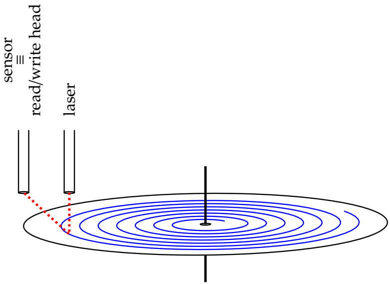
Continued from last lecture ...

- ... so far so good, *but* we need to explore
  1. how the file system supports our assumed access model, *and*
  2. how the underling **storage device** supports the file system.

Mechanism: (mass storage) devices $\leadsto$ blocks (1)

- Example: **optical disks** (inc. CDs and DVDs).



noting that

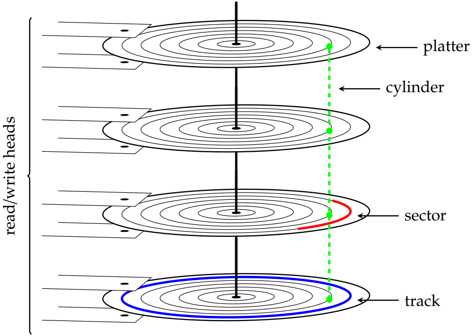
- one might attempt
  1. **random access**, and/or
  2. **sequential access**

  and
- efficiency of said access is limited by

$$\begin{array}{lcl} \text{transfer rate} & \propto & \text{read/write head performance} \\ \text{positioning latency} & \simeq & \textbf{seek latency} + \textbf{rotational latency} \end{array}$$

Mechanism: (mass storage) devices $\leadsto$ blocks (1)

- Example: **magnetic disks**.



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Mechanism: (mass storage) devices $\rightsquigarrow$ blocks (2)

- We add structure to the medium via several steps

medium = $\boxed{}$

Mechanism: (mass storage) devices $\rightsquigarrow$ blocks (2)

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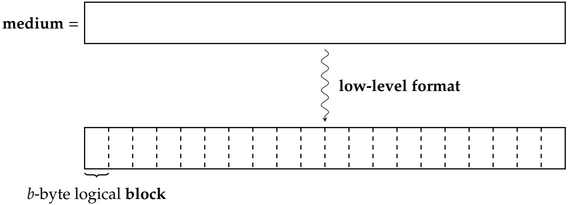

Mechanism: (mass storage) devices $\rightsquigarrow$ blocks (2)

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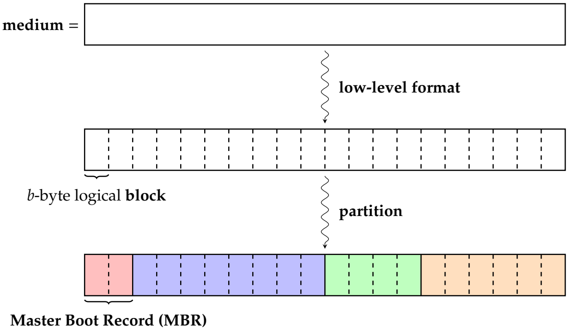

Mechanism: (mass storage) devices $\rightsquigarrow$ blocks (2)

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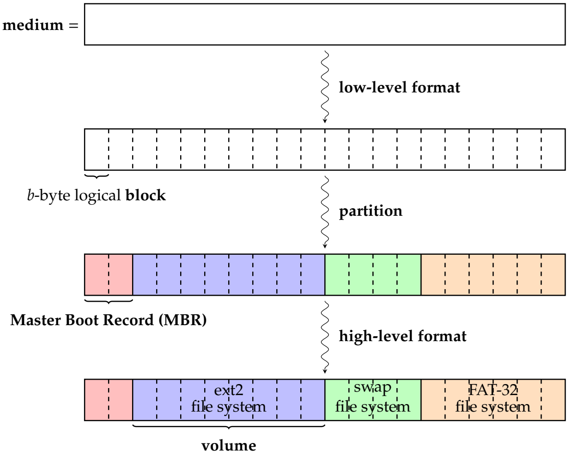
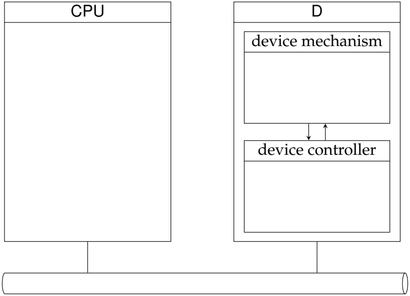


then ...

