Structuring data for efficient I/O

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CERN

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Overall Course Structure

Structuring Data for efficient I/O

- Data formats, data compression
- Data addressing

Many ways to Store Data

- Storage devices and their specificities
- Distributing and parallelizing storage

Preserving data

- Data consistency
- Data safety

Key ingredients to achieve efficient I/O

- Synchronous vs asynchronous I/O
- I/O optimizations and caching

Outline

Data format

Data structure by example - scenario

Scenario

- You are measuring temperatures within a piece of detector
- You have 10K captors and you take one measure every minute
- After a month, you got 432M measures
- That is 1.6GB if you take single precision floats (32bits)

Data structure by example - row storage

Naive structure

- You arrange your captors in a sequential order according to the detector geometry
- Each minute, you create a new "row" of data, with 10K floats representing temperatures given by the captors, in that order

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...	...	...	...	...
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1	a_1	b_1	...	z_1
...	...	...	...	...
n	a_n	b_n	...	z_n

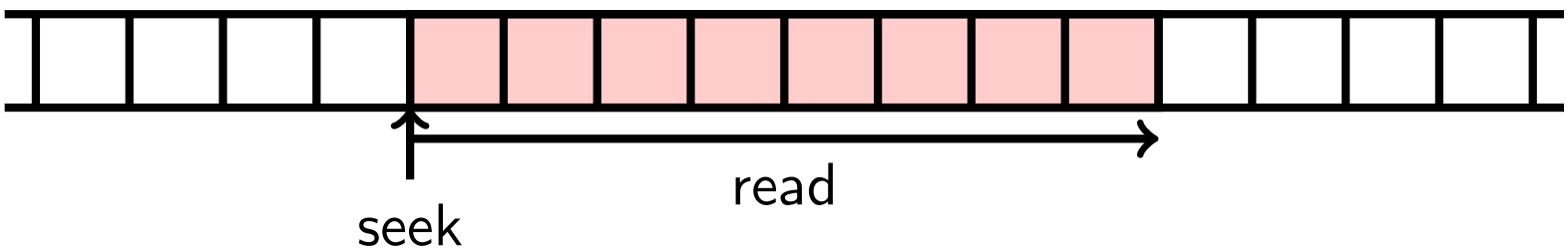
File content

a_0 b_0 ... z_0 a_1 b_1 ... z_1 ... a_n b_n ... z_n

Data structure by example - access

Find out overheated devices at a given time

- find the offset of that time in the file
- read 10K numbers
- apply simple filter



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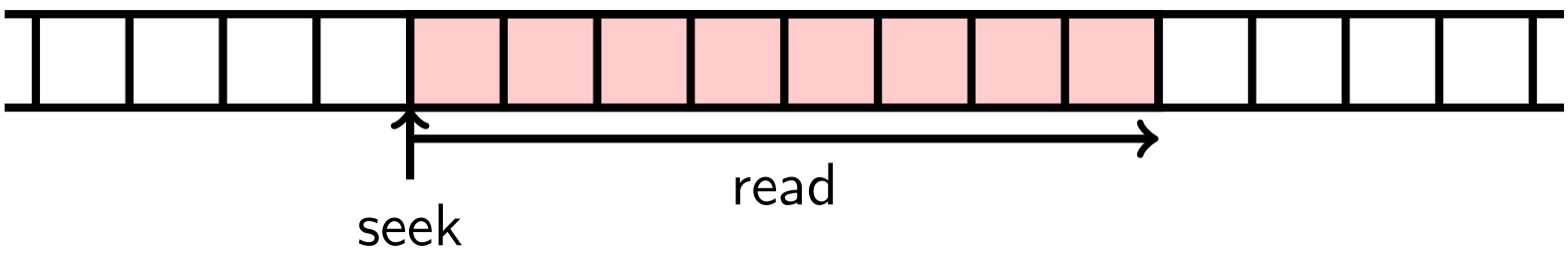


Cost

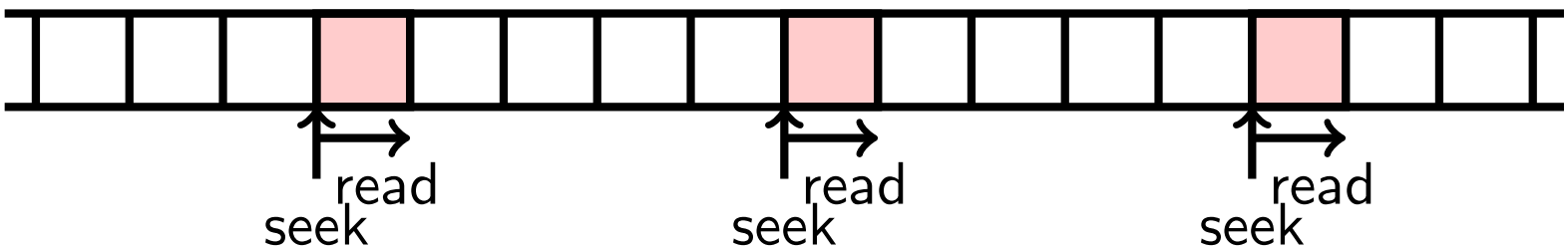
- one seek
- one read of 10K ints

This is efficient !

