File Systems

Main issues:

- performance,
- space usage.

Main considerations:

- file sizes,
- file usage patterns,
- memory vs. disk speeds,
- disk characteristics.

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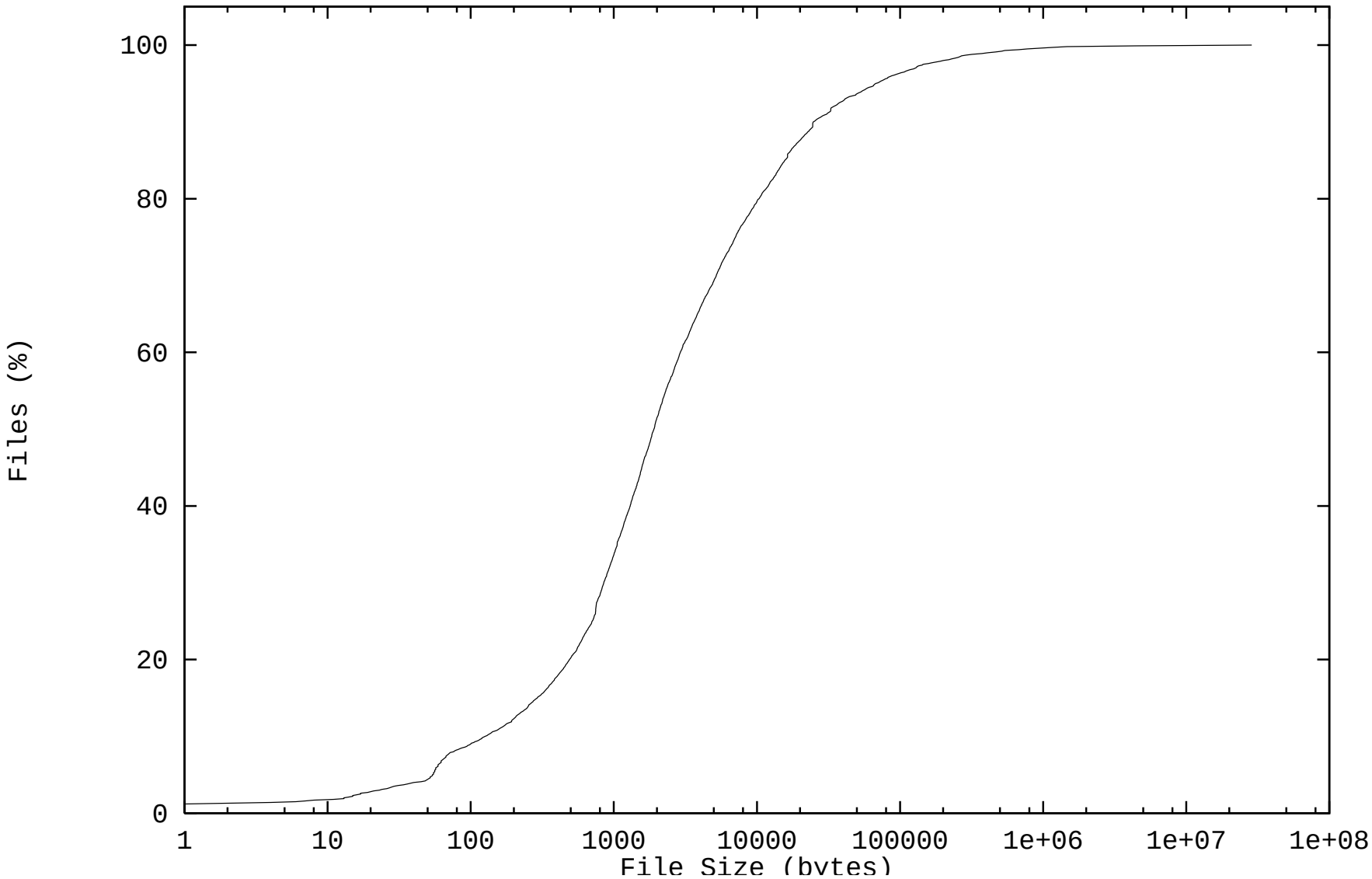

File size distribution in CSE “VaST” network [Elp93].

DISK CHARACTERISTICS

- Unit of access is *sector*, order of kB.
- A number of sectors per *track*,
- *rotational delay* between non-consecutive sectors.
- Several platters, corresponding tracks form *cylinders*.
- Head movement required between cylinders – *seek delay*.
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- Failing discs remap sectors to spare tracks

IBM ULTRASTAR FIBERCHANNEL

Sector size 512bytes
Nr. heads 12
Rotational speed 10 000rpm
Sectors/track varies from 440 (zone 14) to 864 (zone 0)
Number of Cylinders 36 735
Seek time 4.7ms (read) 5.9ms (Write); typical.
Seek time (full stroke) 11ms
Latency 3ms (ave) (based on 6ms for one rotation == 10 000rpm)
Media transfer rate 73.7 (outermost zone) to 37.5 (innermost) MB/s
Interface transfer rate 200MBytes/sec (2G fiberchannel)
Sustained data rate 66.7MB/s (typical)

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- Finally data blocks.

