National Yang Ming Chiao Tung University
Computer Architecture & System Lab

File System-II

IOC5226 Operating System Capstone

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Acknowledgements and Disclaimer

- Slides were developed in the reference with
  - MIT 6.828 Operating system engineering class, 2018
  - MIT 6.004 Operating system, 2018
  - Remzi H. Arpaci-Dusseau etl. , Operating systems: Three easy pieces. WISC

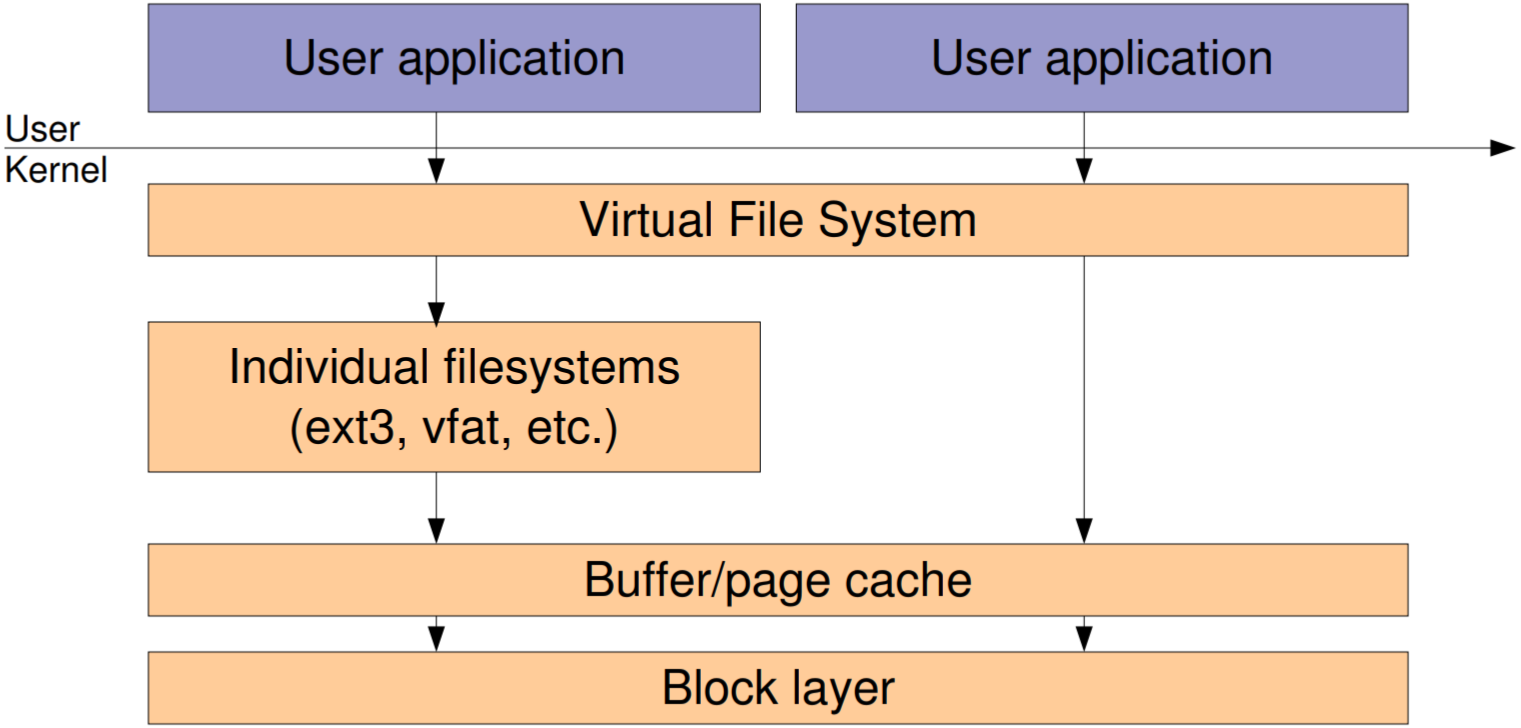
Outline

- Block devices vs. raw flash devices
- Journaled file system
- Flash file systems

Block vs. raw flash device

- Storage devices: **block devices** and **raw flash devices**
  - They are handled by different sub-systems and different file systems
- **Block devices**
  - Can be **read and written to on a per-block basis**, **in random order**, **without erasing**
  - **Hard disks, RAM disks**
  - SSD, SD cards, eMMC: flash-based storage, but have an integrated controller that emulates a block device, managing the flash in a transparent way
- **Raw flash devices** (driven by a controller on the SoC)
  - They can **read, but writing requires prior erasing**
  - **NOR flash, NAND flash**

