BetrFS: A right-optimized, write-optimized file system

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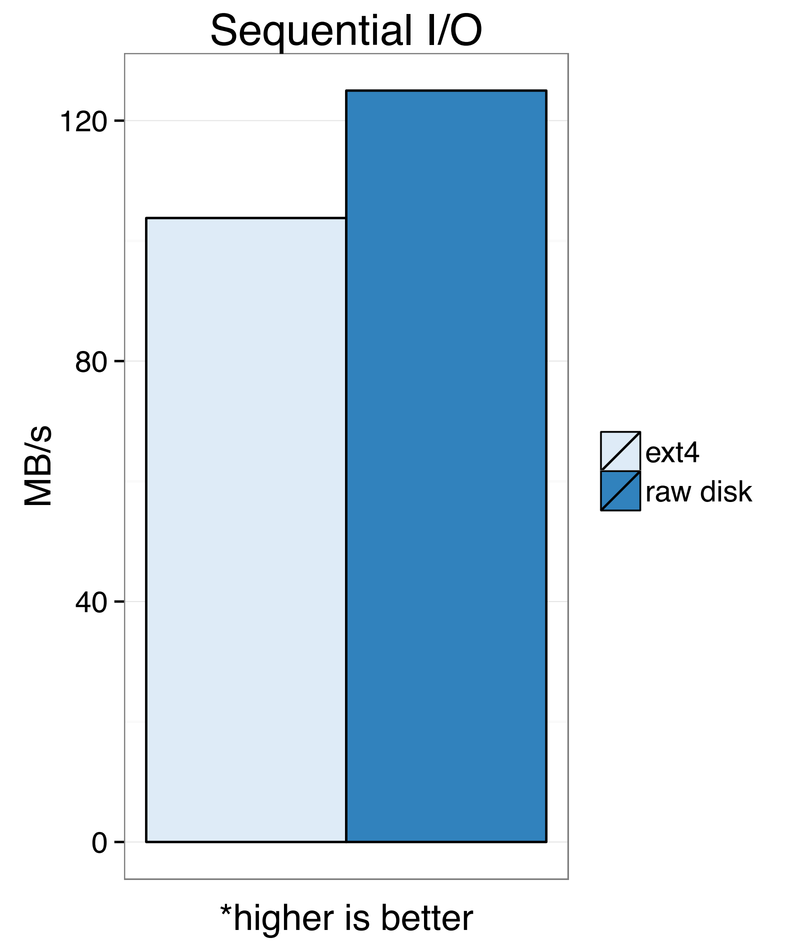
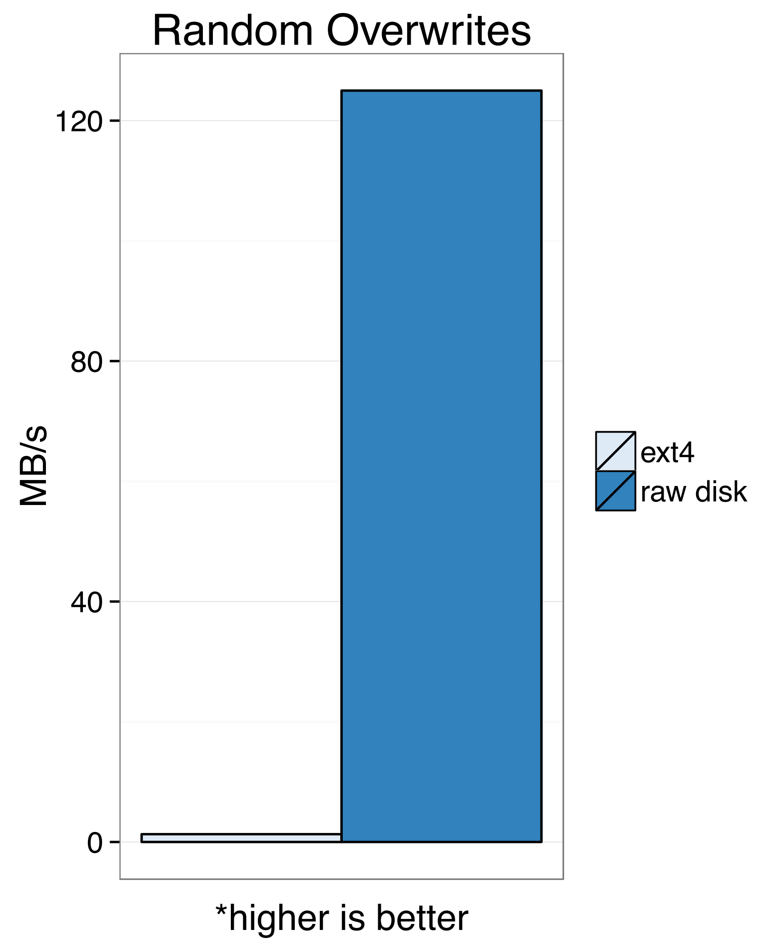
ext4 is good at sequential I/O



- Disk bandwidth spec:
  125 MB/s
- Workload: 1GiB sequential write
- `ext4` bandwidth:
  - 104 MB/s

ext4 struggles with random writes



- Disk bandwidth spec:
  125 MB/s
- Workload: Small, random writes of cached data
- `ext4` write bandwidth:
  - 1.5 MB/s

What is going on here?

- Random write performance dominated by seeks
- Back-of-the-envelope:
  - Average disk seek time is 11ms
  - Seek for every 4KB write
  - Implies maximum 0.4MB/s bandwidth
    - Previous benchmark benefits from locality, good I/O scheduling

Avoiding seeks: log-structured file systems

- Pros:
  - writing data is just an append to the log
- Cons:
  - file blocks can become scattered on disk
  - reading data becomes slow

- Logging still presents a tradeoff between random-write and sequential-I/O performance

BetrFS

- Use **write-optimized indexes** (WOIs)
  - on-disk data structures that rapidly ingest new data while maintaining logical locality
- Create a schema that maps file operations to efficient WOI operations
- Implemented in the Linux kernel
  - exposed new performance opportunities

Advancing write-optimized FSes

- Prior work: WOIs can accelerate FS operations
  - TokuFS [Esmet, Bender, Farach-Colton, Kuszmaul '12], KVFS [Shetty, Spillane, Malpani, Andrews, Seyster, and Zadok '13], TableFS [Ren and Gibson '13],
  - Prior WOFSs in user space
- BetrFS goal: explore all the ways write-optimization can be used in a file system
  - explore the impact of write-optimization on the interaction with the rest of the system