Mechanism: (mass storage) devices $\rightsquigarrow$ blocks (3)

- ... assume an interface as previously described, e.g.



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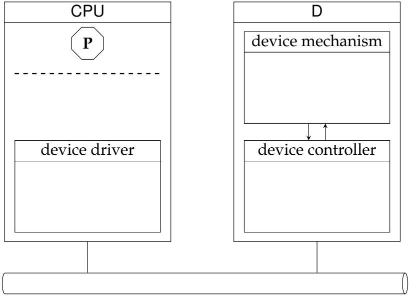

Mechanism: (mass storage) devices ⇝ blocks (3)

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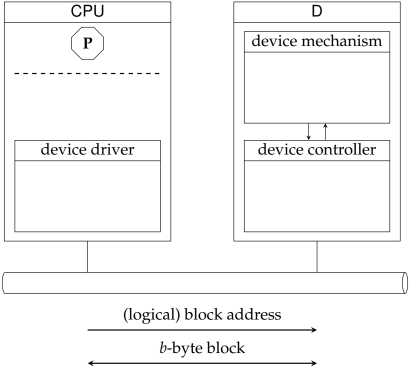

but, since efficiency is crucial we (typically) also

1. amortise overhead by fixing transferring b-byte blocks,
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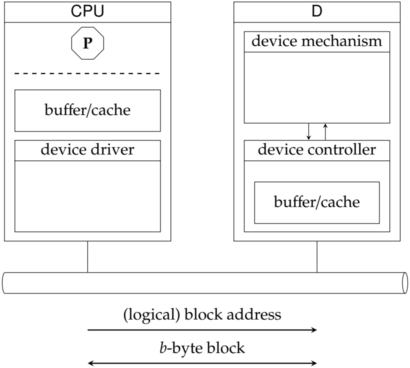


but, since efficiency is crucial we (typically) also

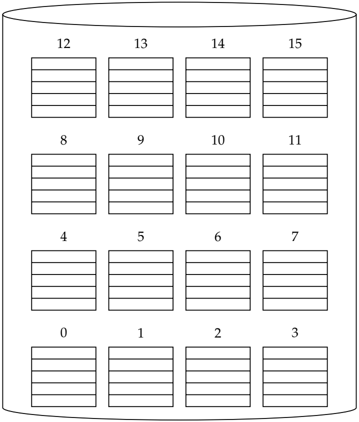
1. amortise overhead by fixing transferring b-byte blocks,
2. use **Logical Block Addressing (LBA)**, forcing translation by the device controller, and
3. buffer and/or cache accesses (in various layers).

Mechanism: blocks $\rightsquigarrow$ files (1)

- Challenge: given a device with
  - fixed number of logical blocks and
  - fixed sized logical blocks,

  realise (hierarchical) file system supporting
  - representation and
  - manipulation

  of
  - variable number of files, and
  - variable sized files.
- Solution: we need
  1. an allocation algorithm, and
  2. a data structure to capture the current allocation state.



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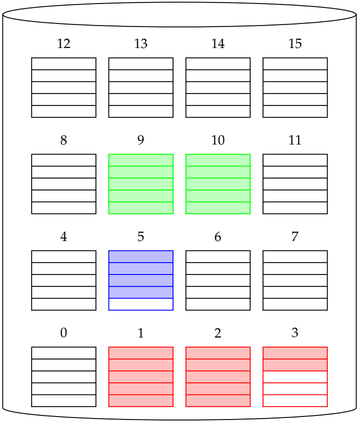
  - variable sized files.
- Idea: **contiguous allocation**.
  - – allocation is more challenging,
  - + sequential *and* random access is efficient,
  - – internal *and* external fragmentation,
  - + no storage overhead.