Block device abstraction

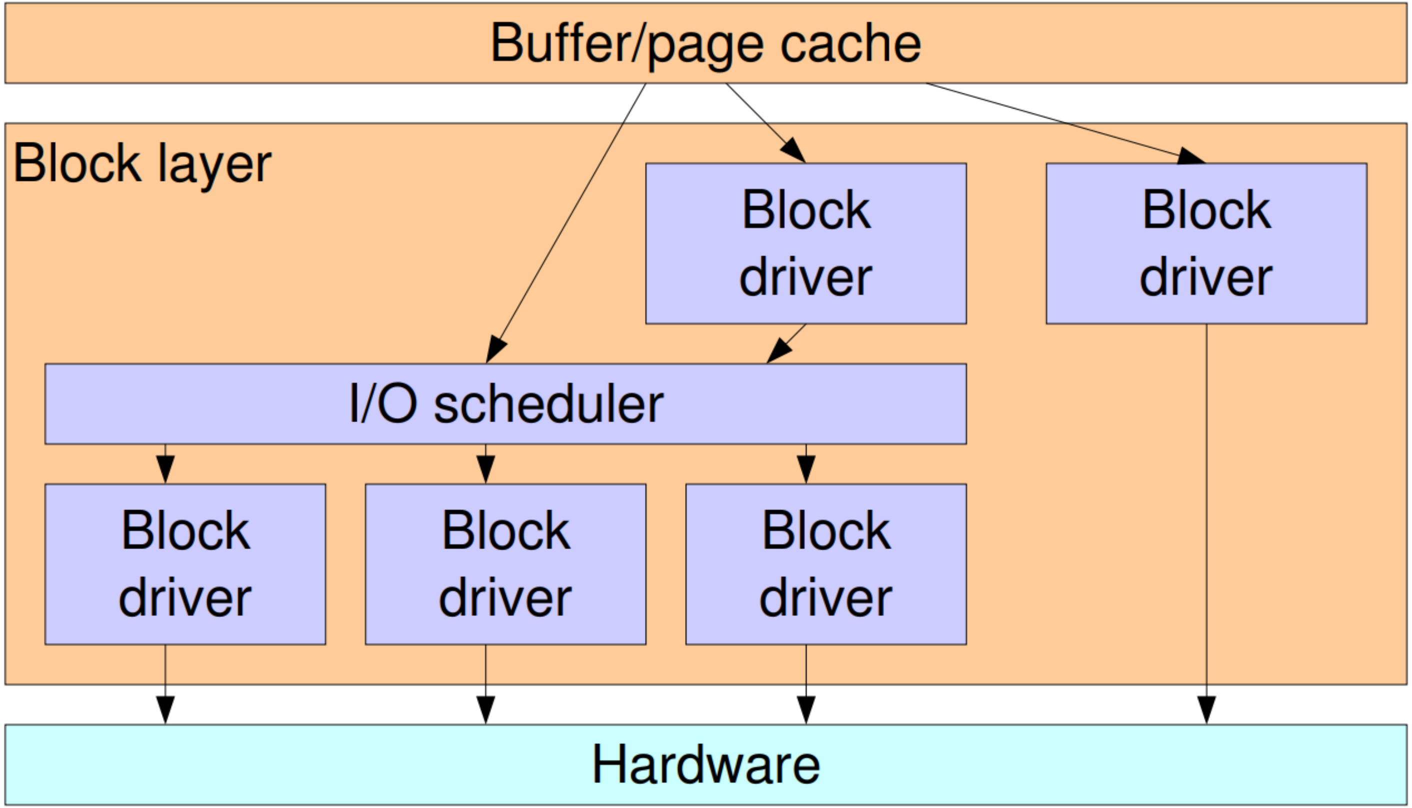


https://bootlin.com/doc/legacy/block-drivers/block_drivers.pdf

Block device abstraction

- An user application can use a block device
    - **Through a file system** -> reading, writing or mapping **files**
    - **Directly** -> reading, writing or mapping **a device file** (e.g. ‘/dev’)
- The **VFS subsystem** in the kernel is the entry point for all accesses
    - **A file system driver** is involved if a normal file is accessed
- **The buffer/page cache** of the kernel stores recently read and written portions of block devices

