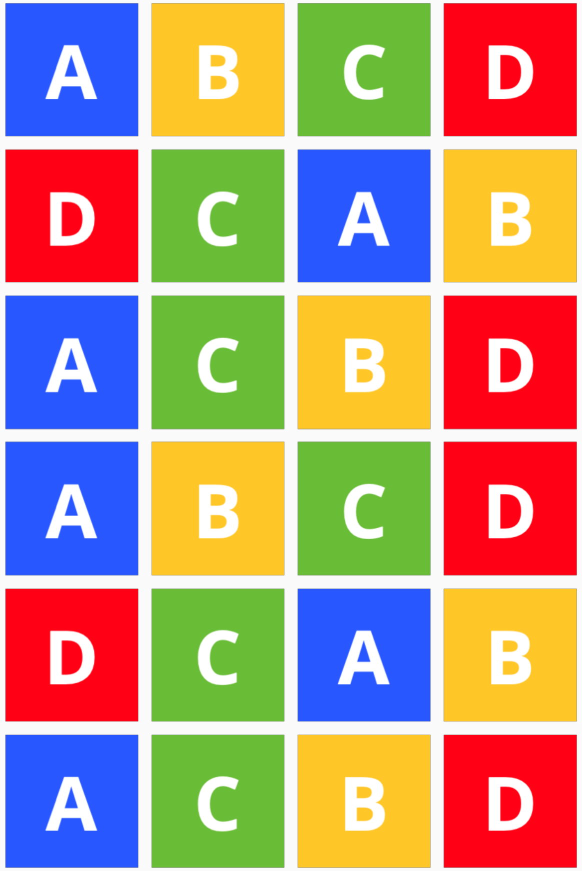
Self-healing data demo

But what if it goes very wrong? (2/2)

```
# zpool status -v
  pool: tank
 state: ONLINE
status: One or more devices has experienced an error resulting in data
        corruption.  Applications may be affected.
action: Restore the file in question if possible.  Otherwise restore the
        entire pool from backup.
   see: http://illumos.org/msg/ZFS-8000-8A
  scan: scrub repaired 19K in 0h0m with 1568 errors on Fri Oct 12 22:46:25 2018
config:

        NAME        STATE     READ WRITE CKSUM
        tank        ONLINE       0     0 1.53K
          mirror-0  ONLINE       0     0 3.07K
            md0     ONLINE       0     0 3.07K
            md1     ONLINE       0     0 3.07K

errors: Permanent errors have been detected in the following files:

        /tank/FreeBSD-11.2-RELEASE-amd64.vhd.xz
        /tank/base-amd64.txz
        /tank/FreeBSD-11.2-RELEASE-amd64-disc1.iso.xz
        /tank/intro_slides.pdf
```

Deduplication

Duplication



A	B	C	D
D	C	A	B
A	C	B	D
A	B	C	D
D	C	A	B
A	C	B	D

Intentional duplication

- Backups, redundancy

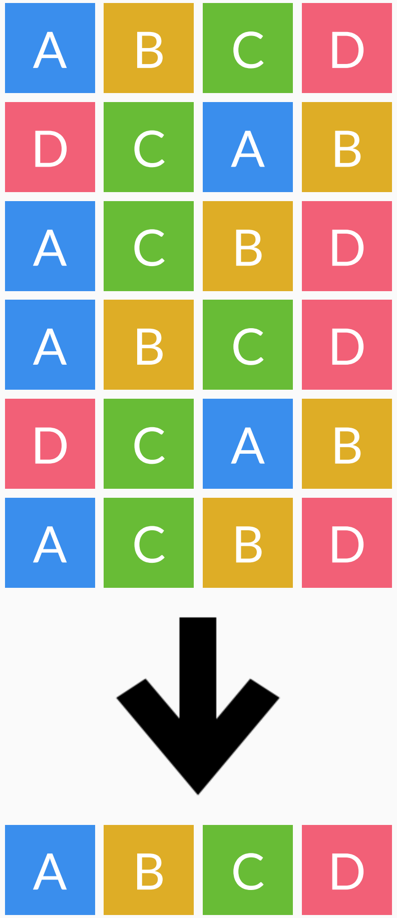
Unintentional duplication

- Application caches
- Temporary files

- Node.js (Grrr!)