Data structure by example - access (2)

Graph the temperature evolution of a given device

- read 43.2K numbers from the file, every 40K bytes
- graph them



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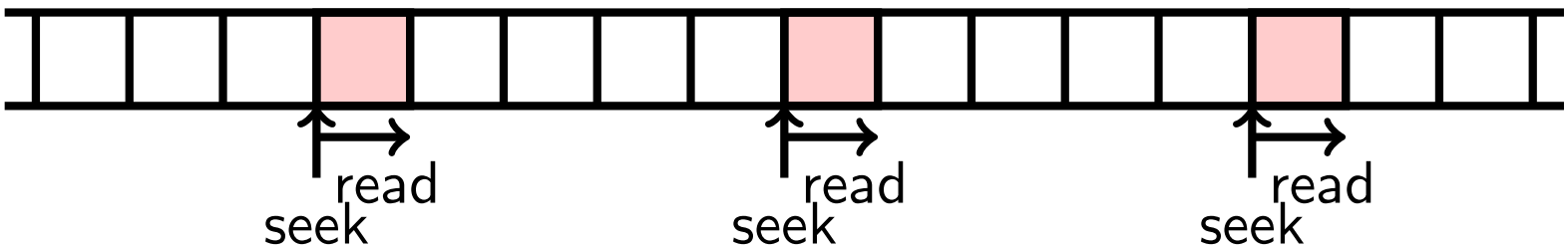

Cost

- 43.2K reads of 4 bytes and 43.2K seeks !
- on top typical block size in a filesystem is 8k
- you will probably read effectively 20% of the file !
- actually reading the whole file will be more efficient

Here the structure of our data is a killer

Column storage

Time (mn)	Captor 1	Captor 2	...	Captor c
0	a_0	b_0	...	z_0
1	a_1	b_1	...	z_1
...	...	...	...	...
n	a_n	b_n	...	z_n

Column storage

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...	...	...	...	...
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File content

a_0 a_1 ... a_n b_0 b_1 ... b_n ... z_0 z_1 ... z_n

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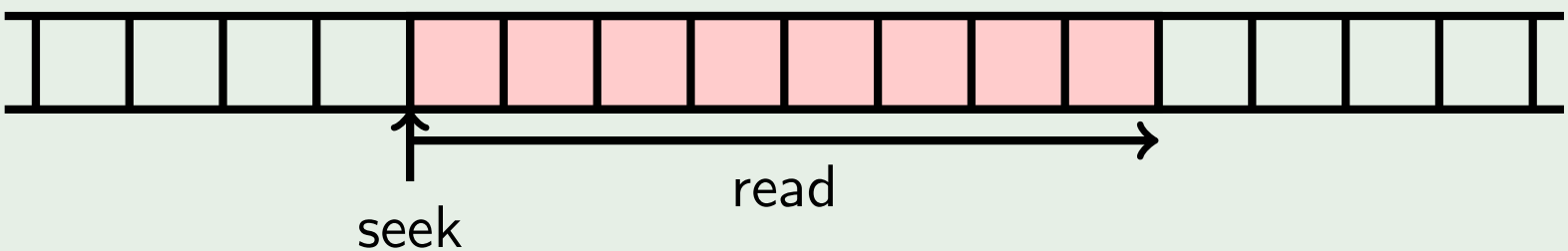
Back to efficient read



Row vs column storage

Definition

Row storage respects internal structure of the data and puts the different items one next in a sequence

Column storage breaks the internal structure of the data to collate similar pieces

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Why to use column ?

- to optimize I/O in general and avoid scattered reads
- to optimize data compression
- to optimize parallelization of processing

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Drawback of column storage

- a column organized file cannot be updated easily
- column storage is usually created from row storage in a postprocessing phase.

The parallelization view

Row/Column

- naming
  - Row storage
  - Column storage
- goal
  - Storage efficiency, data on disk

AoS/SoA

- naming
  - Array of structs (AoS)
  - Struct of arrays (SoA)
- goal
  - Algorithmic efficiency, data in RAM

A lot in common

- Same advantages/disadvantages
- Same compromises
- Same ultimate solution ? : column per block / AoSoA

Column per block storage

Time (mn)	Captor 1	Captor 2	...	Captor c
0	a_0	b_0	...	z_0
...	...	...	...	...
p	a_{p-1}	b_{p-1}	...	z_{p-1}
p-1	a_p	b_p	...	z_p
...	...	...	...	...

File content

$a_0\ a_1\ \ldots\ a_{p-1}\ b_0\ b_1\ \ldots\ b_p\ \ldots\ z_0\ z_1\ \ldots\ z_p\ \ a_p\ a_{p+1}\ \ldots\ a_{2p-1}\ b_p\ b_{p+1}\ \ldots\ b_{2p-1}\ \ldots$

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Advantages

- limits number of seeks per data to $frac1p$
- allows updates, providing a small cache

Compressing data

Data compression

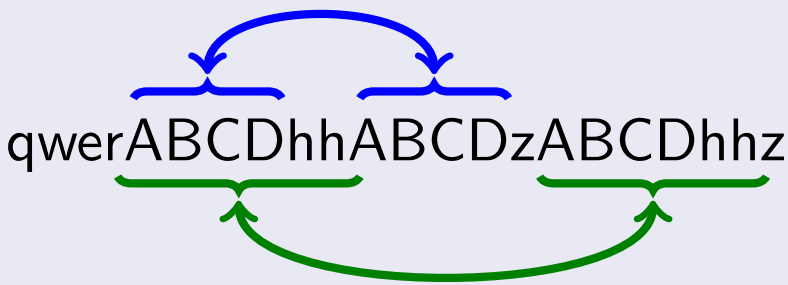
Main idea

- eliminate redundancy (e.g. LZ77)
- optimize encoding (Huffman coding)
- to squeeze more information into less bytes

Eliminate redundancy

LZ77

Replace redundancy with pointers



qwerABCDhh(6,4)z(11,6)z

Optimize encoding

Huffman coding idea

- use short codes for symbols repeated often
- build an optimal code set depending on symbols' frequencies

Optimize encoding

Encoding “faeaebacdeeabadeacdfbdaddadcafdacbaababbaaccaa”

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Frequencies

a	17	d	8
b	7	e	5
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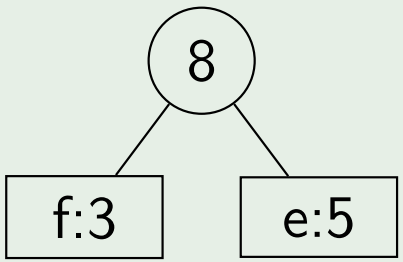

Optimize encoding

Encoding "faeaebacdeeabadeacdfbdaddadcafdacbaababbaaccaa"