BetrFS uses B^{ε}-Trees

- B^{ε}-trees: an asymptotically optimal key-value store
- B^{ε}-trees asymptotically dominate log-structured merge-trees
- We use Fractal Trees, an open-source B^{ε}-tree implementation from Tokutek

For this talk, we treat B^{ε} as a black box that performs fast insertions and fast point and range queries

B^{ε}-Tree Operations

- Implement a dictionary on key-value pairs
  - `insert(`**`k`**`,`**`v`**`)`
  - **`v`** `= search(`**`k`**`)`
  - `delete(`**`k`**`)`
  - **`k'`** `= successor(`**`k`**`)`
  - **`k'`** `= predecessor(`**`k`**`)`
- New operation:
  - `upsert(`**`k`**`,` f`)`

get, put, and delete elements one-at-a-time

query a range of values

B^{ε}-trees search/insert asymmetry

- Queries (point and range) comparable to B-trees
  - with caching, ~1 seek + disk bandwidth
  - hundreds of random queries per second
- Extremely fast inserts
  - tens of thousands per second

To get the best possible performance,
we want to do blind inserts (without searches)

upsert = update + insert

`upsert(k,f)`

- An `upsert` specifies a **mutation** to a value
  - e.g. increment a reference count
  - e.g. modify the 5th byte of a string
- `upserts` are encoded as messages and inserted into the tree
  - defer and batch expensive queries
  - we can perform tens of thousands of `upserts` per second

File System → B^{ε} Tree

- Maintain two separate B^{ε}-tree indexes:

metadata index: `path -> struct stat`

data index: `(path,blk#) -> data[4096]`

- Implications:
  - fast directory scans
  - data blocks are laid out sequentially

Operation Roundup

Operation	Implementation
read	range query
write	upsert
metadata update	upsert
`readdir`	range query
`mkdir/rmdir`	upsert
`unlink`	*delete each block
`rename`	*delete then reinsert each block

Fast `atime`

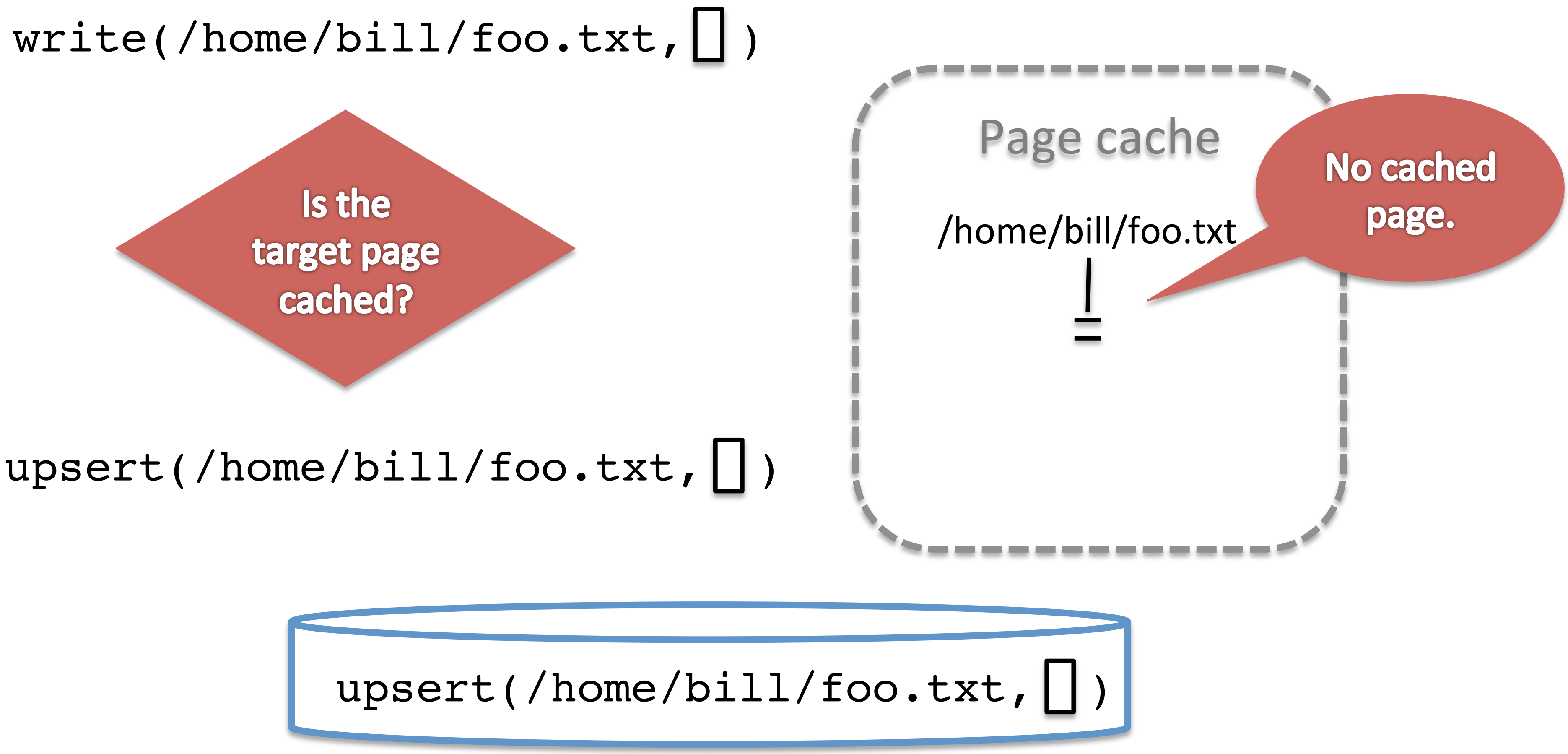
Efficient directory scans

cannot map to single WOI operation

Integrating BetrFS with the page cache

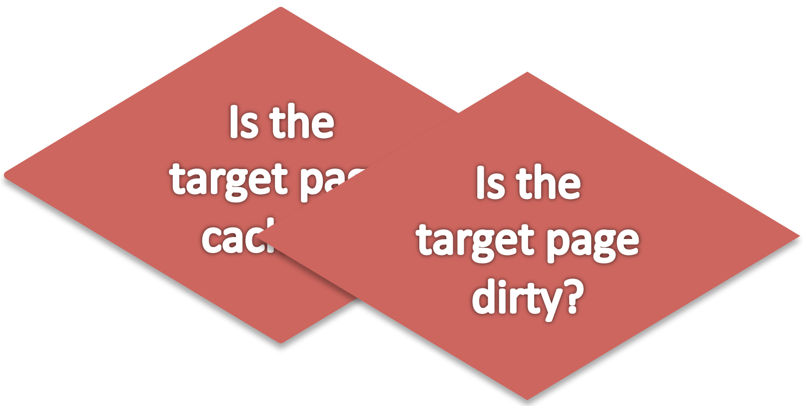
- Write-back caching can convert single-byte to full-page writes
- `upserts` enable BetrFS to avoid this write amplification