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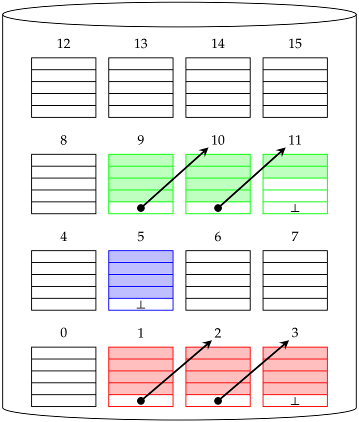
- Idea: **linked allocation**.
  - \+ allocation is less challenging,
  - \+ sequential access is efficient,
  - − random access is inefficient,
  - \+ internal fragmentation only,
  - − some storage overhead due to pointers.



Mechanism: blocks $\leadsto$ files (1)

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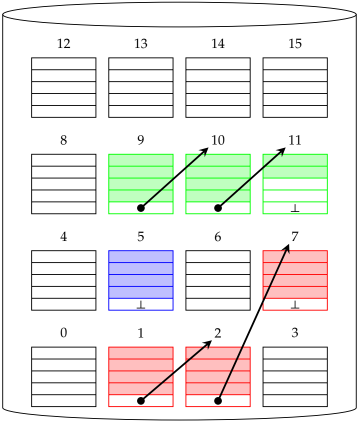

Mechanism: blocks $\rightsquigarrow$ files (1)

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  realise (hierarchical) file system supporting
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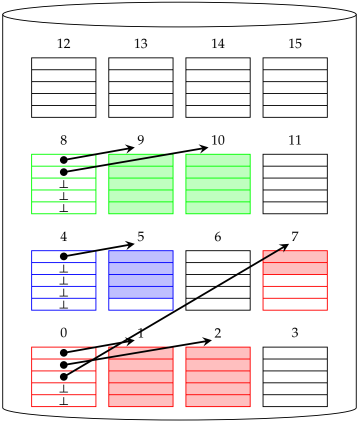
  - variable number of files, and
  - variable sized files.
- Idea: **indexed allocation**.
  - \+ allocation is less challenging,
  - \+ sequential *and* random access is efficient,
  - \+ internal fragmentation only,
  - − some storage overhead due to pointers.



Mechanism: blocks $\rightsquigarrow$ files (1)

- Challenge: given a device with
  - fixed number of logical blocks and
  - fixed sized logical blocks,

  realise (hierarchical) file system supporting
  - representation and
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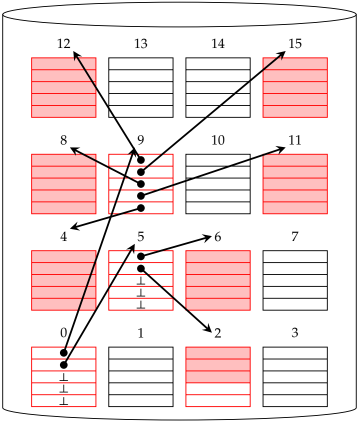
  of
  - variable number of files, and
  - variable sized files.
- Problem: what if the index block is full?
- Solution(s): use *multiple* index blocks, e.g., via
  1. linked list,
  2. linked tree, or
  3. various hybrid(s) ...



Mechanism: blocks $\rightsquigarrow$ files (2)

- **Problem**: larger storage capacity means more logical blocks, so
  1. larger logical block addresses,
  2. decreased access locality, and
  3. greater overhead (in time and space) wrt. allocation.
- **Solution**: use a hybrid part contiguous, part non-contiguous approach, e.g.,
  1. **cluster** $\simeq$ fixed size, contiguous group of logical blocks:
     - e.g., divide w-bit logical block address into two

       $$\text{logical block group address} = \overset{w-1 \qquad\qquad t\;\; t-1 \qquad\qquad 0}{\boxed{\quad\text{offset}\quad}\boxed{\quad 00\ldots0\quad}}$$

     - each offset now addresses a contiguous group of 2^t logical blocks.
  2. **extent** $\simeq$ variable size, contiguous group of logical blocks:
     - e.g., divide w-bit logical block address into two

       $$\text{logical block group address} = \overset{w-1 \qquad\qquad t\;\; t-1 \qquad\qquad 0}{\boxed{\quad\text{offset}\quad}\boxed{\quad\text{length}\quad}}$$

     - each offset now addresses a contiguous group of logical blocks whose length is given by the t LSBs,
     - this is more flexible, *but* yields complications wrt. seeking and allocation.

  although from here on we ignore this option.