Inside the block layer



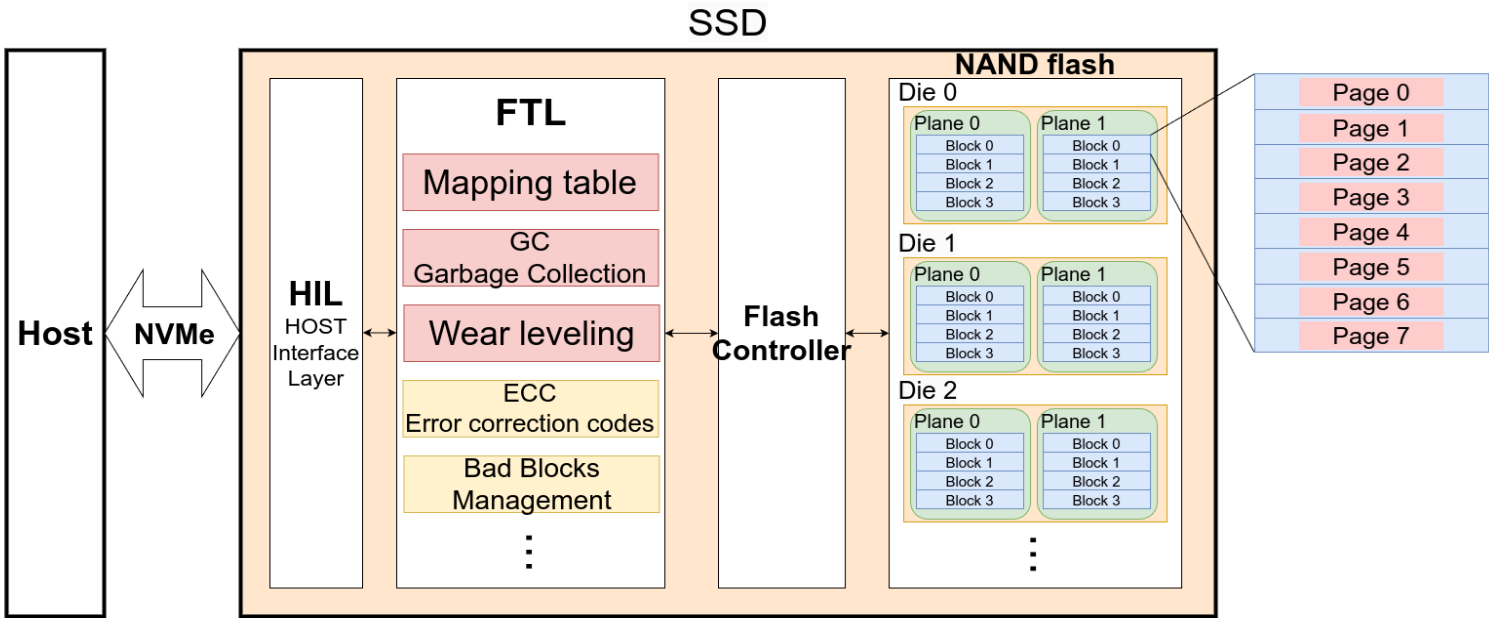
https://bootlin.com/doc/legacy/block-drivers/block_drivers.pdf

Inside the block layer

- **The block layer allows**
  - Block device drivers to receive I/O requests
  - In charge of I/O scheduling
- **I/O scheduling allows**
  - Merge requests so that they are of greater size
  - Re-order requests to optimize disk head movement
- Linux has several I/O schedulers with different policies

SSD Intrinsic Characteristics

- FTL (Flash Translation Layer) firmware manages the data stored in NAND flash



Block device list

- The list of all block devices available can be found in '/proc/partitions'
- **/sys/block**
  - Stores information about each block device
  - <u>A major number </u>is a unique identifier assigned to a device driver in the Linux kernel
  - <u>Minor numbers </u>are used to identify specific devices within a major device class, such as different partitions on a hard disk drive

```
major minor  #blocks  name

   8        0   41943040 sda
   8        1     512000 sda1
   8        2     512000 sda2
   8        3   40916992 sda3
  11        0     759172 sr0
 253        0   36720640 dm-0
 253        1    4194304 dm-1
```

Partitioning

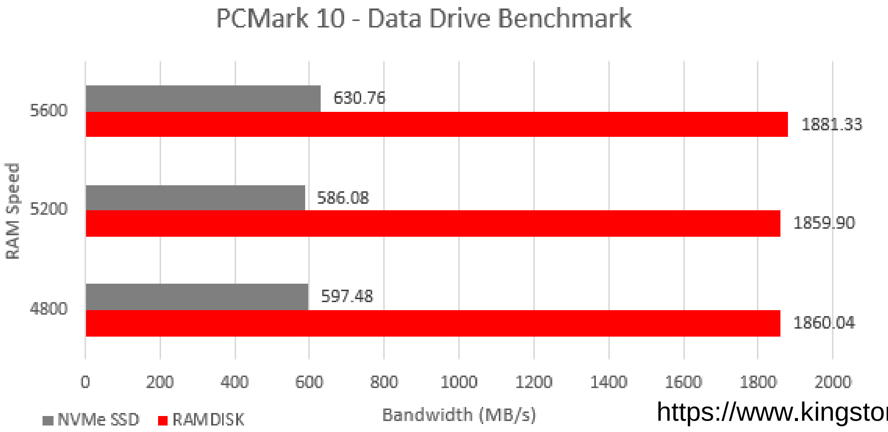
- Block devices can be partitioned to store different parts of a system
  - **The partition table** is stored inside the device itself, and is read and analyzed automatically by the Linux kernel
    - **mmcblk0** is the entire device
    - **mmcblk0p2** is the second partition of mmcblk0
  - Two partition table formats
    - **MBR (Master Boot Record)**
    - **GPT (GUID Partition Table)** supports disk bigger than 2TB
  - Numerous tools to create and modify partitions on a block device
    - fdisk, cfdisk, sfdisk, parted, etc.