NEW THINGS

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- Directories maintained by OS, just name ⇔ inumber
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  - Block allocation using free list leads to randomisation of file's blocks.
  - Generally no attempt to minimise rotational and seek latencies.

The Berkeley Fast File System (FFS)

FFS was designed to overcome the problems of UFS [MJLF84]

FFS MAIN FEATURES:

- *Cylinder groups* to improve locality.
  - Copy of superblock in each cylinder group (on different platters) to improve fault tolerance.
  - *Free block bitmap* per cylinder group, supports allocation of consecutive blocks.

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- *Fragments* (1/2 – 1/8 blocks) to reduce fragmentation.
- Pre-allocated inodes scattered throughout cylinder groups,
- *Bitmap free list* for fast allocation.
- Ability to *rebuild free lists* after crash (fsck).

CYLINDER GROUPS:

- If possible, file direct-blocks and index blocks are allocated from same CG as inode,
- up to a maximum (25 % of CG capacity) to avoid squeezing out small files.
- Attempt to allocate consecutive logical blocks *rotationally optimal*.
  - Aided by bitmap free list.
- Attempt to allocate (plain) files' inodes in same CG as *directory*.
- Spread directories across CGs.

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- Fragment array is unaligned but must not span blocks.
- When extending:
  - ⋆ try allocating extra fragment from same block,
  - ⋆ otherwise copy.
- Allocation supported by using fragment granularity in free block bitmap.

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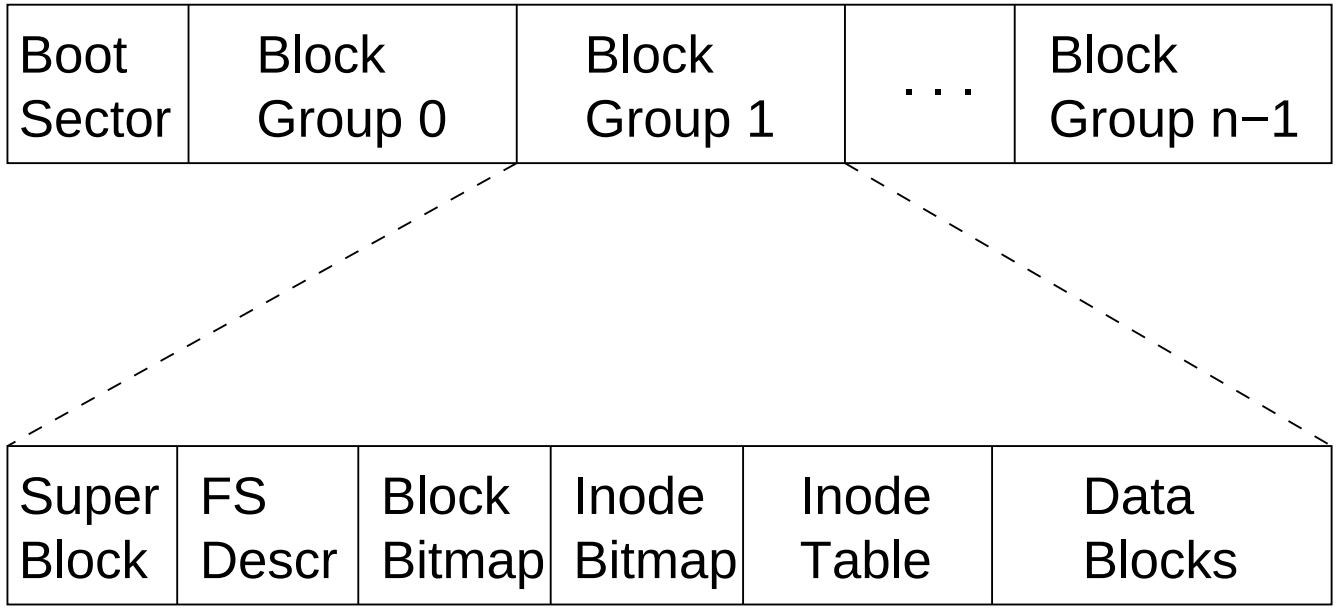
VARIANT: LINUX EXTENDED-2 FILE SYSTEM (EXT2FS)

- (Logical) *block groups* rather than cylinder groups.
- Inode array in each block group.
- Store (short) symbolic links in inode.
- Preallocates contiguous blocks.



Ext2FS Disk layout

FFS PROBLEM: SYNCHRONOUS UPDATES

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  - ⋆ On file extension:
    - ① Write data block *before* inode (for security).
    - ② Write updated inode/indirect block before updating bitmap.
  - ⋆ Similarly on file truncation.

- Running `fsck` after crash rebuilds consistent bitmaps.
- Synchronous I/O limiting when creating/deleting many files.

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- Cost:
  - Slightly more loss of user data during crash.
  - Much more complicated disk scheduling and interrupt

processing.

- Disks can reorder write requests internally

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- Cedar [Hag87]:
  - ⋆ Log written twice a second, grouping metadata updates.
  - ⋆ Must ensure that log records are written *before* the logged metadata.
  - ⋆ Other updates can be undone if crash before log write.
  - ⋆ Use B-tree for directories.
  - ⋆ Keep other metadata just before first data block.