Frequencies

a	17	d	8
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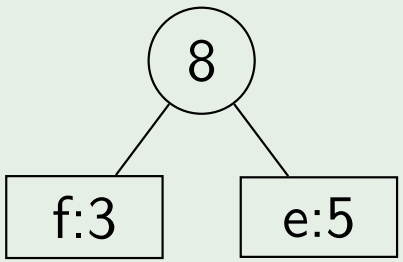
c	5		

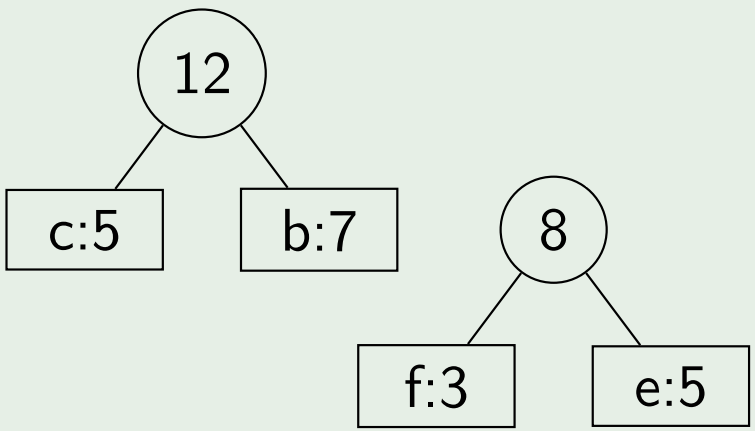


Optimize encoding

Encoding "faeaebacdeeabadeacdfbdaddadcafdacbaababbaaccaa"

Frequencies

a	17	d	8
bc	12	ef	8



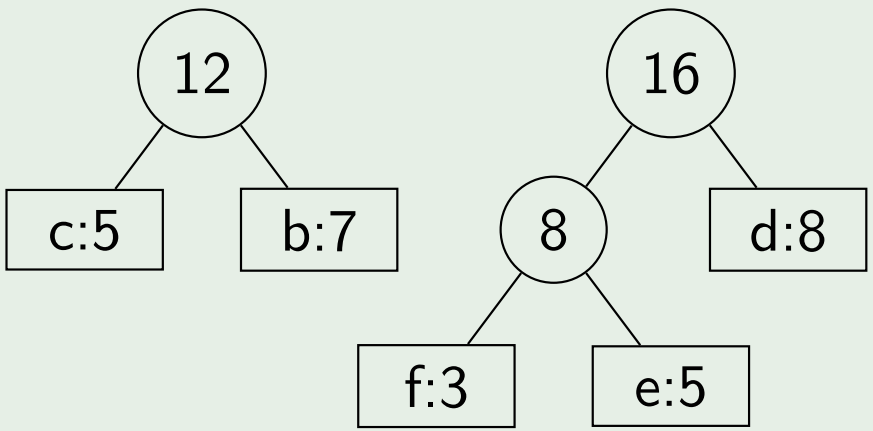
Optimize encoding

Encoding "faeaebacdeeabadeacdfbdaddadcafdacbaababbaaccaa"

Frequencies

a 17 def 16

bc 12



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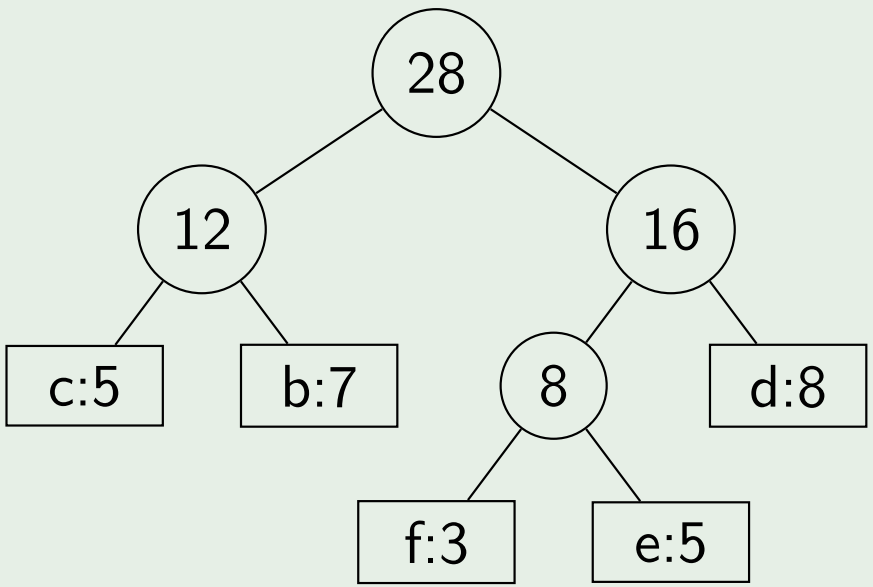

Frequencies

a 17 bcdef 28

Optimize encoding

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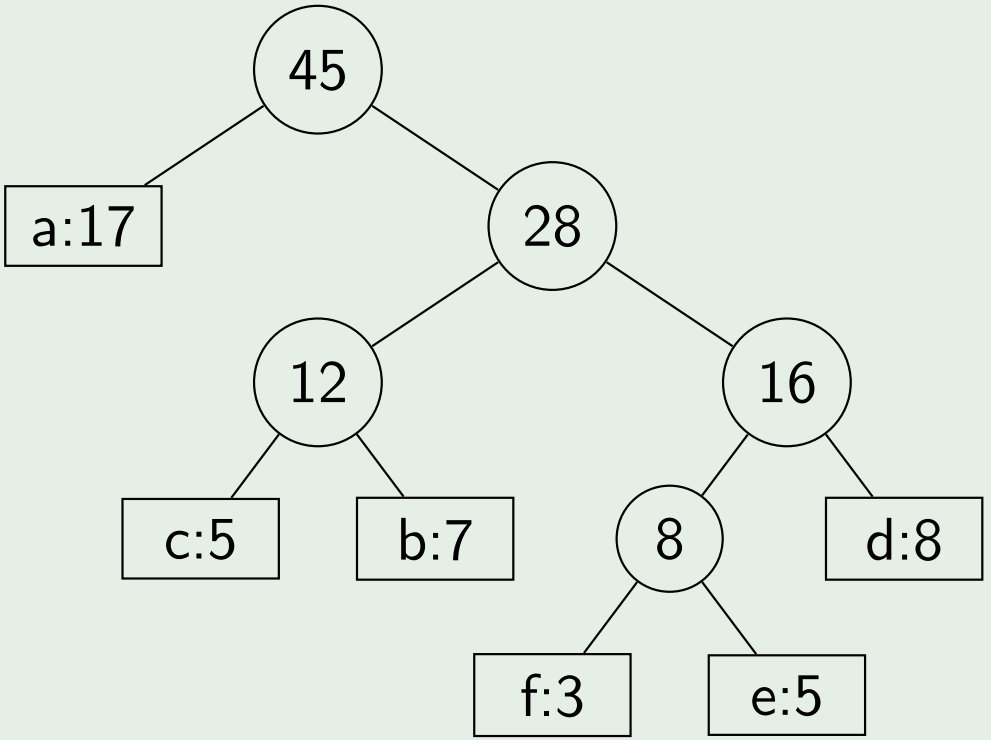