Transfer data to a block device

- Transfer data to or from a block device in a raw way
  - This directly writes to the block device itself, **bypassing any filesystem layer**
  - The block devices in ‘/dev/’ allow such raw access
  - dd (**d**isk **d**uplicate) is the tool of choice for such transfers
    - **dd if=/dev/mmcblk0p1 of=testfile bs=1M count=16**
      Transfer 16 blocks of 1 MB from /dev/mmcblk0p1 to testfile
    - **dd if=testfile of=/dev/sda2 bs=1M seek=4**
      Transfer the complete contents of testfile to /dev/sda2, by blocks of 1 MB, but starting at offset 4 MB in /dev/sda2
    - **dd if=/dev/zero of=/dev/sda bs=512 count=1**
      Delete the partition table

RAM Disk

- **A RAM disk**
  - A virtual storage location that can be accessed the same as an HDD, SSD, or other storage device on a computer
  - RAM disks are created from system memory (RAM)
  - Provide fast I/O (read and write) performance



https://www.kingston.com/en/blog/pc-performance/what-is-ram-disk

RAM Disk

- The ramdisk config is stored in Linux kernel
  - Load brd (block ram disk) module before using ramdisk
    - ‘sudo modprobe brd’
  - GRUB_CMDLINE_LINUX="ramdisk_size=512000“
    - ‘sudo grub-mkconfig -o /boot/grub/grub.cfg’

```
magiclen@magiclen-linux:~$ ls /dev/ram*
/dev/ram0    /dev/ram11  /dev/ram14  /dev/ram3  /dev/ram6  /dev/ram9
/dev/ram1    /dev/ram12  /dev/ram15  /dev/ram4  /dev/ram7
/dev/ram10   /dev/ram13  /dev/ram2   /dev/ram5  /dev/ram8
magiclen@magiclen-linux:~$
```

RAM Disk

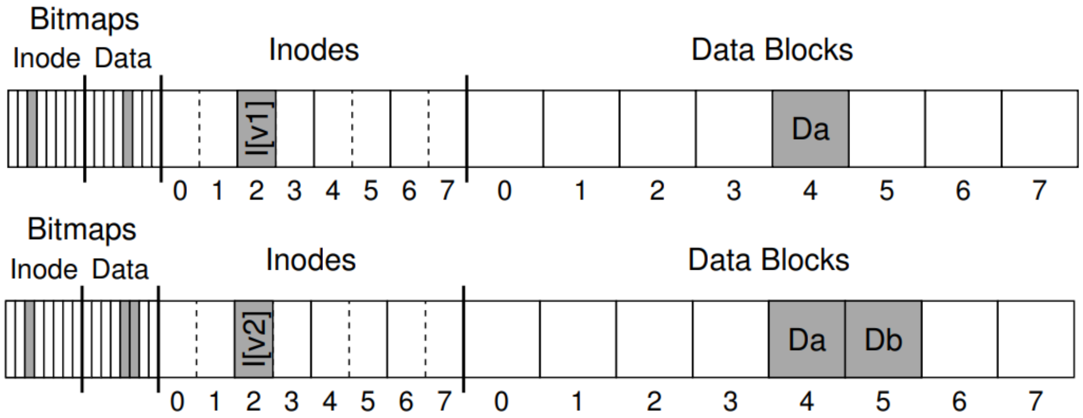
- **ramdisk**
  - Use the ramdisk before the formatting
  - sudo mkfs -t ext4 /dev/ram1; sudo mount /dev/ram1 /mnt/ramdisk
- **ramfs**
  - Use VFS (Virtual File System) to manage files, no formatting need
  - sudo mount -t ramfs ramfs /mnt/ramfs
- **tmpfs**
  - Will also use SWAP space, don’t worry tmpfs take too much RAM
  - sudo mount -t tmpfs tmpfs /mnt/tmpfs
  - sudo mount -t tmpfs tmpfs /mnt/tmpfs -o size=5120m

tmpfs: file system in RAM

- **Not a block file system**
- **Store temporary data in RAM**
  - System log files, connection data, temporary files …
  - More space-efficient than ramdisks: files are directly in the file cache, grows and shrinks to accommodate stored files
- **How to use ?**
  - mount –t tmpfs run /var/run
  - mount –t tmpfs shm /dev/shm