- Linux ext3

SGI's XFS

- Scalable FS for high-performance computing [SDH+96]:
  - ➜ many files,
  - ➜ big directories,
  - ➜ huge files,
  - ➜ sparse files.
  - ➜ big file systems (TB),
  - ➜ fast crash recovery,
  - ➜ high bandwidth (uncompressed video), 500MB/s!

- Extensive use of B^+ trees:
  - ➜ directories (keyed by 4-byte hash of file name)
  - ➜ indirect block maps (using block ranges, *extents*),
  - ➜ free-block maps,
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- *Allocation groups* (large sub-partitions) to localise metadata.
  - ⋆ Limits size of free space and inode maps.
  - ⋆ Allows use of 32-bit pointers.
  - ⋆ Limits bottlenecks due to single-threaded updates.
  - ⋆ Used similar to FFS CGs (cluster files, spread directories).

- Write-ahead logging for metadata updates:
  - inodes,
  - directory blocks,
  - free block maps,
  - inode maps,
  - file block maps,
  - AG headers,
  - superblock
- Batch and asynchronously write log.
- Buffer log to avoid blocking further metadata updates.
- Support separate log device.
- *Dynamically allocated inodes*.
- Block size up to 64kB.

- Block allocation as contiguous as possible:
  - *Extents*: large (up to 2^{21}) unaligned contiguous block ranges.
  - Physical pointers are extent descriptors:
    - file offset (for sparsity),
    - block address,
    - extent size.
  - Actual allocation of disk blocks is delayed as much as possible.
    - Allows maximising extents.
    - Prevents short-lived files from ever going to disk.
    - Requires extensive buffering in RAM.
- Aggressive read-ahead and write clustering.
- *Direct I/O*: DMA to user buffers.
- Multiple concurrent readers and writers supported to same file.
- Log is only shared data structure on SMP system.

Microsoft Windows-NT File System (NTFS)

Designed as a replacement of DOS FAT and OS/2 HPFS [Cus94].

- Requirements:
  - large files and devices ($>$ 2GB),
  - protection,
  - reliability and recoverability.

- Features:
  - transaction semantics on metadata updates,
  - support for mirroring and striping,
  - Unicode file names,
  - secondary indices (not implemented),
  - extensible attribute set, incl.
    - *multiple data streams*,
  - unified access to all attributes (incl. data),
  - POSIX features: case-sensitive names, creation time stamp, hard links.
  - Many others every non-PC user expects from a file system.

FILE SYSTEM META-METADATA: The *master file table* (MFT).

- "Relational database" of file metadata:
  - transaction semantics,
  - secondary indices for accessing files (only implemented on names),
  - indices are B^+ trees,
  - extensible on a per-record basis.
- One entry per file.
- Everything on disk is a file, including all metadata.
- Fixed length record (1–4kB) of variable-length attributes, incl.:
  - *all names* of each file (hard links, DOS name),
  - ACL
  - *data* (for small files ore directories).
- Entries are mostly one record, but can span several.

- Each attribute is represented by *header* and *value*.
- Value can be:
  - *resident*, i.e., in-line, or
  - *non-resident*, i.e., in separate file.
- Any value can be resident.
- Any value that can grow can be non-resident, incl.:
  - data,
  - file index (for directory),
  - ACL,
  - attribute list.
- Non-resident values
  - represented as array of: *(logical block #, physical block #, # blocks)*.
  - Supports sparse files (if *compression* attribute is on).
  - Also supports compression of data in extents.

INDICES

- Directories are indices of file names, containing:
  - file number (= MFT record number),
  - time stamps (duplicate of MFT value),
  - size (duplicate of MFT value).
- All file names are also contained in MFT.
- Indices are B^+ trees, represented as:
  - root node of names (key values),
  - corresponding child node (extent) pointers,
  - bitmap indicating which blocks in child extents are in use.

NTFS METADATA

- All metadata is in files, described by the first 16 records of the MFT:
  - MFT,
  - partial copy of MFT (for fault tolerance),
    - mirrors entries for metadata files,
    - is allocated in the middle of the disk;
  - log file,
  - root directory,
  - *boot file* (at known address, contains address of MFT),
  - free block bitmap,
  - bad block file,
  - *volume file* (volume label),
  - ...

NTFS RECOVERABILITY

- Uses write-ahead logging for metadata updates.
  - ➜ Log contains *redo* and *undo* info.
  - ➜ Log entries are *idempotent*.
  - ➜ Log records may contain data or operations.
- Logging operation:
  - ① Logs transaction sequentially in cache.
  - ② Flushes log file.
  - ③ Updates metadata in cache.
  - ④ Writes *commit* record to log file.
- Occasionally writes *checkpoint records* to log:
  - ➜ Location recorded in (shadow-paged) log header.
  - ➜ Indicates starting point for recovery.
- When log full:
  - ① stalls metadata update,
  - ② flushes buffers,
  - ③ restarts log.

MICRO$PEAK TRANSLATION TABLE

Cluster	Block
Volume	Partition
Run	Extent
Virtual cluster number	Logical block number
Logical cluster number	Physical block number

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- Seeks are expensive:
  - Average seek costs as much as 100's of kB of data transfer.
- Big caches eliminate most reads:
  - Write costs become critical.