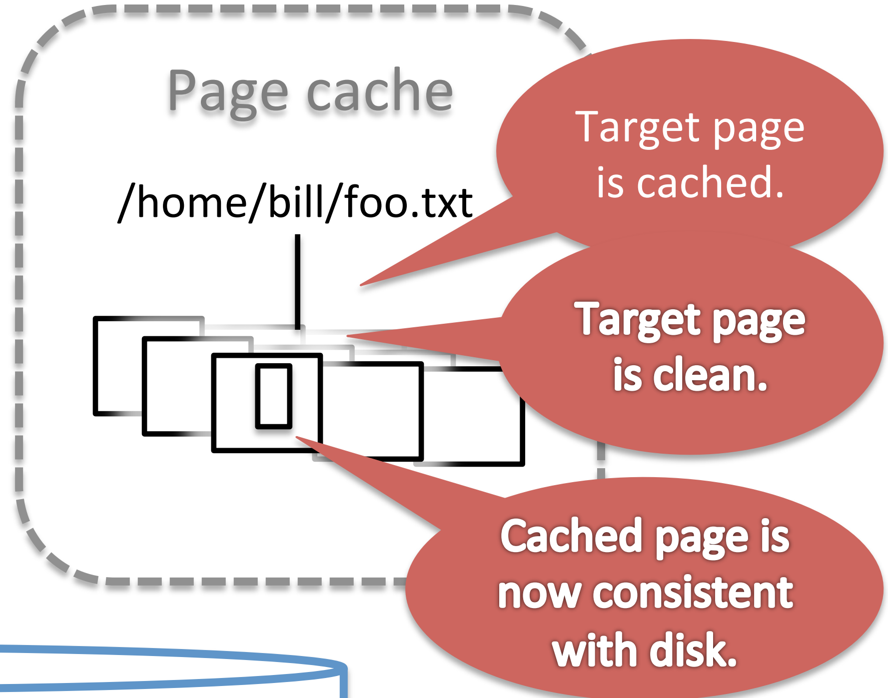
Page cache integration #1: blind write



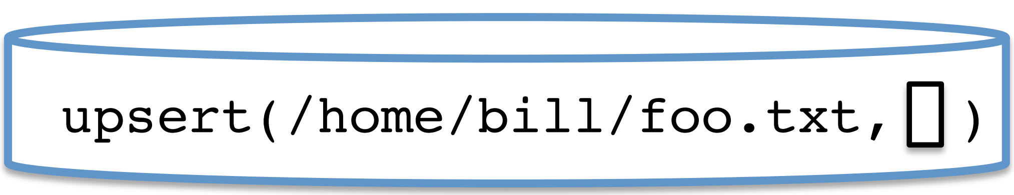
Page cache integration #2: write-after-read

```
write(/home/bill/foo.txt,▯)
```