File system in-consistency

- A single inode is allocated (inode number 2) marked in the inode bitmap, and a single allocated data block (data block 4)
- The inode is denoted I[v1], as it is the first version of this inode



- When appending to the file, we add a new block (Db) to it
- Update the inode, new data block, and a new version of the data bitmap B[V2]

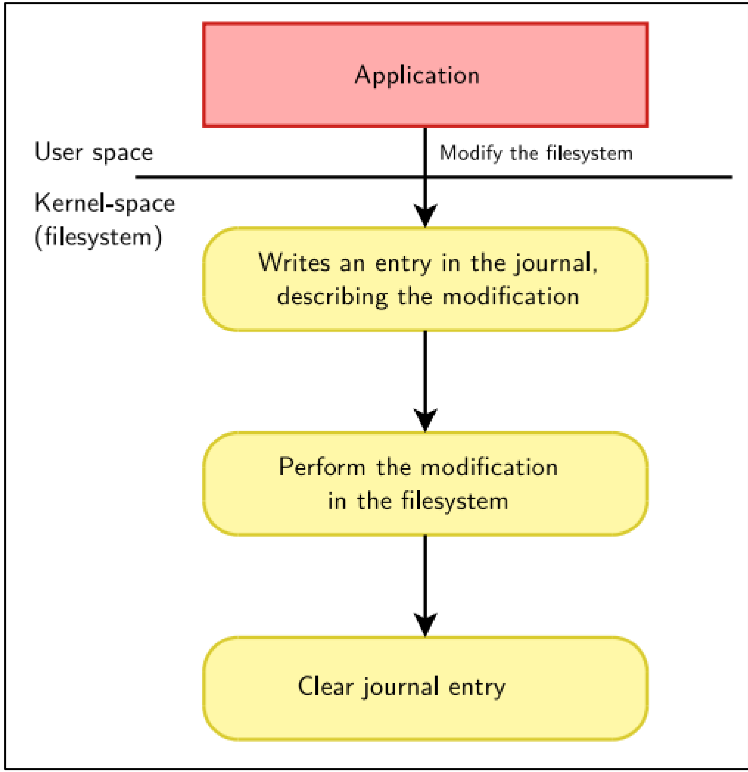
https://pages.cs.wisc.edu/~remzi/OSTEP/file-journaling.pdf

File system in-consistency

- However, the **writes** of appending data **don’t happen immediately** when the user issues a write() system call
  - The dirty inode, bitmap, and **new data will sit in main memory** (in the buffer cache) **for some time first**
  - Then, the file system will issue the requisite write requests to disk
  - <u>**A crash happens after one or two of these writes -> cause file-system in-consistency**</u>

Journaled filesystems

- **Write-ahead logging**
  - When updating the disk
  - Before overwriting the structures in place
  - First write down a little **note** on the disk
  - The note describes what you are about to do
  - By writing the note to disk -> guarantee that if a crash takes place during the update



https://bootlin.com/doc/training/embedded-linux/embedded-linux-slides.pdf

Data journaling

- **In ext2 file system**
  - The disk is divided into block groups
  - Each block group contains an inode bitmap, data bitmap, inodes, and data blocks
- **In ext3 file system**
  - The journal occupies some small amount of space within the partition or on another device
  - Before writing each block group to its final disk location, we are now first going to write them to the log

https://pages.cs.wisc.edu/~remzi/OSTEP/file-journaling.pdf

Data journaling

- **The transaction begin (TxB)**
  - Tells us about the update, including information about the pending update (I[V2], B[V2], and Db) to the file system and transaction identifier (TID)
- **The transaction end (TxE)**
  - TxE is a marker of the end of the transaction, also include TID
- **Checkpoint**
  - Once the transaction is safely on disk, we are ready to overwrite the old structures in the file system
  - We issue the writes I[V2], B[V2], and Db to their disk locations
  - If these writes complete successfully, we have done checkpointed

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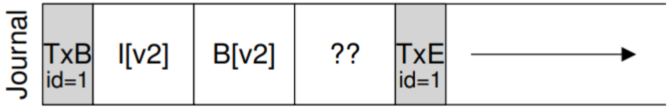
Data journaling

- **Journal write**
  - Write **a transaction-begin block** to the log
  - Write **all pending data and metadata updates** to the log
  - Write **a transaction-end block** to the log
  - Wait for these writes to complete
- **Checkpoint**
  - Write the pending metadata and data updates to their final locations in the file system
- How about a crash occurs during the writes to the journal ?

Data journaling

- **How about a crash occurs during the writes to the journal ?**
  - **One simple way to do is to issue each one item** (TxB, I[V2], B[V2], Db, TxE) at a time, waiting for each to complete -> **too slow**
  - **How about issue all five block writes at once ? (unsafe, why ?)**
  - Given such a big write, the disk may **perform scheduling and complete small pieces of the big write in any order**
    - (1) write TxB, I[v2], B[v2], and TxE
    - (2) write Db
    - How about the disk loses power between (1) and (2) ?