Deduplication

- Implemented at the block layer
- ZFS detects when it needs to store an exact copy of a block
- Only a reference is written rather than the entire block
- Can save a lot of disk space



Deduplication

Memory cost

- ZFS must keep a table of the checksums of every block it stores
- Depending on the blocksize, this table can grow very quickly
- Deduplication table must be fast to access or writes slow down
- Ideally, the deduplication table should fit in RAM
- Keeping a L2ARC on fast SSDs can reduce the cost somewhat

Rule of thumb:

5GB of RAM for each TB of data stored

Deduplication

Is it worth it? (1/2)

- The ZFS debugger (`zdb`) can be used to evaluate if turning on deduplication will save space in a pool
- In most workloads, compression will provide much more significant savings than deduplication
- Consider whether the cost of RAM is worth it
- Also keep in mind that it is a lot easier and cheaper to add disks to a system than it is to add memory

Deduplication demo

Is it worth it? (2/2)

```
# zdb -S tank
Simulated DDT histogram:

bucket              allocated                       referenced
______   ______________________________   ______________________________
refcnt   blocks   LSIZE   PSIZE   DSIZE   blocks   LSIZE   PSIZE   DSIZE
------   ------   -----   -----   -----   ------   -----   -----   -----
     1    25.1K   3.13G   3.13G   3.13G    25.1K   3.13G   3.13G   3.13G
     2    1.48K    189M    189M    189M    2.96K    378M    378M    378M
 Total    26.5K   3.32G   3.32G   3.32G    28.0K   3.50G   3.50G   3.50G

dedup = 1.06, compress = 1.00, copies = 1.00, dedup * compress / copies = 1.06
```

Deduplication demo

Control experiment (1/2)

```
# zpool list tank
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  7.50G  79.5K  7.50G        -         -     0%     0%  1.00x  ONLINE  -

# zfs get compression,dedup tank
NAME  PROPERTY     VALUE          SOURCE
tank  compression  off            default
tank  dedup        off            default

# for p in `seq 0 4`; do
> portsnap -d /tmp/portsnap -p /tank/ports/$p extract &
> done

# zpool list tank
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  7.50G  2.14G  5.36G        -         -     3%    28%  1.00x  ONLINE  -
```

Deduplication demo

Control experiment (2/2)

```
# zdb -S tank
Simulated DDT histogram:

bucket              allocated                       referenced
______   ______________________________   ______________________________
refcnt   blocks   LSIZE   PSIZE   DSIZE   blocks   LSIZE   PSIZE   DSIZE
------   ------   -----   -----   -----   ------   -----   -----   -----
     4     131K    374M    374M    374M     656K   1.82G   1.82G   1.82G
     8    2.28K   4.60M   4.60M   4.60M    23.9K   48.0M   48.0M   48.0M
    16      144    526K    526K    526K    3.12K   10.5M   10.5M   10.5M
    32       22   23.5K   23.5K   23.5K      920    978K    978K    978K
    64        2   1.50K   1.50K   1.50K      135    100K    100K    100K
   256        1     512     512     512      265    132K    132K    132K
 Total     134K    379M    379M    379M     685K   1.88G   1.88G   1.88G

dedup = 5.09, compress = 1.00, copies = 1.00, dedup * compress / copies = 5.09
```

Deduplication demo

Enabling deduplication

```
# zpool list tank
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  7.50G  79.5K  7.50G        -         -     0%     0%  1.00x  ONLINE  -

# zfs get compression,dedup tank
NAME  PROPERTY     VALUE           SOURCE
tank  compression  off             default
tank  dedup        on              default

# for p in `seq 0 4`; do
> portsnap -d /tmp/portsnap -p /tank/ports/$p extract &
> done

# zpool list tank
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  7.50G   670M  6.85G        -         -     6%     8%  5.08x  ONLINE  -
```