HOW CAN WE ELIMINATE

- synchronous writes, and
- seeks on writes?

Normal logging helps only partially.

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  ➜ Ensures consistency of updates (like delayed writes).

- Keep track of live data in previously written segments.
  ➜ Segments without live data can be reclaimed.
  ➜ Partially live segments can be compacted.

- Uses garbage collector process, called *cleaner*.

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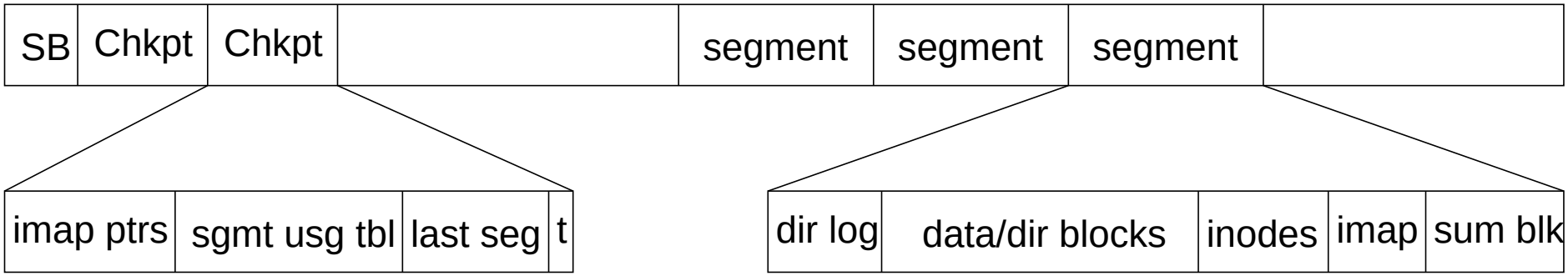
- Occasionally checkpoint metadata (using shadow paging).
  ➜ Avoids processing whole log on restart.

LFS METADATA:

- In segments:
  - ➜ inodes (as in FFS, but pointers change frequently),
  - ➜ directories (as in FFS),
  - ➜ inode map, giving locations of inodes (changes frequently),
  - ➜ log of directory changes (to avoid multiple updates),
  - ➜ segment summary:
    - ➜ number of next segment,
    - ➜ summary of contents,
    - ➜ checksums of contents (to verify successful write).
- In checkpoint:
  - ➜ timestamp,
  - ➜ address of last segment written,
  - ➜ segment usage table,
  - ➜ address of inode map.

LFS DISK LAYOUT



- LFS allows *fast restart* from crash:
  - Segment usage table allows locating unused segments to write.
  - Last segment pointer, and next pointer in segment summary allow recovery.
  - Imap pointers allow finding inode maps.
  - Time stamp allows locating last successful checkpoint.
- LFS provides *transaction semantics* on metadata updates.

LFS CLEANING

- Cleaning is critical:
  - ➜ LFS can only operate fast if plenty free segments available
  - ➜ Segments utilisation drops over time as files get modified.
  - ➜ Most segments will not become totally empty.
  - ➜ Need garbage collection to compact partially-used segments.

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- Cleaning is tricky:
  - ➜ Normal log use is dominated by writes and minimises seeks.
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  - ➜ Cleaner potentially destroys performance [SBMS93, SSB+95].

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- Basic approach:

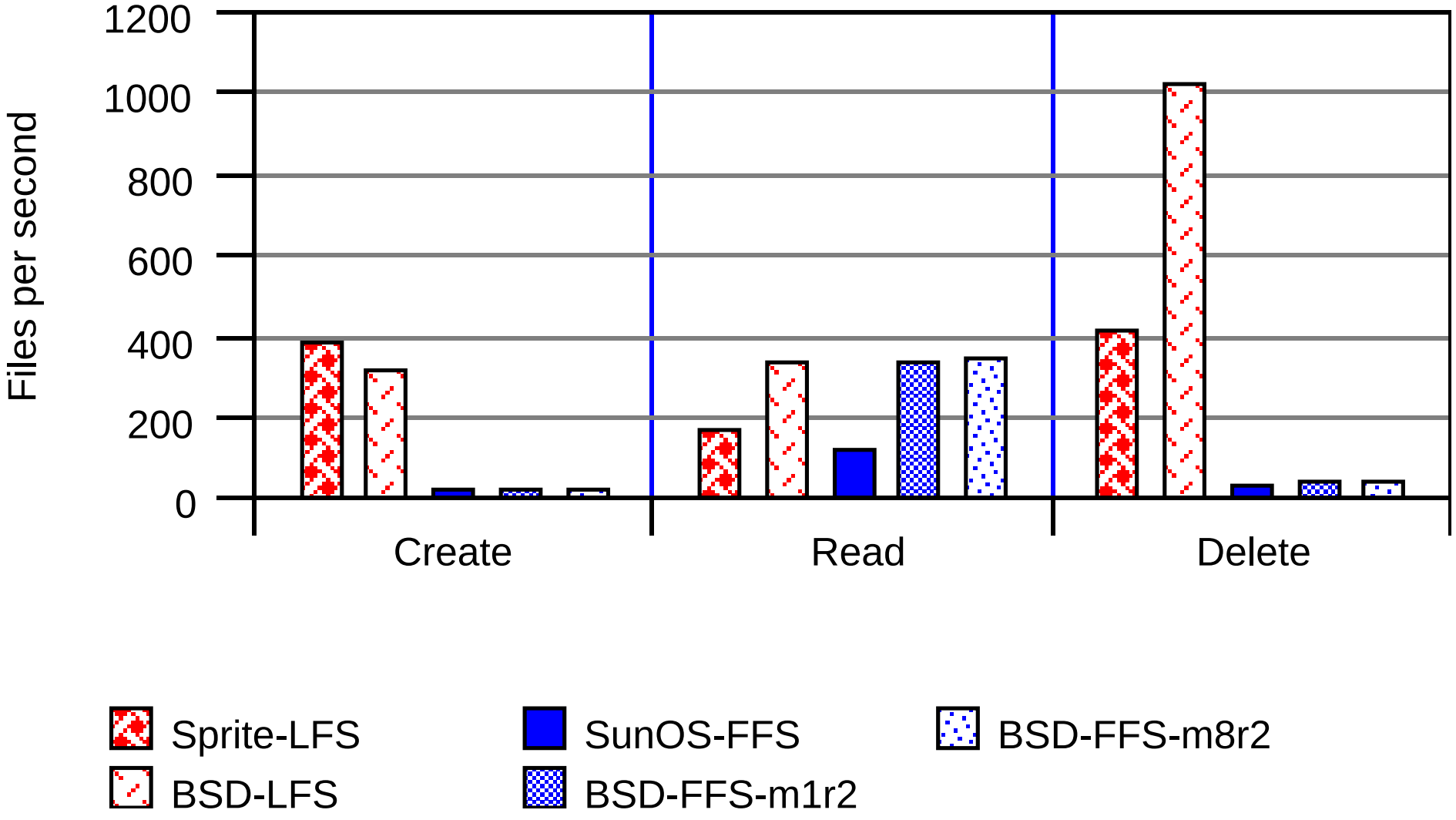
- ➜ Try cleaning at times of low disk activity;
- ➜ Try keeping disk utilization low ($< 80\,\%$).
- ➜ Preferably clean lowly utilised segments.
- ➜ Group files of similar age.

LFS Performance: Comparison with FFS

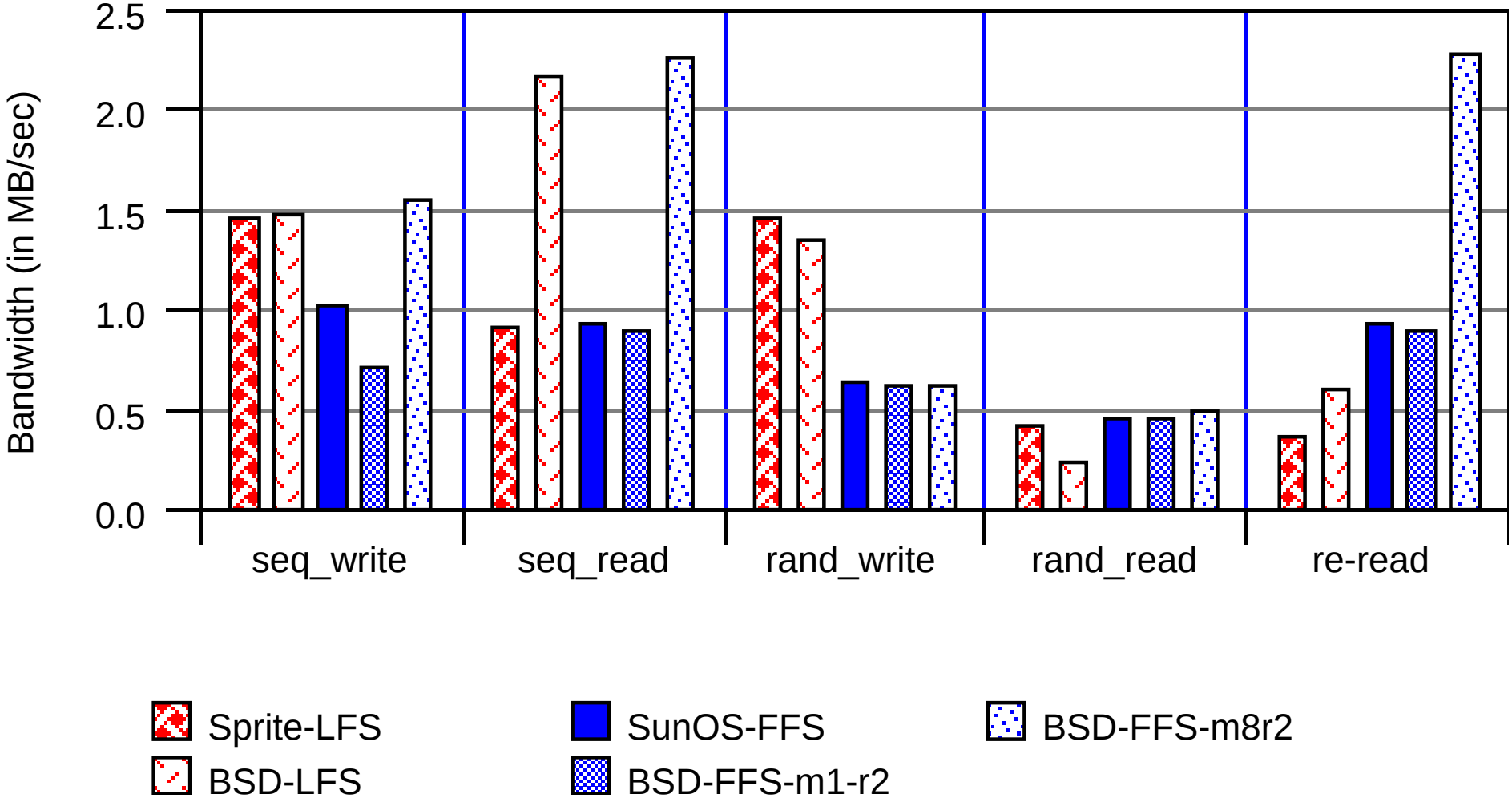
SELTZER ET AL [SSB+95]:

- Compared Seltzer's BSD implementation of LFS to BSD-FFS
  - without clustering,
  - with clustering.
- Also compared to Ousterhout's Sprite implementation of LFS (for calibration).
- Used a range of benchmarks testing performance under different scenarios.

SMALL FILE MICROBENCHMARKS

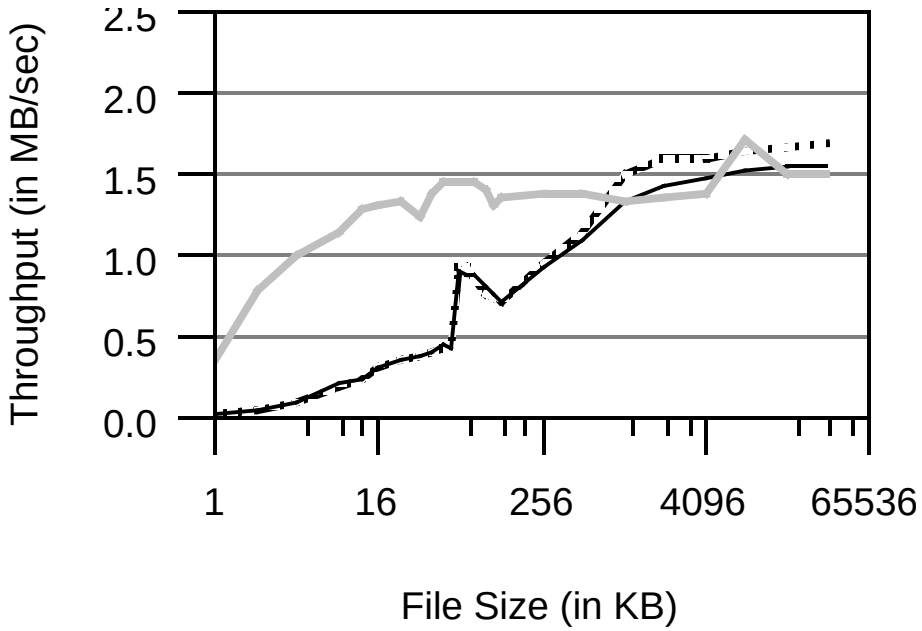


LARGE FILE MICROBENCHMARKS



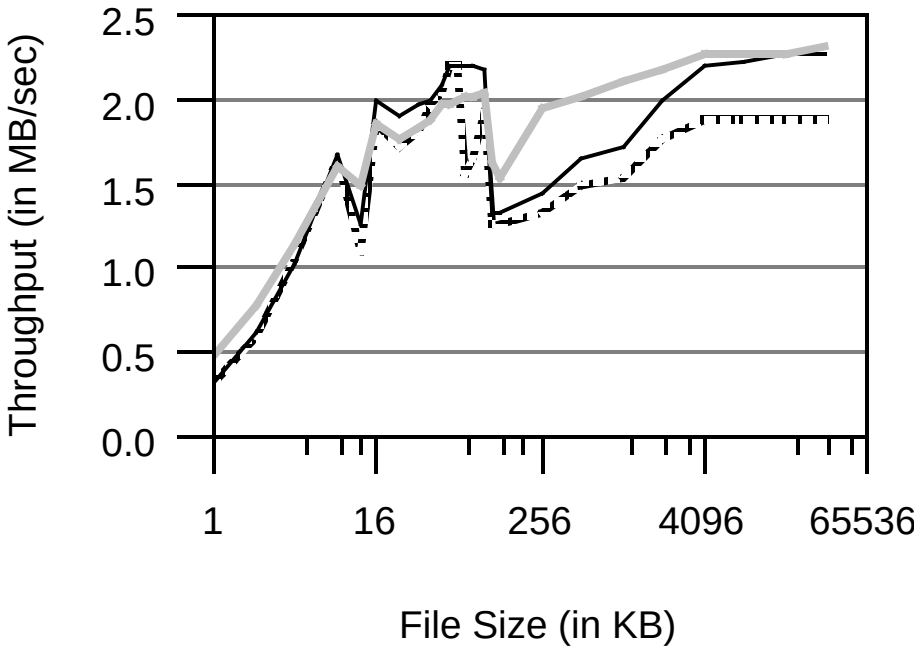
THROUGHPUT BENCHMARKS

Create



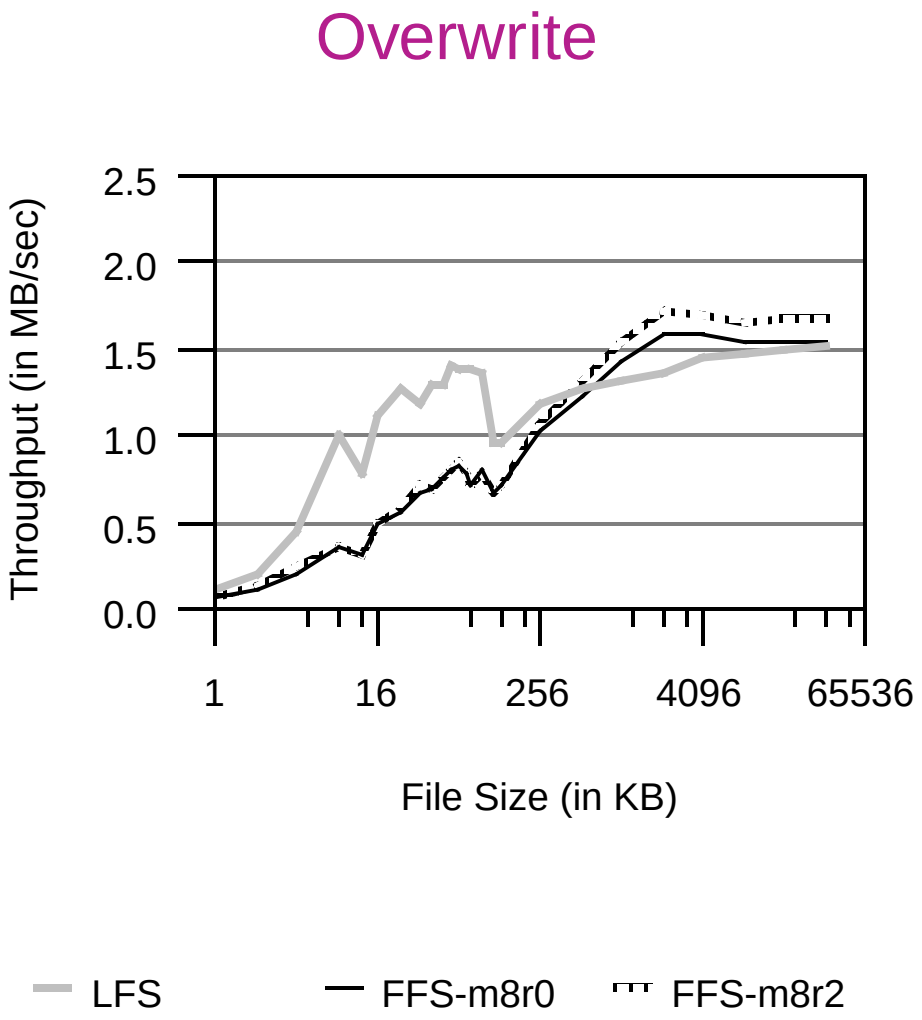
LFS FFS-m8r0 FFS-m8r2

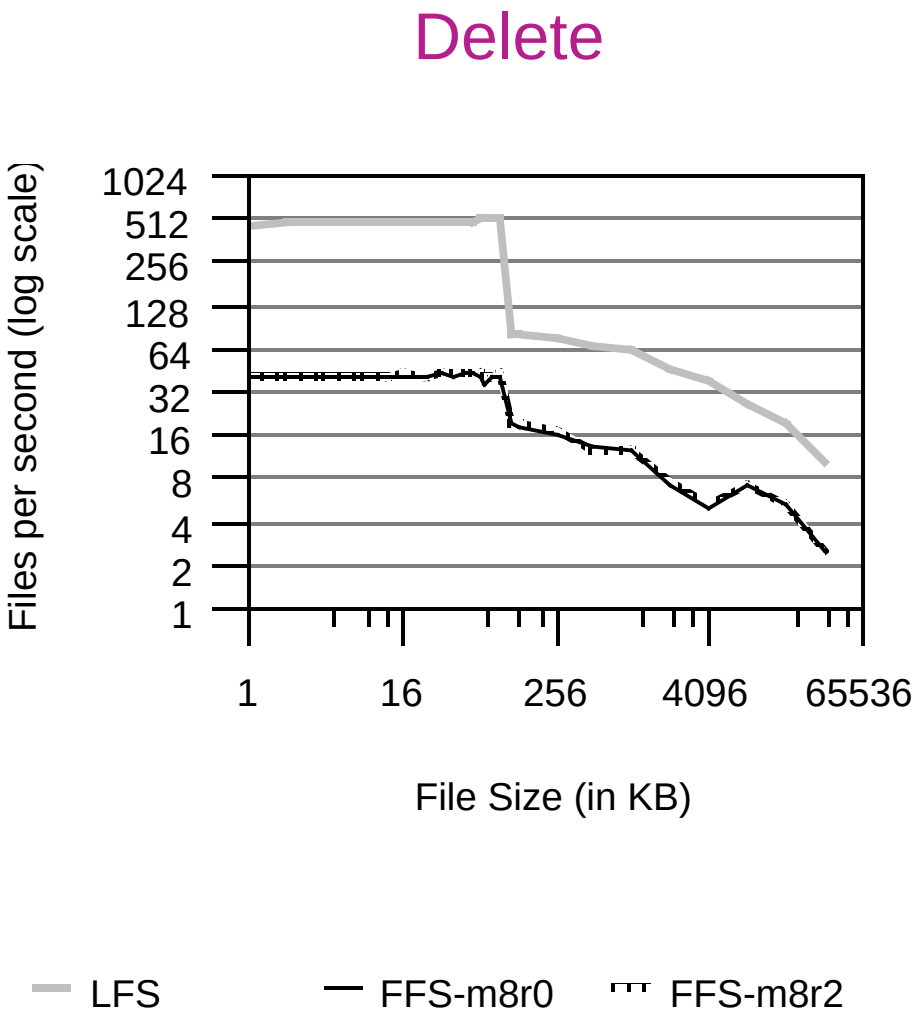