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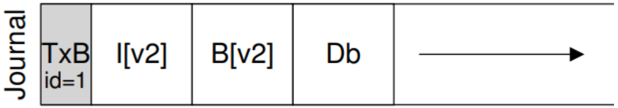
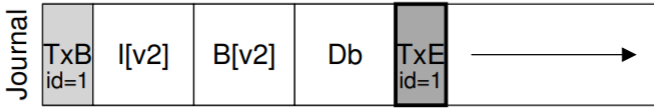
Data journaling



- **How about a crash occurs during the writes to the journal ?**
  - The file system issues the transactional write in two steps
  - <u>First, write all blocks except the TxE block to the journal</u>
  - <u>Second, issue the write of the TxE block</u>
  - Why does this two-step method work ?
    - <u>The disk guarantees that any 512-byte write (one block) will either happen or not</u>



- **Three phases on the current protocol to update file system**
  - **Journal write:** write TxB, metdata, and data to the log
  - **Journal commit:** write TxE to the log, wait for write to complete
  - **Checkpoint:** write the contents of the update to their final on-disk location

https://pages.cs.wisc.edu/~remzi/OSTEP/file-journaling.pdf

File system recovery after crashes

- The **crash happens before the transaction is written** safely to the log
  - The pending update is simply skipped
- The **crash happens after the transaction has committed** to the log and before the checkpoint is complete
  - The file system can **recover the update when the system boots**
  - The file system recovery process will **scan the log and look for transactions that have committed to the disk**
  - These transactions are replayed to write blocks to their final on-disk locations (redo-logging)

Batch log updates

- **How to reduce excessive write traffic** during the update of log back to the disk ?
  - To create one file, one has to update several on-disk structures
    - **Inode bitmap** (to allocate a new inode)
    - **The newly-created inode of the file**
    - **The data block of the parent directory**
    - **The parent directory inode**
  - The **Linux ext3 don't commit each update to disk one at a time**
    - **Buffer all updates into a global transaction**
    - **Only marks** the in-memory structures as dirty
    - The single global transaction is committed when it is finally time to write blocks to disk

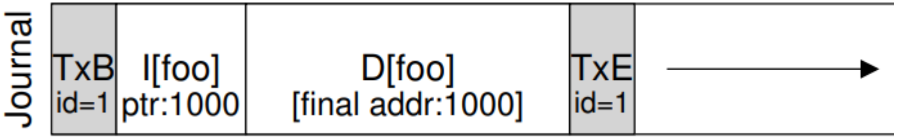
Finite size journaling

- **The log is of a finite size**. What happens if the log is full ?
  - The larger the log, the longer recovery will take
  - No further transactions can be committed to the disk
- **Circular log**
  - Journaling file systems **treat the log as a circular data structure, re-using it over and over**
  - Once a transaction has been checkpointed, the file system should free the space it was occupied, allow the log space to be reused
  - E.g. The journal superblock records enough information to know which transactions have not yet been checkpointed

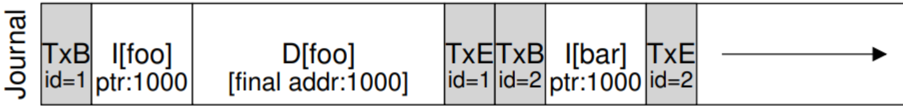
Metadata journaling

- In **journaling file system**, we are writing to the journal first for each write to disk -> **double write traffic**
    - **One write to the journal, the other writes to the main file system**
- **Data journaling** (ordered journaling in Linux ext3)
    - **The data block (Db) is not written to the journal**
    - The I[v2], B[v2] are both metadata and will be logged and then check-pointed
    - The Db will only be written once to the file system
    - Linux ext3 write data blocks to the disk first before related metadata. Why ?

Block reuse



- **In some form of metadata journaling**
  - Data blocks for files are not journaled
  - A directory called foo, which contents are written to the log
- **When a user deletes everything in the directory**
  - Freeing up block 1000 for reuse
  - A new file (bar) is created
  - The inode of bar is committed to disk
  - Only the inode of bar is committed to the journal because metadata journaling is in use
  - The newly-written data in block 1000 in the file bar is not journaled



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Block reuse

- **Assume a crash occurs**
  - The newly-written data in block 1000 in the file bar is not journaled
  - The recovery simply replays everything in the log
  - Write the directory data in block 1000, which overwrites the ‘bar’ data with old directory contents ! Something is wrong !!
- **In Linux ext3**
  - Add a new type of record to the journal, known as a **revoke** record
  - Deletes the directory would cause a revoke record to be written to the journal
  - **Any such revoked data is never replayed**

Other approach

- How to keep file system metadata consistent ?
- **Copy-on-write (COW) file system**
  - Sun’s ZFS
  - **Never overwrites files or directories in place**
  - Places new updates to previously unused locations on disk
  - After a number of updates are completed, COW file systems flip the root structure of the file system to include pointers to the newly updated structures

Other journaled Linux/UNIX file systems

- **btrfs**
  - Integrates data check-suming, volume management, snapshots, etc.
- **XFS**
  - High-performance file system inherited form SGI IRIX
- **ZFS**
  - Provide standard and advanced file system and volume management (CoW, snapshot, etc.)
- All those file system provide the necessary functionalities
  - Symbolic links, permissions, ownership, device files, etc.