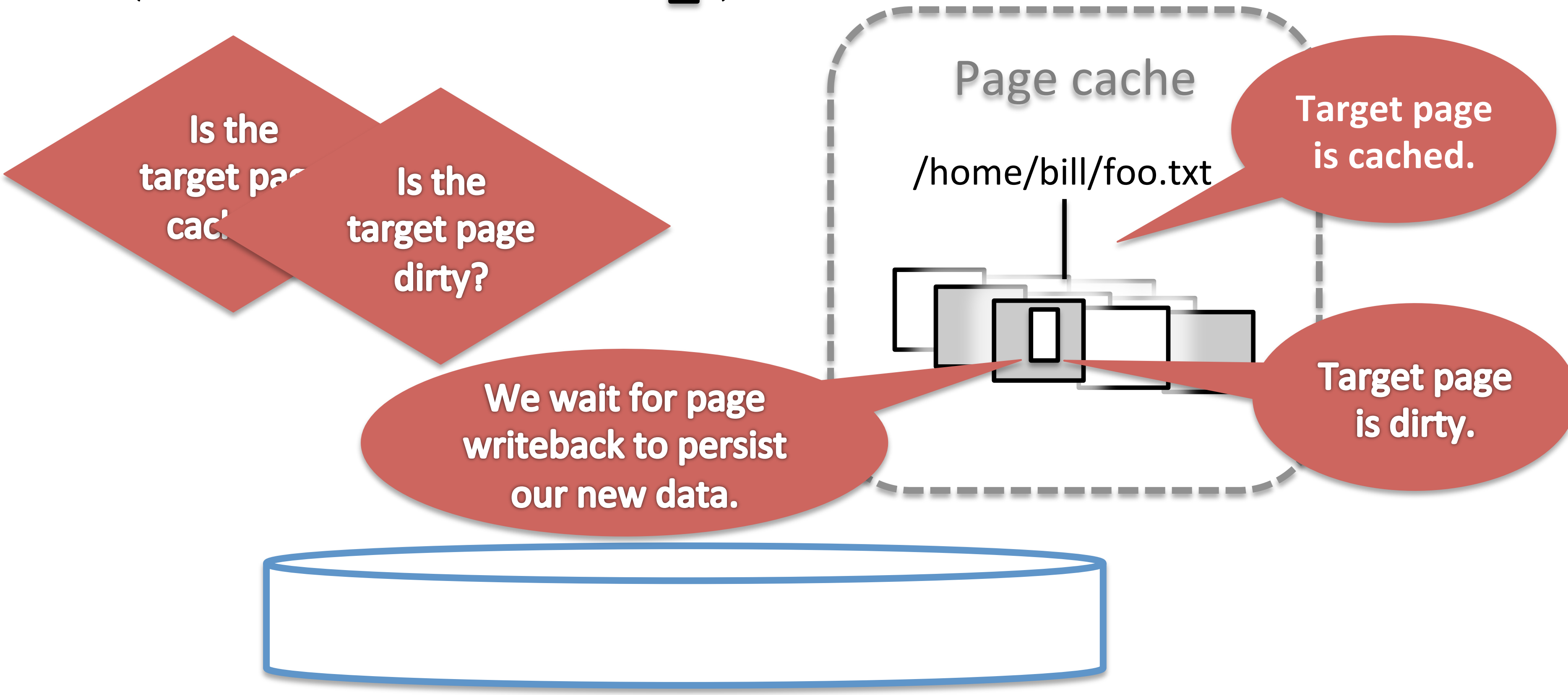



```
upsert(/home/bill/foo.txt,▯)
```



Page cache integration #3: write to mmap'ed file

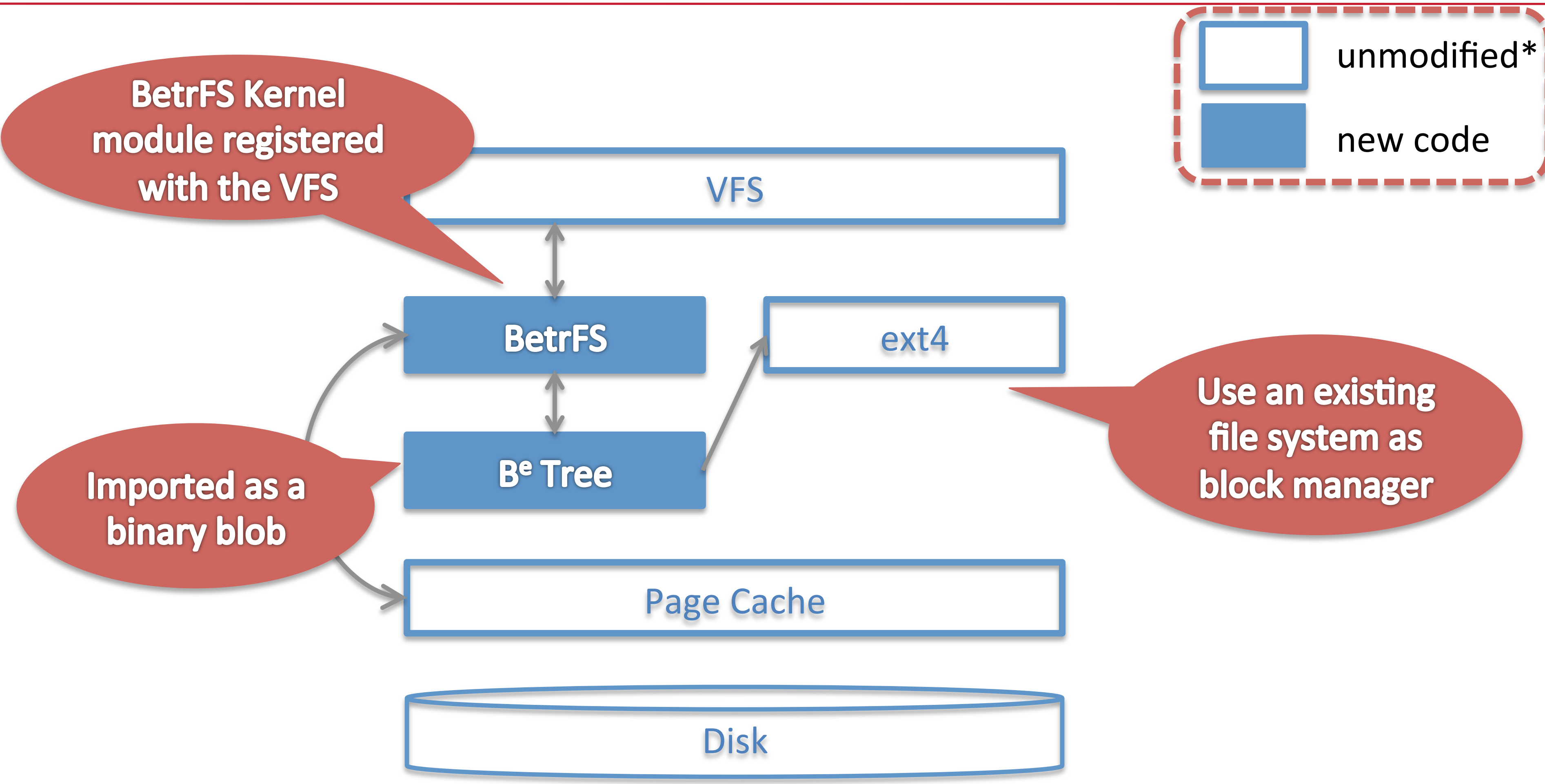
`write(/home/bill/foo.txt,▯)`



Page-cache takeaways

- By rethinking the interaction between the page cache and the file system, we benefit more than simply speeding up individual operations
  - use `upserts` to avoid unnecessary reads
  - use `upserts` to avoid write amplification