Read



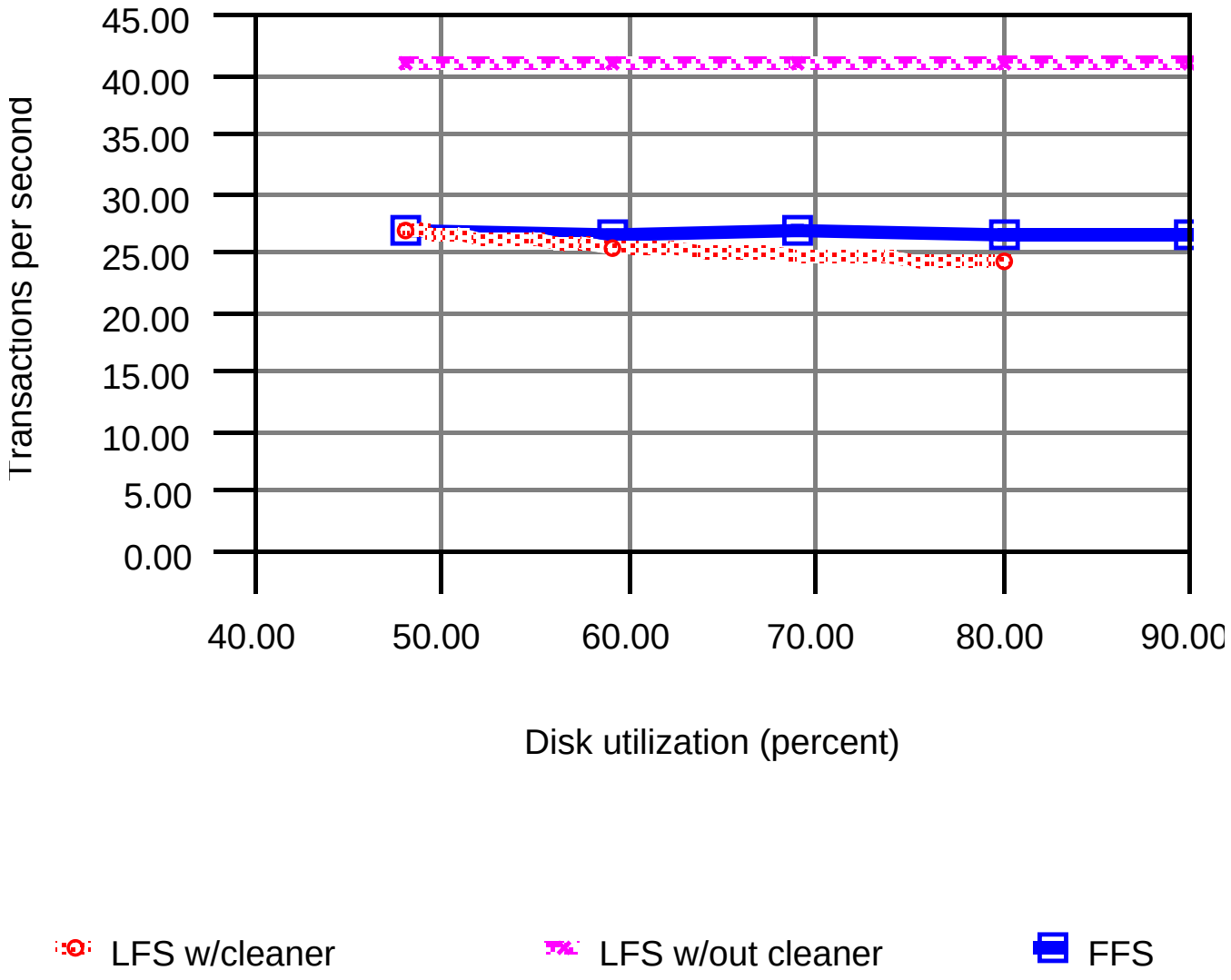
LFS FFS-m8r0 FFS-m8r2

THROUGHPUT BENCHMARKS





TRANSACTION PROCESSING (TPC-B BENCHMARK)



Random read-update-record, using logging to separate disk.

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