Recap: block device vs. raw flash devices

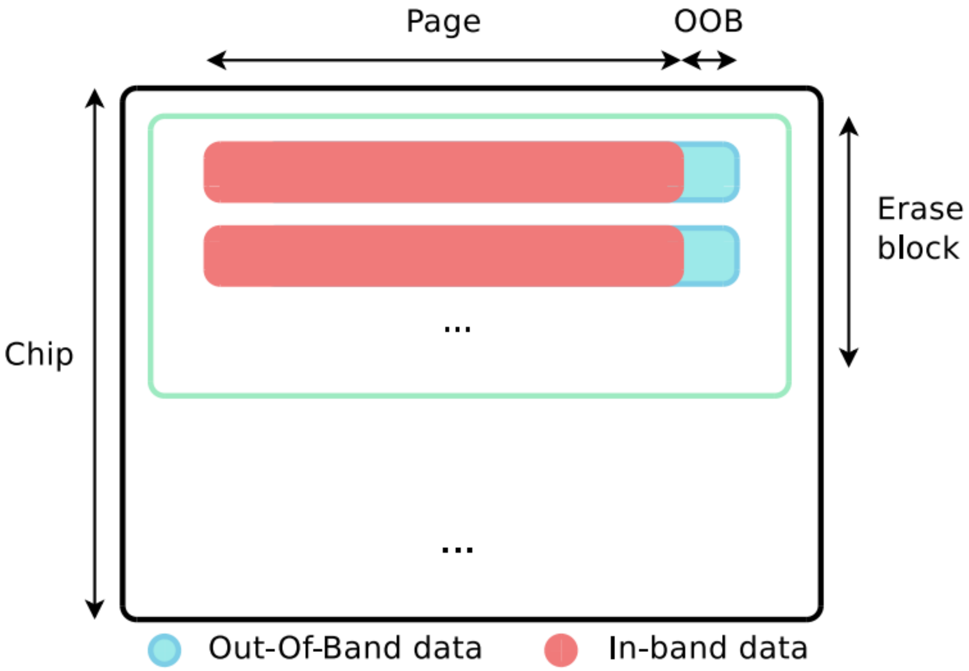
- **Block devices**
  - Allow for random data access using fixed size blocks
  - Block size is small (minimum 512 bytes, can be increased)
  - Considered as reliable (rely on the hardware and software support)
- **Raw flash devices**
  - Allow for random data access, too
  - Require special care before writing on the media (erasing the region that is about to write on)
  - Erase, write and read operations might not use the same block size
  - Reliability depends on the flash technology

NAND flash chips: how they work ?

- **Encode bits with voltage levels**
  - **SLC (single level cell)** – 1 bit per memory cell
  - **MLC (multi level cell)** – multiple bits per cell
- **Start with all bits set to 1**
  - Writing implies changing some bits from 1 to 0 (assuming 1 bit per cell)
  - Restore bits to 1 is done via the ERASE operation
  - Writing and erasing are not done on a per bit or per byte basis
- **Organization**
  - **Page:** minimum unit for PROGRAM (write), example size: 4K
  - **Block**: minimum unit for ERASE, example size: 128 K

NAND flash storage: organization

- Microchip SAMA5D3 Xplained
  - **Page size**
    - 2048 bytes
  - **OOB size**
    - 64 bytes
  - **Erase block size**
    - 131072 bytes



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NAND flash storage: constraints

- **Reliability**
  - Require mechanisms to recover from bit flips: ECC (Error Correcting Code)
  - ECC information stored in the OOB (Out-of-band area)
- **Lifetime**
  - Short lifetime compared to other storage media (between 1,000,000 and 1,000 erase cycles per block)
  - Wear leveling mechanisms are required to erase blocks evenly
  - Bad block detection/handling required, too