System Architecture



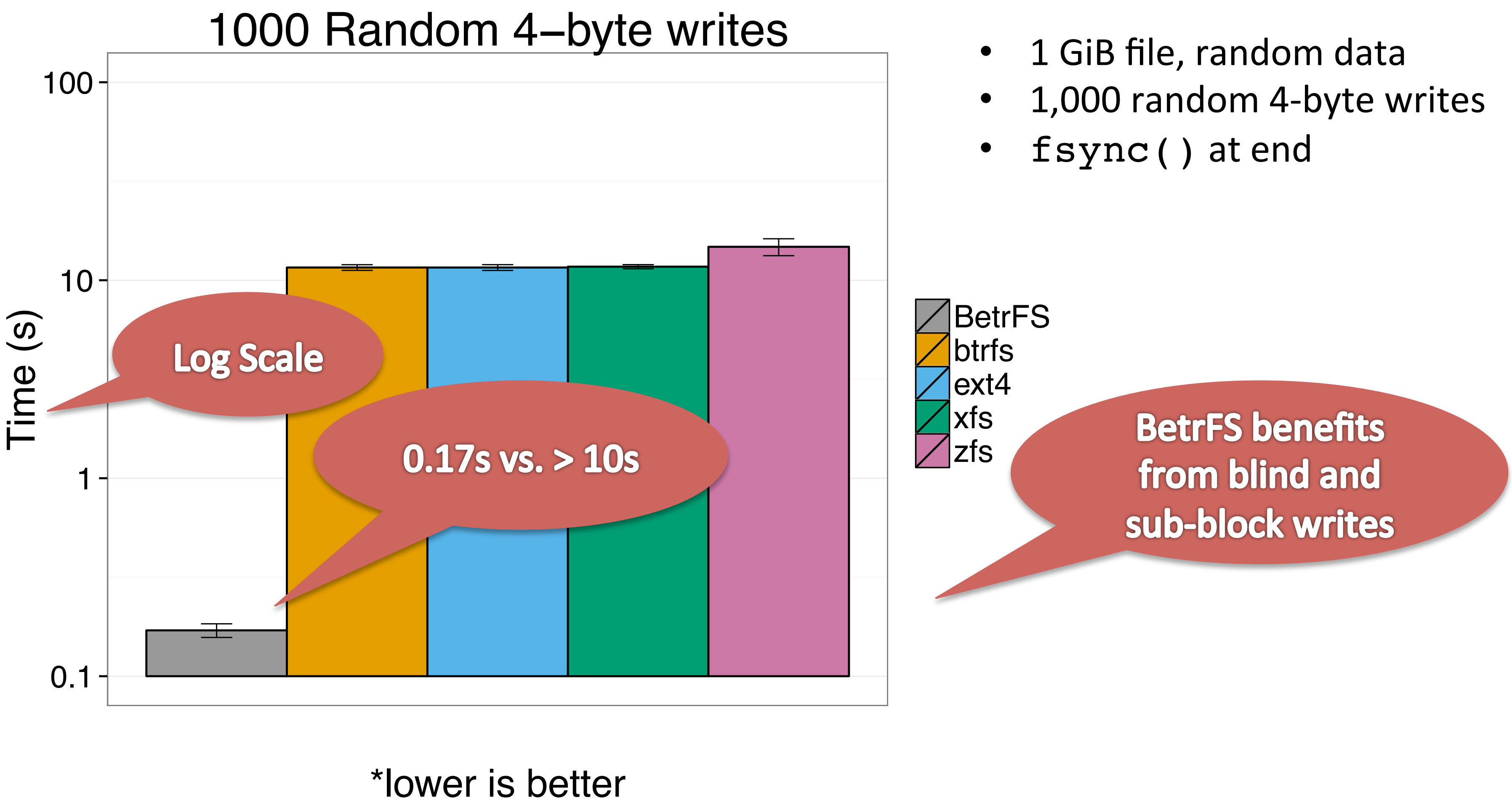
Performance Questions

- Do we meet our performance goals for small, random, unaligned writes?
- Is BetrFS competitive for sequential I/O?
- Do any real-world applications benefit?

Experimental Setup

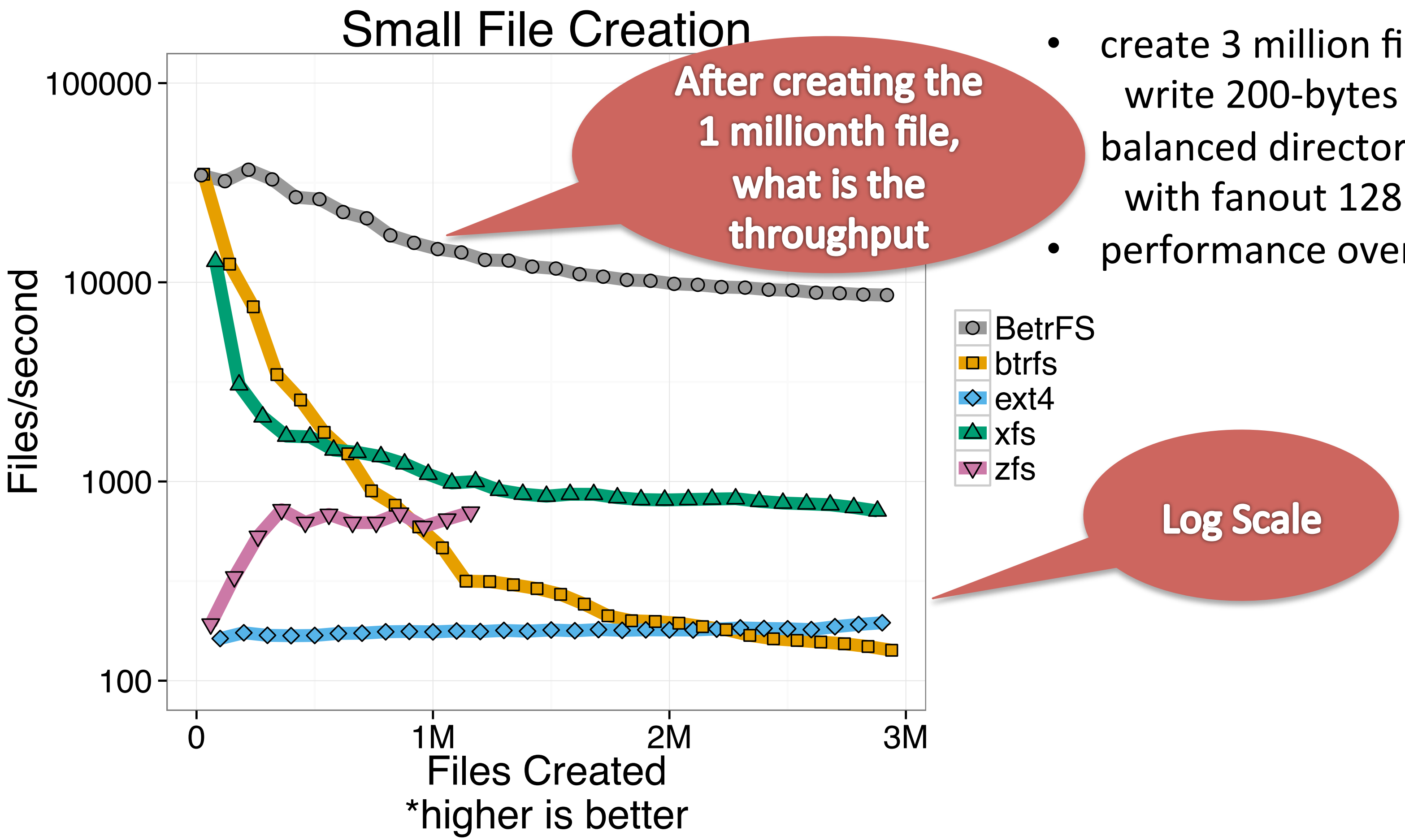
- Dell optiplex desktop:
  - 4-core 3.4 GHz i7, 4 GB RAM
  - 7200RPM 250GB Seagate Barracuda
- Compare with btrfs, ext4, xfs, zfs
  - default settings for all
- All tests are cold cache