Deduplication demo

Compare with compression

```
# zpool list tank
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  7.50G  79.5K  7.50G        -         -     0%     0%  1.00x  ONLINE  -

# zfs get compression,dedup tank
NAME  PROPERTY     VALUE          SOURCE
tank  compression  gzip-9         local
tank  dedup        off            default

# for p in `seq 0 4`; do
> portsnap -d /tmp/portsnap -p /tank/ports/$p extract &
> done

# zpool list tank
NAME   SIZE  ALLOC   FREE  CKPOINT  EXPANDSZ   FRAG    CAP  DEDUP  HEALTH  ALTROOT
tank  7.50G   752M  6.77G        -         -     3%     9%  1.00x  ONLINE  -
```

Deduplication

Summary

- ZFS deduplication can save a lot of space under some workloads but at the expense of a lot of memory
- Often, compression will give similar or better results
- Always check with `zdb –S` whether deduplication would be worth it

Control experiment	2.14G
Deduplication	670M
Compression	752M

Serialisation

Encrypted backups over the network

Excercises

Lab preliminaries

- Take a snapshot of your virtual machine before you start the exercises.

- Your USB stick has useful data on it. Mount it read-only in the virtual machine so you do not accidentally destroy it.

Exercises

Storage pools

Storage pools (1/3)

1. Create eight fake disks on your virtual machine
   - Use `truncate(1)` and `mdconfig(8)`
   - Bonus points: write a shell loop!
2. Create a pool with one disk
3. Add a second disk to the pool
4. Add a mirror of two more disks to the pool

```
# truncate -s 1TB diskX

# mdconfig -a -t vnode -f diskX

# zpool create
# zpool add
# zpool attach
# zpool destroy


NOTE: If you want to use fake disks larger
      than the disk in your virtual machine
      you must set this sysctl(8) first:

      # sysctl vfs.zfs.vdev.trim_on_init=0

 Your VM will run out of space if you forget!
```

Storage pools (2/3)

1. Destroy the pool from the previous exercise and create a new pool with one disk
2. Convert the pool to a mirror by attaching a second disk
3. Add a third disk to the pool

```
# truncate -s 1TB diskX

# mdconfig -a -t vnode -f diskX

# zpool create
# zpool add
# zpool attach
# zpool destroy


NOTE: If you want to use fake disks larger
      than the disk in your virtual machine
      you must set this sysctl(8) first:

      # sysctl vfs.zfs.vdev.trim_on_init=0

 Your VM will run out of space if you forget!
```

Storage pools (3/3)

1. Destroy the pool from the previous exercise and create a new pool with two mirrored disks
2. Add a raidz set of four disks to the pool
3. Add the last two disks to the pool as an extra mirror

```
# truncate -s 1TB diskX

# mdconfig -a -t vnode -f diskX

# zpool create
# zpool add
# zpool attach
# zpool destroy


NOTE: If you want to use fake disks larger
      than the disk in your virtual machine
      you must set this sysctl(8) first:

      # sysctl vfs.zfs.vdev.trim_on_init=0

 Your VM will run out of space if you forget!
```

Self-healing data

1. Create a raidz pool with four disks and copy the FreeBSD ports tree to it.
2. Export the pool and destroy one disk at random.
3. Import the pool.
4. Scrub the pool and export it again.
5. Destroy a second disk and try to import the pool.
6. Explain what happens.
7. How would you protect against this eventuality?

Exercises

Datasets

Quotas

1. Create the datasets as shown in the example below
2. Set a quota of 500M on `tank/users` and 1G on `tank/users/bob`
3. Copy a 1G file to `/tank/users/bob`
4. Explain what happens

```
# zfs list -r tank
NAME                  USED  AVAIL  REFER  MOUNTPOINT
tank                  176K  1.75G    23K  /tank
tank/users             92K  1.75G    23K  /tank/users
tank/users/alice       23K  1.75G    23K  /tank/users/alice
tank/users/bob         23K  1.75G    23K  /tank/users/bob
tank/users/eve         23K  1.75G    23K  /tank/users/eve
```

Reservations

1. Repeat the previous exercise, but set a reservation of 500M on tank/users instead of a quota.
2. Now what happens?

Exercises

Snapshots

Credits

- ZFS: The last word in filesystems
  Jeff Bonwick and Bill Moore
  URL:
  https://wiki.illumos.org/download/attachments/1146951/zfs_last.pdf

- Introduction to the ZFS filesystem
  Benedict Reuschling
  URL: `[offline]`