NAND flash: ECC

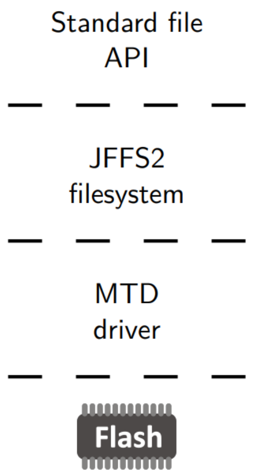
- **Error Correcting Code (ECC)**
  - Operates on chunks of usually 512 or 1024 bytes
  - ECC data are stored in the OOB area
- **Three algorithms**
  - Hamming: can fix up a single bit per chunk
  - Reed-Solomon: can fix up several bits per chunk
  - BCH: can fix up several bits per chunk

Flash wear leveling

- Wear leveling
  - Distributing erases over the whole flash device to avoid quickly reaching the maximum number of erase cycles on blocks
  - The wear leveling implementation affects the life time of the flash memory
- Can be done in
  - The file system (JFFS2, YAFFS2)
  - An intermediate layer dedicated to wear leveling (UBI)

Flash file system: JFFS2

- **Flash file systems**
  - Rely on the MTD layer to access flash chips
  - Legacy flash file system: JFFS2, YAFFS2
- **Journaling flash file system version 2 (JFFS2)**
  - <u>Supports on-the-fly compression</u>
  - Wear leveling, power failure resistant
  - Available in the official Linux kernel
  - The large partitions affects the boot time
  - http://www.linux-mtd.infradead.org/doc/jffs2.html



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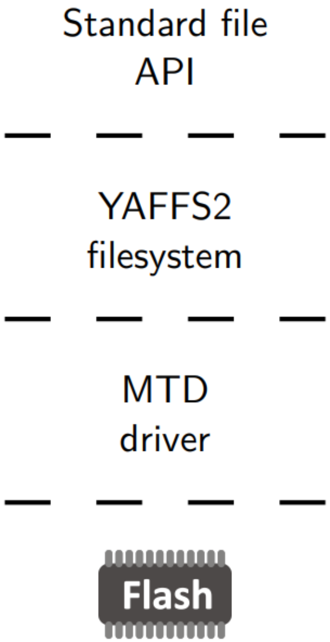
Flash file system: YAFFS2

- Yet another flash file system version 2 (YAFFS2)
  - Mainly supports NAND flash
  - No compression
  - Wear leveling, power failure resistant
  - Fast boot time
  - Not part of the official Linux kernel
  - https://yaffs.net/



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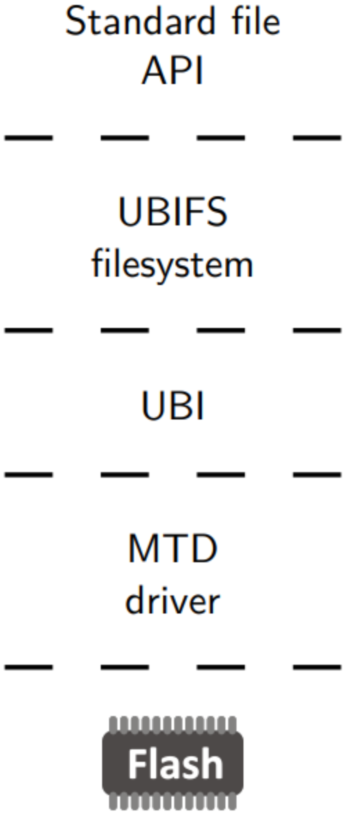
UBI/UBIFS

- Unsorted block images (UBI)
  - Aimed at replacing JFFS2 by addressing its limitations
  - Volume management system on top of MTD devices
  - Allows to create multiple logical volumes and spread writes across all physical blocks
  - Managing the erase blocks and wear leveling
- Drawback
  - Noticeable space overhead



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Conclusion

- Journaling reduces recovery time
  - From O(size-of-the-disk-volume) to O(size-of-the-log)
  - Speeding recovery substantially after a crash and restart
- The ordered metadata journaling
  - Reduce the amount of traffic to the journal while still preserving reasonable consistency guarantees for both file system metadata and user data
- Flash file systems
  - JAFFS2, YAFFS2, UBI/UBIFS

Takeaway Questions

- What is the result of ‘dd if=/dev/zero of=/dev/sda bs=512 count=1’?
  - (A) Transfer 512 bytes data to /dev/sda
  - (B) Erase the partition table
  - (C) Copy 512 bytes data to /dev/sda
- How to prevent the crash occur during the write to the journal?
  - (A) Issue each one item (TxB, I[V2], B[V2], Db, TxE) at a time
  - (B) Issue all five block writes at once
  - (C) Issues the transactional write in two steps

Takeaway Questions

- How to reduce excessive write traffic during the update of log back to the disk ?
  - (A) Buffer all updates into a global transaction
  - (B) Only marks the in-memory structures as dirty
  - (C) Commit each update to disk one at a time
- How to reduce the size of journaling (logs)?
  - (A) Treat the log as a circular data structure
  - (B) Using copy-on-write method
  - (C) Re-using the log space over and over