Small, random, unaligned writes are an order-of-magnitude faster



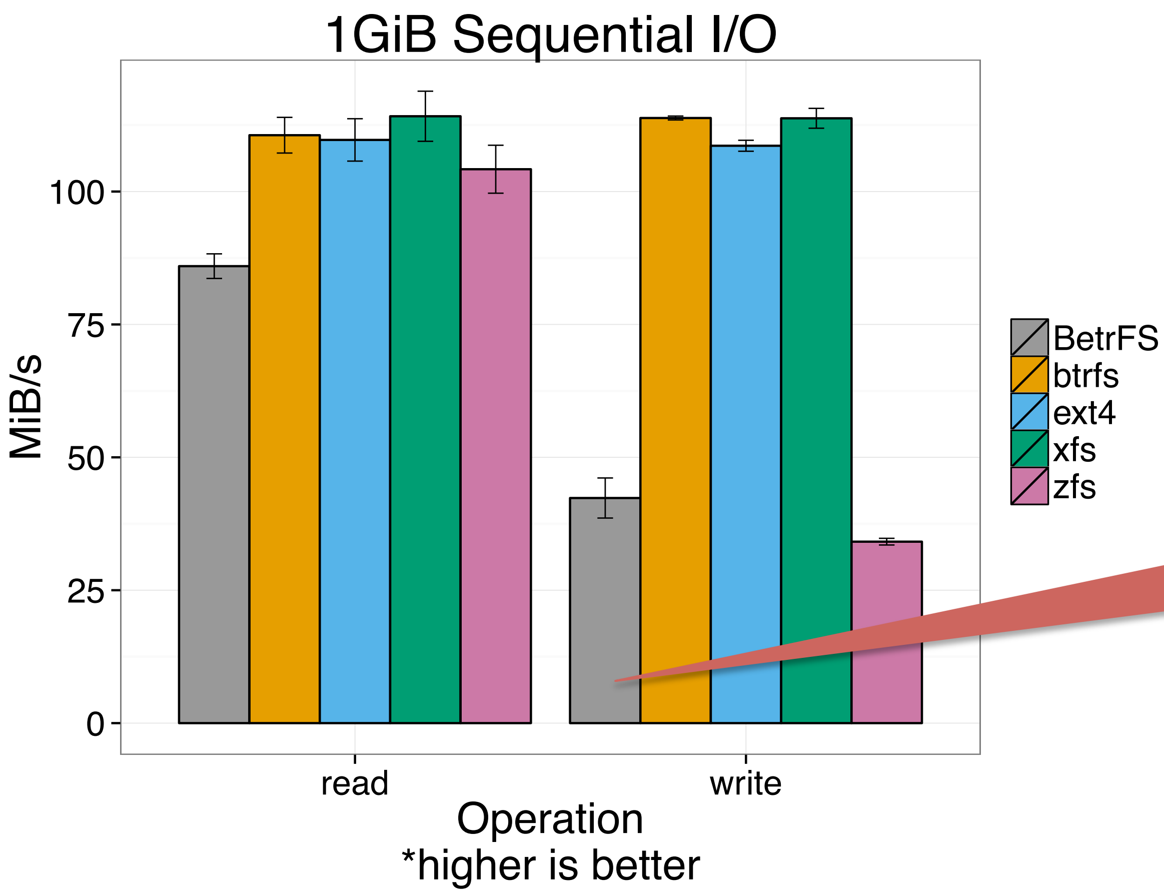
- 1 GiB file, random data
- 1,000 random 4-byte writes
- `fsync()` at end

Small file creates are an order-of-magnitude faster



- create 3 million files and write 200-bytes to each
- balanced directory tree with fanout 128
- performance over time