Frequencies

all 45

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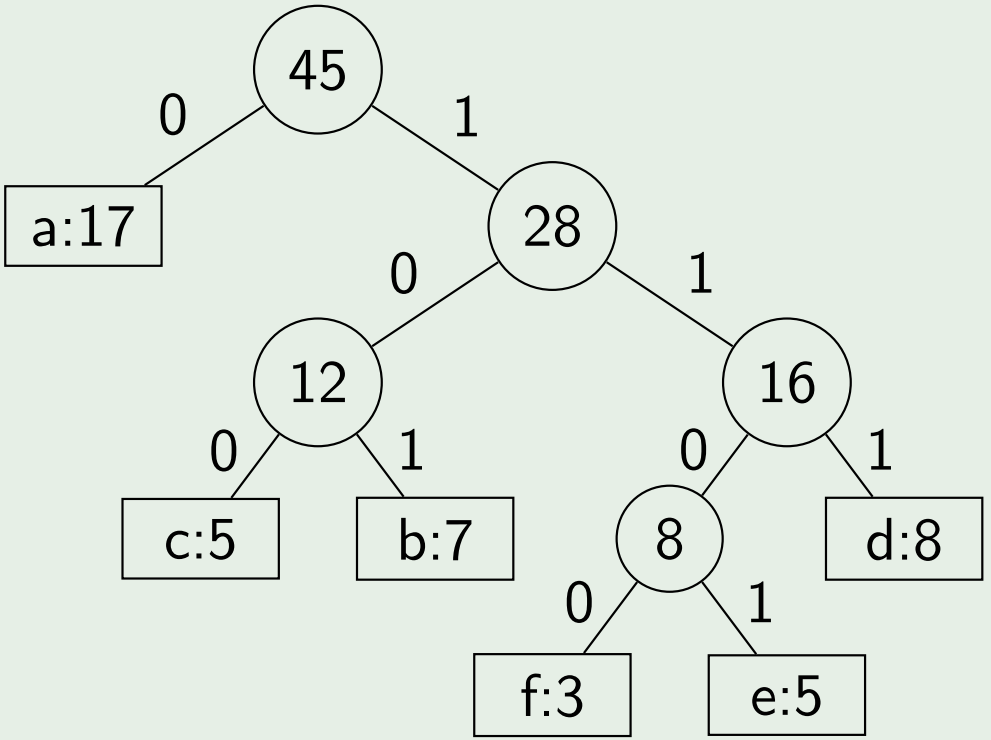

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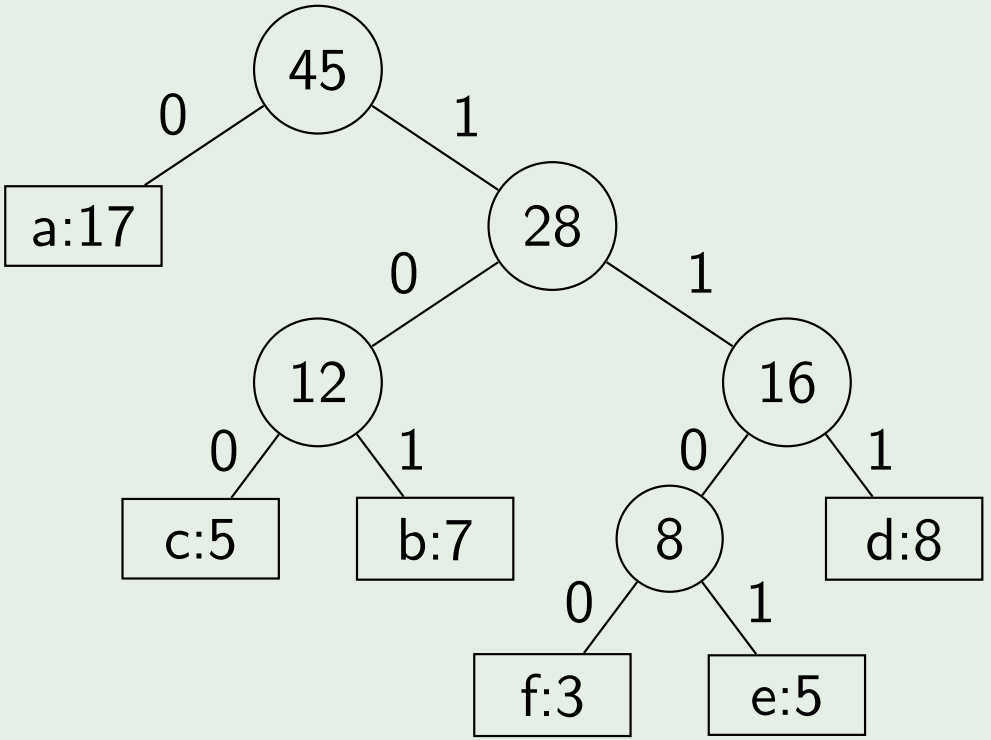