Mechanism: blocks $\rightsquigarrow$ files (3)

- Problem: each write requires one or more of

  1. update the allocation state,
  2. update the file meta-data, *and*
  3. update the file data

  which *must* be **atomic**: if not, the file system can become inconsistent.

- Solution:

  - describe update in write-ahead log (or journal),
  - commit update to file system iff. write to log is complete

Mechanism: blocks $\leadsto$ files (4)

- Question: what *is* a directory?
- Answer: a mapping, e.g.,

$$\text{identifier} \mapsto (\text{meta-data}, \text{data})$$

or

$$(\text{identifier}, \text{meta-data}) \mapsto \text{data}$$

which also hint at

1. options for where meta-data should reside, and
2. the fact a file might not *itself* have an identifier!

Mechanism: blocks $\rightsquigarrow$ files (4)

- Question: what *is* a directory?
- Answer: a mapping, e.g.,

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  which also hint at

  1. options for where meta-data should reside, and
  2. the fact a file might not *itself* have an identifier!

- Problem: *how* should a directory be represented?
- Solution:
  1. list,
  2. tree,
  3. hash table,
  4. ...

Mechanism: blocks $\rightsquigarrow$ files (4)

- Question: what *is* a directory?
- Answer: a mapping, e.g.,

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$$(\text{identifier}, \text{meta-data}) \mapsto \text{data}$$

which also hint at

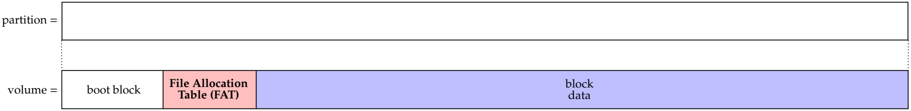
1. options for where meta-data should reside, and
2. the fact a file might not *itself* have an identifier!

- Problem: *where* should a directory representation be stored?
- Solution:

1. as a file, plus special-purpose rules for access,
2. as a special-purpose structure,
3. ...

i.e., unified or segregated wrt. the rest of the file system.

- Idea: **File Allocation Table (FAT)** ≃ fancy linked allocation.

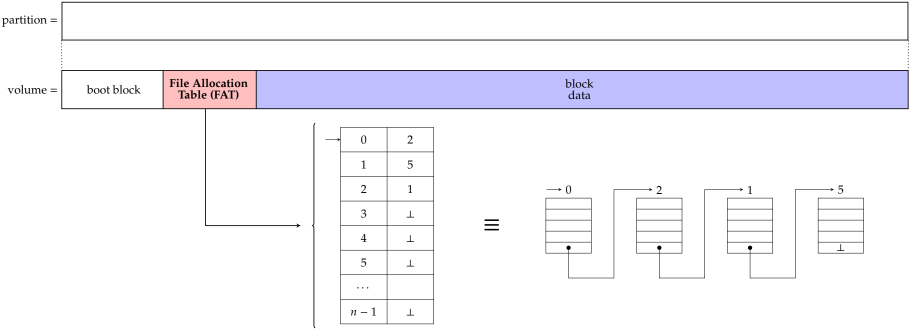


noting that

+ resolves issue of random access wrt. linked allocation,
– need to retain FAT in memory ... which, for n logical blocks, can be large!

Implementation: devices $\rightsquigarrow$ file systems (1)
Windows-centric: FAT

- Idea: **File Allocation Table (FAT)** $\simeq$ fancy linked allocation.



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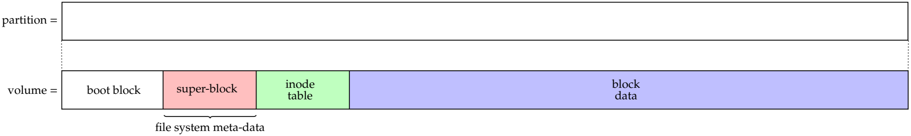
- **Idea**: **Unix File System (UFS)** [15, Section 4] ≃ fancy indexed allocation.