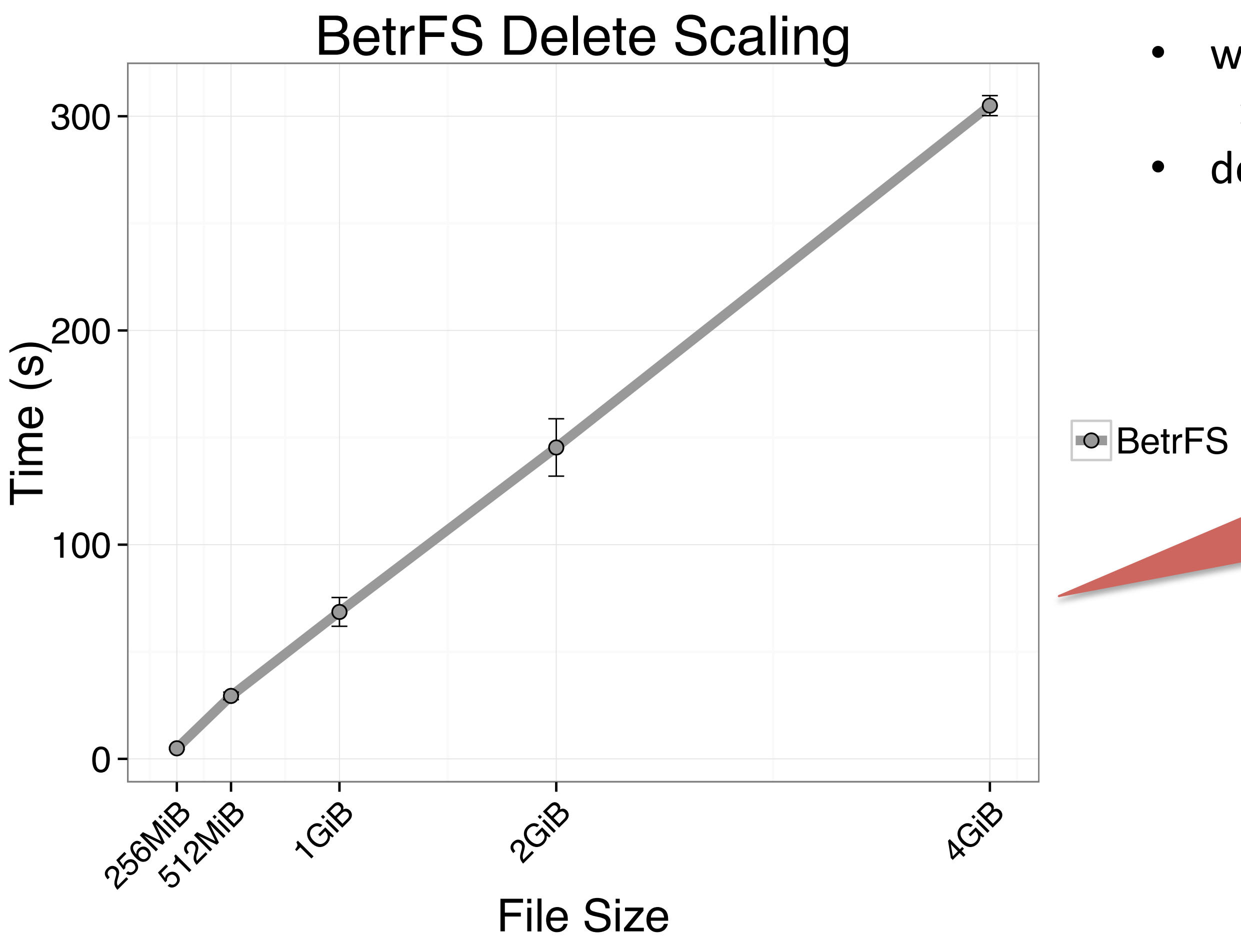
Sequential I/O



- Write random data to file, 10 4K-blocks at a time
- Sequentially read data back

Write all data at least 2x (B^{ε}-tree journaling)

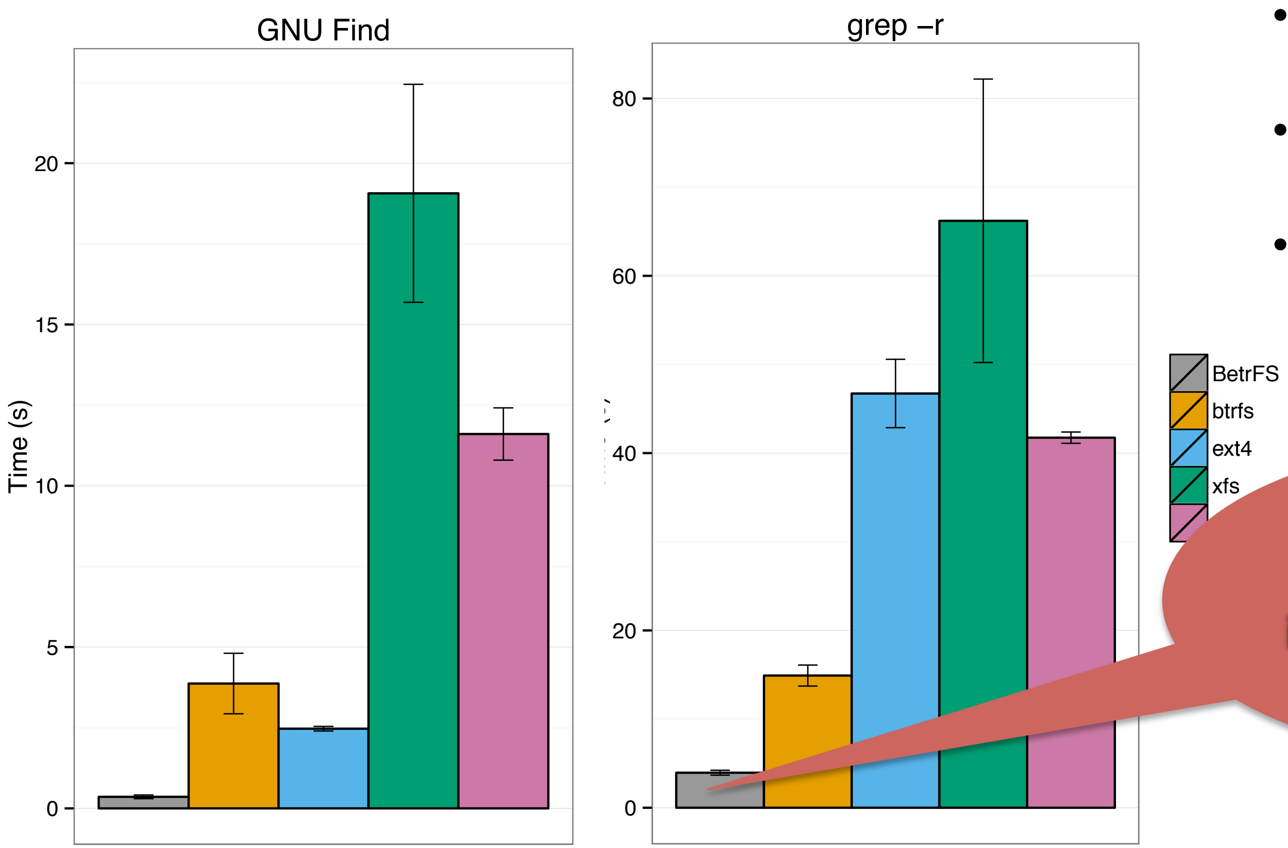
BetrFS forgoes indirection for locality: delete, rename O(n)