Frequencies

a	17	d	8
b	7	e	5
c	5	f	3

Codes

a	0	d	111
b	101	e	1101
c	100	f	1100

Optimize encoding

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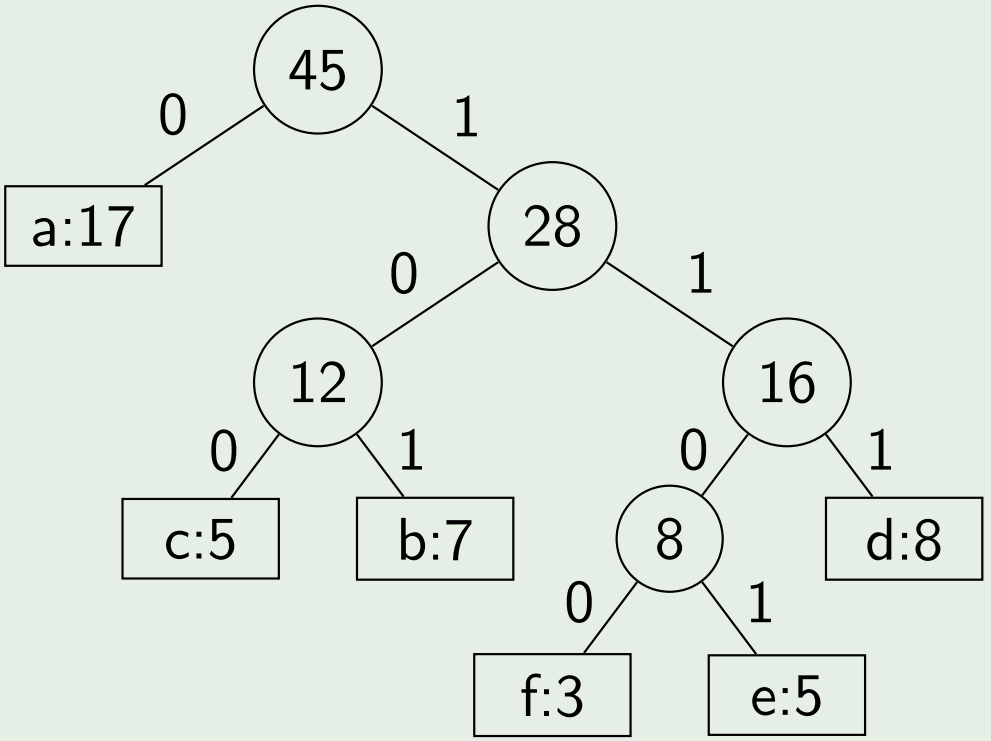

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Codes

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b	101	e	1101
c	100	f	1100

*f*6*b*6*a*7*dd*57*d*4*ff*7*bf*78*fe*94*ab*490

28+6 bytes instead of 46

Classical compression algorithms

Best compression first

bzip2 high quality, size within 10% to 15% to best compressors and twice faster to compress, six times faster to decompress

gzip classical ziping with *deflate* algorithm, combination of LZ77 and Huffman Coding

LZO fast - twice faster than gzip - but less good - 50% bigger result. Composed of small blocks of 256 kB of compressed data

Snappy even faster - 250MB/s encoding, 500MB/s decoding on single core i7 - but even less good. Use internally by Google

A word on lossy compression

What does it mean, lossy ?

- that you will lose part of your data !
- but that you may not see the difference
- and it may allow to compress MUCH better

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Classical examples

jpg did you notice the images may be slightly blured ?

mp3 removes all the frequencies you cannot hear

A word on lossy compression

The main ideas

1. tranformation of the data, usually based on fourier transforms
2. sensibility (nb bits) is reduced on less important parts
   - e.g. high frequencies
3. thanks to the previous cuts, a lot of similar values (0) appear
4. use standard compression

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Usage in scientific computing

- mostly when encoding the data, that is within a subdetector
- very seldom at the level of complete data files

Compression efficiency factors

Algorithm - a small factor

- always a tradeoff between speed and compression
- best algorithms will gain maximum a factor 2 in size compared to fast ones

Data - the main factor

content some contents are most compressable than others - zeros compress very well, while already compressed data don't

format human readable formats (XML) tend to compress very well as they are full of redundant markers

structure column storage compresses better than raw storage, as identical data types are close to each other

Globally, is compression interesting ?

Yes if

- you data are very cold, that is not frequently accessed
  - and the gain of space is worth the annoyance
  - tapes are compressing systematically
- if you are really I/O bound and compression factor is high
- you use a fast compression algorithm (snappy) and gain space for little price

No if

- you become CPU bound due to (de)compression
  - typical with bzip2
- you do frequent partial reads
- you need to split and cannot use LZO or bzip2

Data addressing

Data addressing

The most important part of your data is your metadata

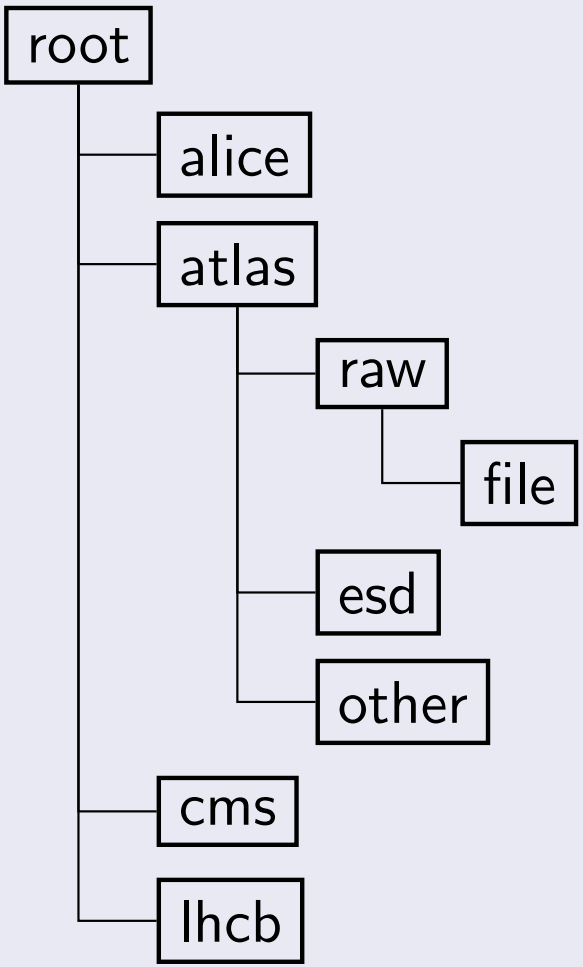
Addressing options

- good old hierarchical namespace
- databases
- object store approach

Traditionnal, hierarchical data addressing

Directory tree

- structured via "directories"
- containing "files" and subdirectories
- filesystem like