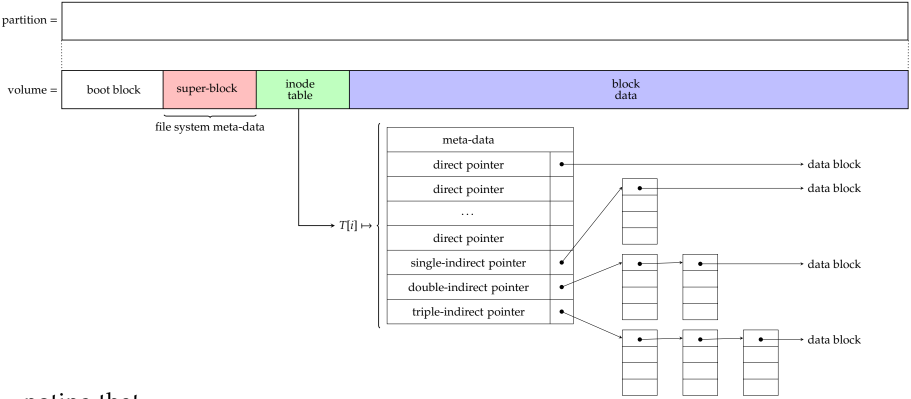
noting that

+ inodes are of (small) fixed size, so indexing into the inode table is efficient,
– linked representation of free space (for inodes *and* blocks).

Implementation: devices ⇝ file systems (2)

UNIX-centric: UFS

- Idea: **Unix File System (UFS)** [15, Section 4] ≃ fancy indexed allocation.



noting that

+ inodes are of (small) fixed size, so indexing into the inode table is efficient,
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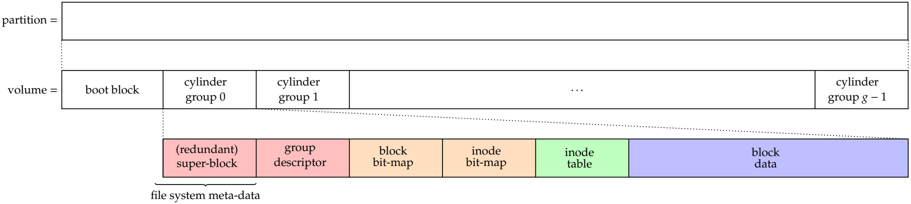
- **Idea**: **Fast File System (FFS)** [8] $\simeq$ UFS + larger block size ($\geq$ 4KiB).

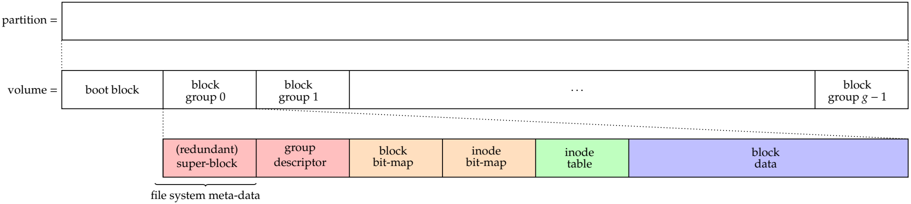


noting that

+ bit-map representation of free space (for inodes *and* blocks),
+ redundant copy of super-block improves fault tolerance (for overhead of space),
+ cylinder groups increase access locality,
+ includes additional features such as soft links.

Implementation: devices ⇝ file systems (4)
UNIX-centric: ext2

- Idea: **Second Extended File System (ext2)** [9] ≃ FFS + caching.



noting that

+ improved directory representation via hash tables [9, Section 4.2],
+ caching and asynchronous writes improve performance ...
– ... but with disadvantages wrt. coherence (viz. robustness).

Conclusions

- Take away points:
  - This is a broad and complex topic: it involves (at least)
    1. a hardware aspect:
       - an interrupt controller,
       - a block device
    2. a low(er)-level software aspect:
       - an interrupt handler,
       - a device driver,
       - a file system driver
    3. a high(er)-level software aspect:
       - some data structures (e.g., mount and file descriptor tables),
       - any relevant POSIX system calls (e.g., `write`)
  - Keep in mind that, even then,
    - we've excluded and/or simplified various (sub-)topics,
    - there are numerous trade-offs involved, meaning it is often hard to identify one ideal solution.

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