- write random data to file, `fsync()` it
- delete file

O(n) scaling: must delete each block individually

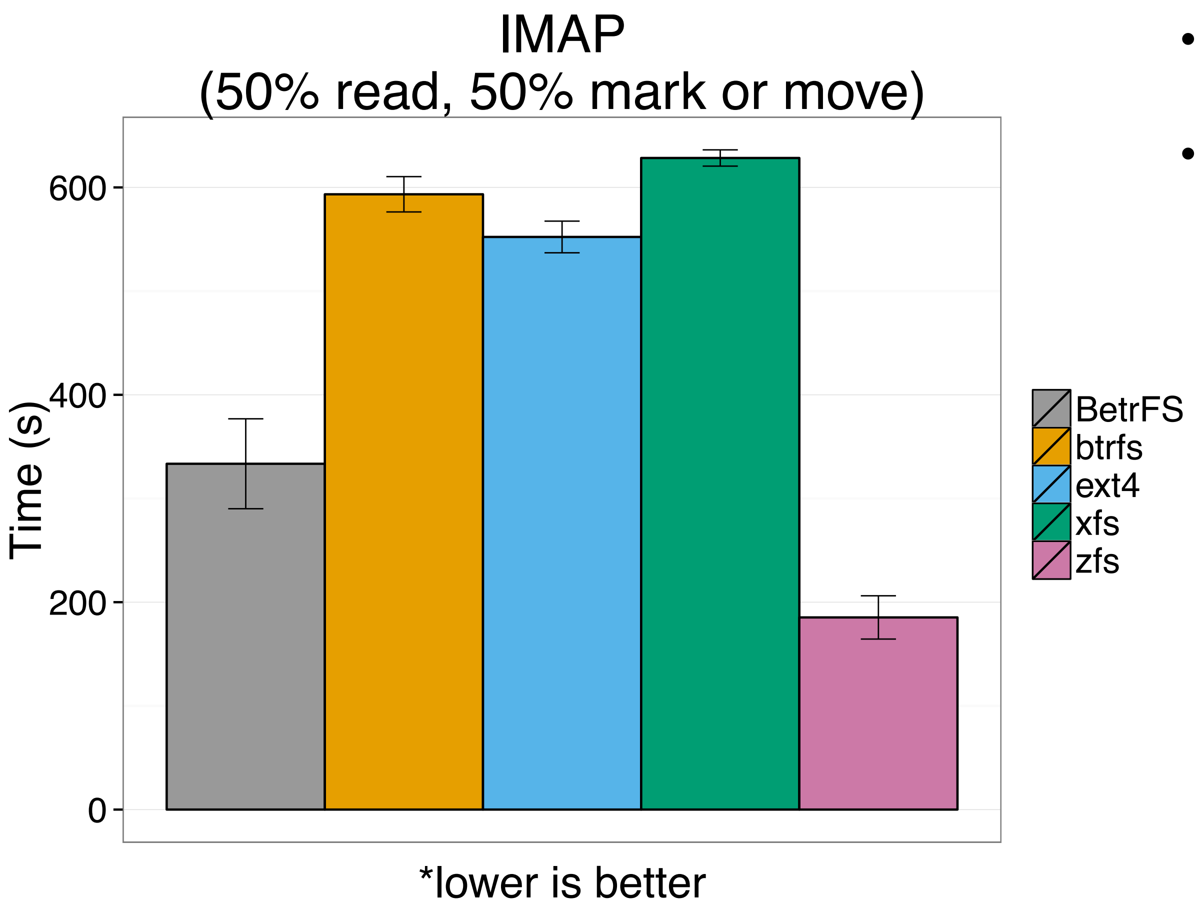
BetrFS forgoes indirection for locality: fast directory scans



- recursive scans from root of Linux 3.11.10 source
- GNU `find` scans file metadata
- `grep –r` scans file contents

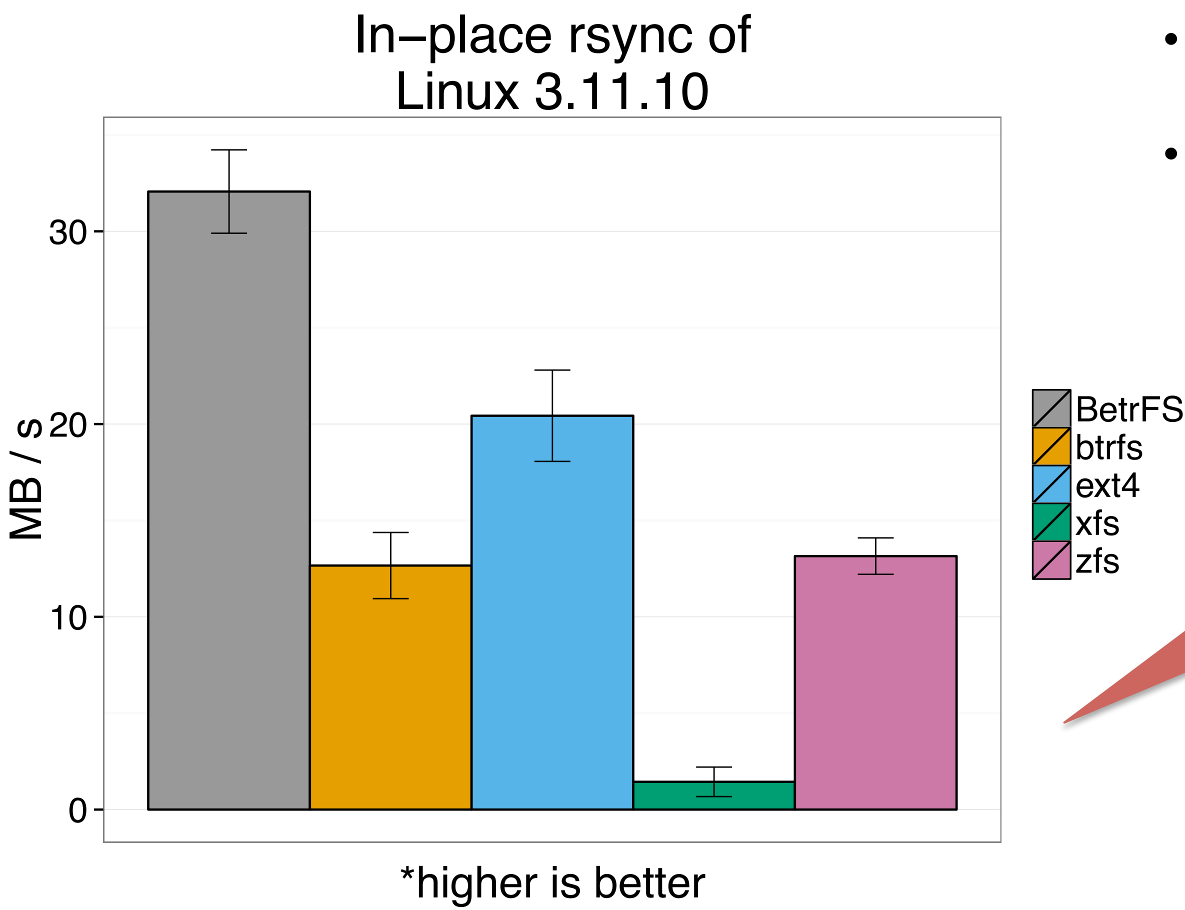
full-path keys let BetrFS efficiently implement scans using range queries

BetrFS Benefits Mailserver Workloads



- Dovecot 2.2.13 mail server using **maildir**
- 26,000 `sync()` operations

BetrFS Benefits `rsync`



- `rsync` Linux source tree to new directory on *same* FS
- copying to an empty directory

`--in-place`
flag lets BetrFS issue blind writes

Performance Questions

- Do we meet our performance goals for small, random writes?
- Is BetrFS competitive for sequential I/O? *
  - * More work to do here
- Do any real-world applications benefit?
  - More experiments in paper

BetrFS

- Cake && Eat: One file system can have good sequential and random I/O performance
- WOI performance requires revisiting many design decisions
  - inodes
  - write-through vs. write-back caching
  - perform blind writes whenever possible

`betrfs.org` – github.com/oscarlab/betrfs