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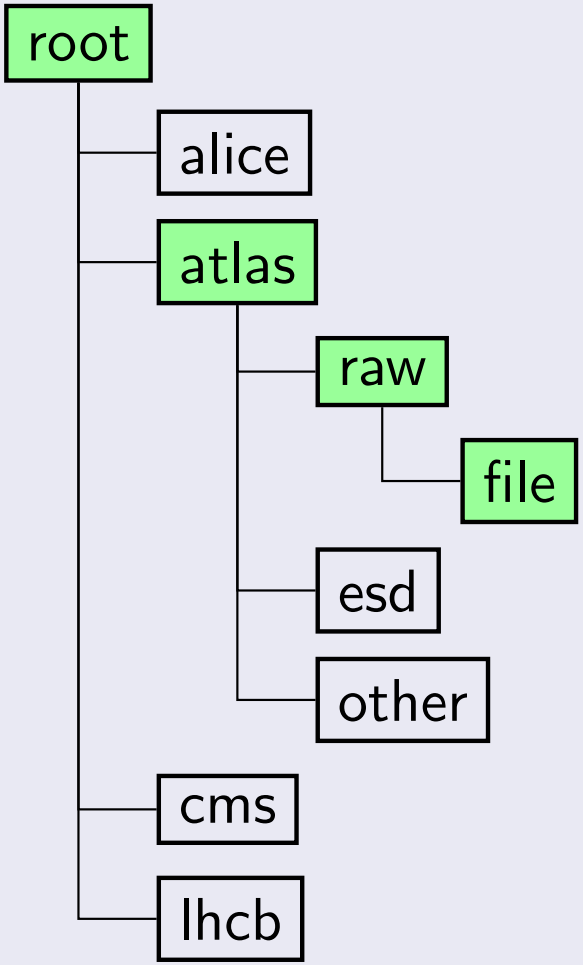
/atlas/raw/file



Hierarchy pros and contras

Pros

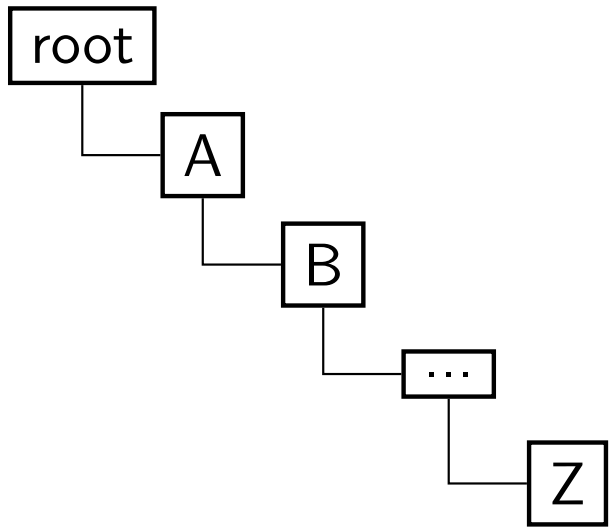
- easiness of use (for humans)
- helps to structure the data sets
  - easy to list/erase/deny access to a whole subtree
  - allows to implement quotas per directory
- atomic operations
  - in particular moves, removals
  - change of permissions
- always consistent

Contras

- becomes slow for deep hierarchies
- in general scales badly

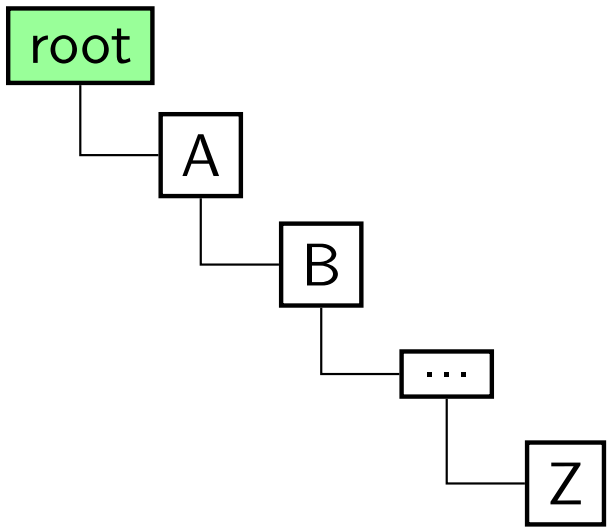
Influence of depth

- Suppose you access '/A/B/C/.../Z'
- The following will happen :



Influence of depth

- Suppose you access '/A/B/C/.../Z'
- The following will happen :
  - find *root*
  - check you have execution right



Influence of depth

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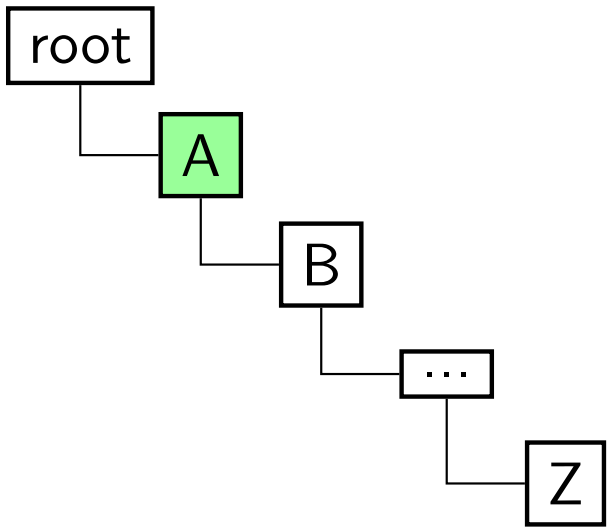
  - find *A* within *root*
  - check you have execution right



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- The following will happen :
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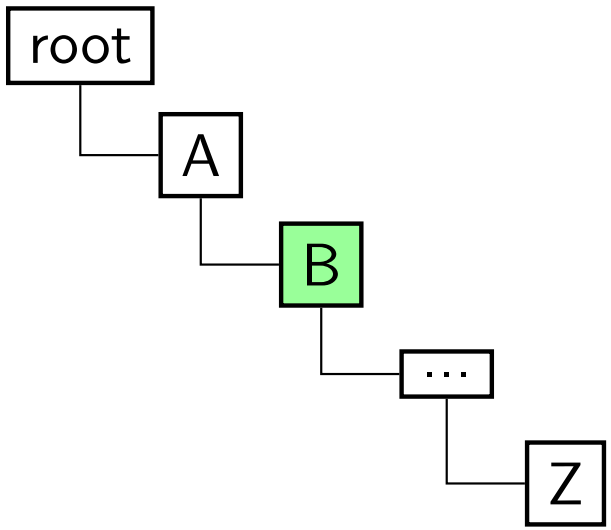
  - check you have execution right
  - find *A* within *root*
  - check you have execution right
  - find *B* within *A*
  - check you have execution right



Influence of depth

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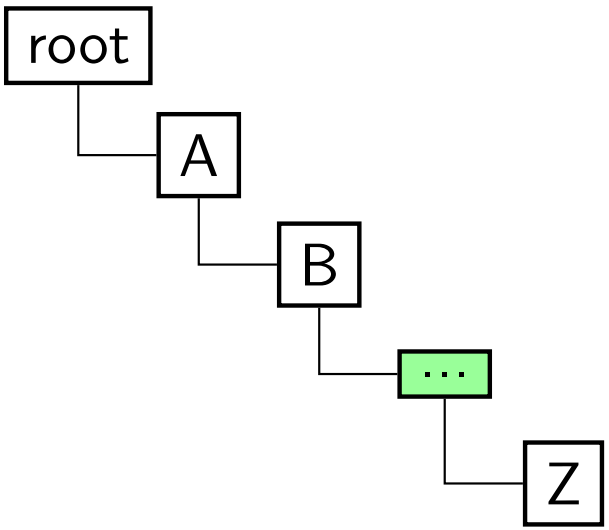
  - check you have execution right
  - find *B* within *A*
  - check you have execution right
  - ... repeat until *Y* ...



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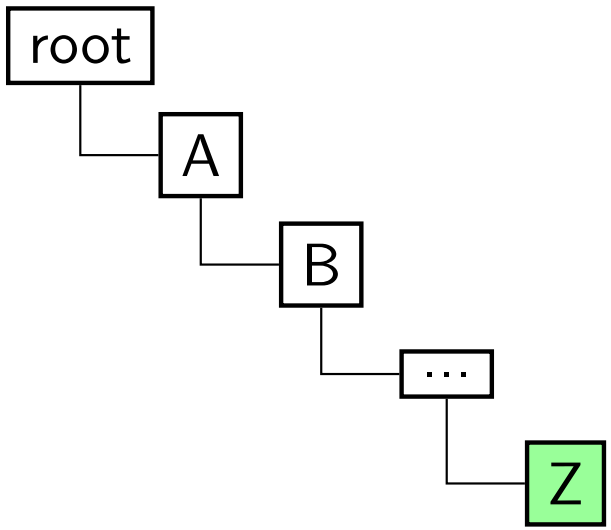
  - check you have execution right
  - ... repeat until *Y* ...
  - find *Z* within *Y*
  - check you have read/write rights



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  - check you have execution right
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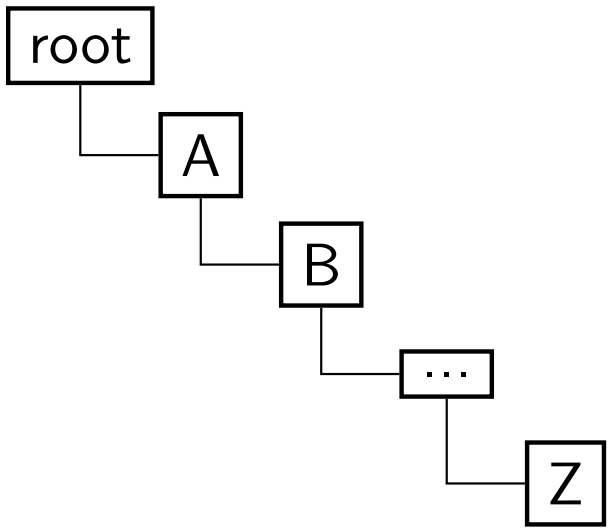
  - find *Z* within *Y*
  - check you have read/write rights



→ $2n + 1$ operations for depth n

depth seen at CERN (AFS, CASTOR) : 20-25

Atomicity and consistency consequences

root is a bottle neck

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- no easy parallelization of this part because of atomicity

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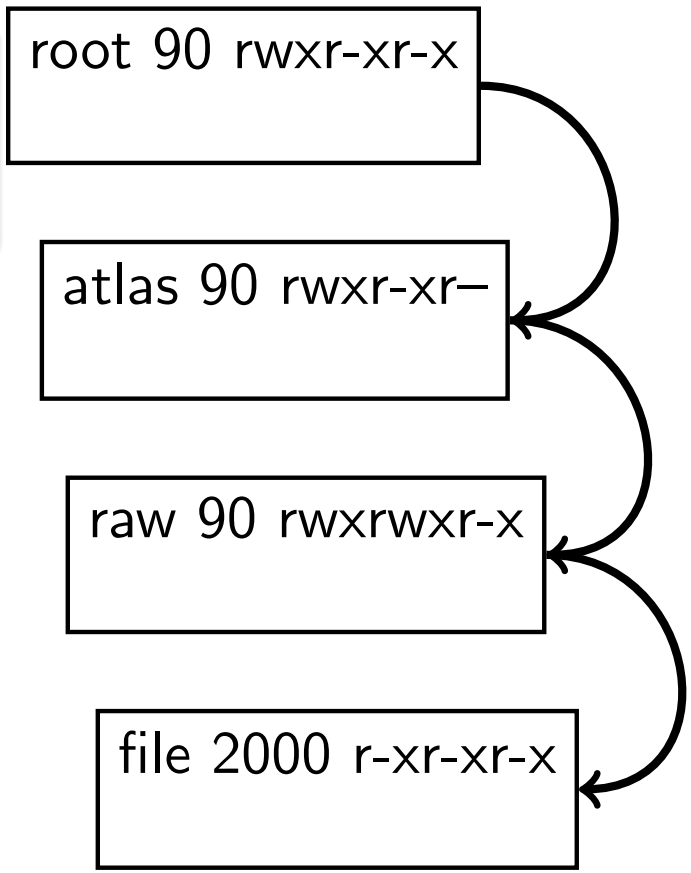
consistent recursive listing/searching is a nightmare

- you would need to lock all subtree for the whole listing time
- makes full listing impossible

Some partial solutions - rights

Precomputation

- precompute effective rights/size/... at every level



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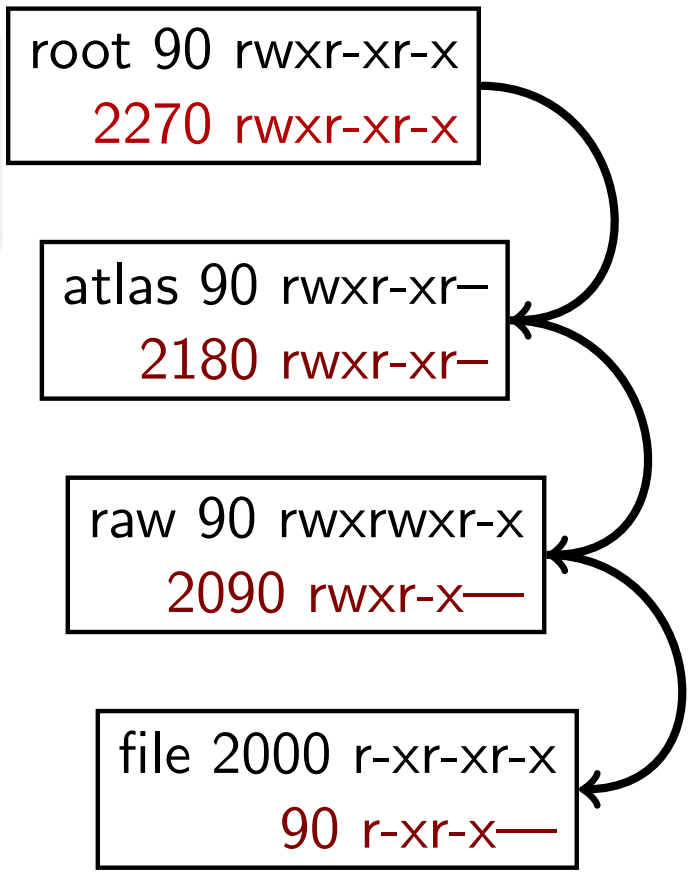
Precomputation

- precompute effective rights/size/... at every level



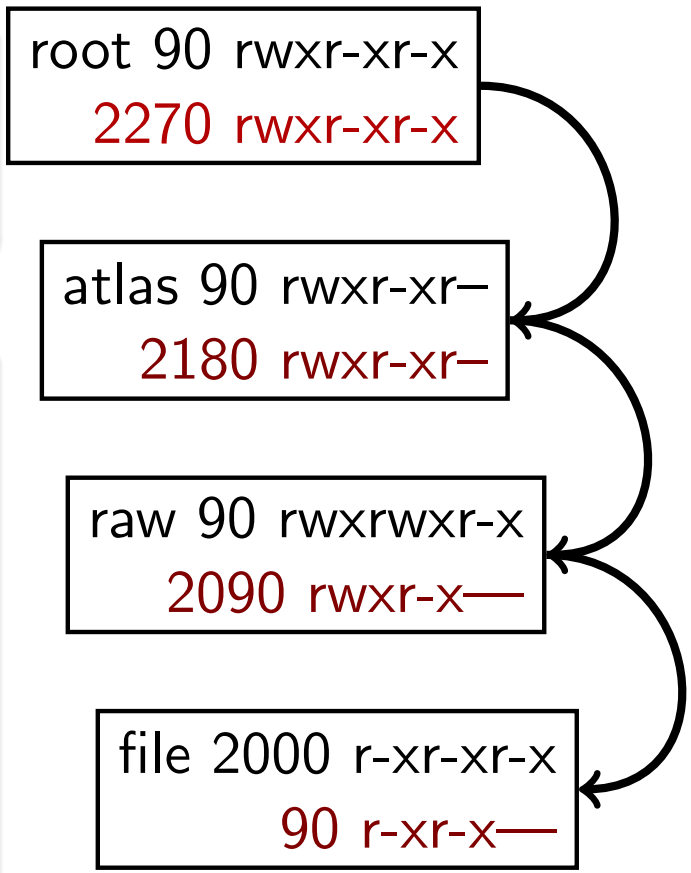
Some partial solutions - rights

Precomputation

- precompute effective rights/size/... at every level

But...

- updating a top level right means full recomputation !
- the complete expansion for each file may be extremely heavy
- especially if complex ACLs are used at directory levels



Some partial solutions - rights

Avoiding full recomputation

- one can mark a subtree as "dirty"
- can then be recomputed offline
- in case we hit a dirty tree, we go back to tree scanning

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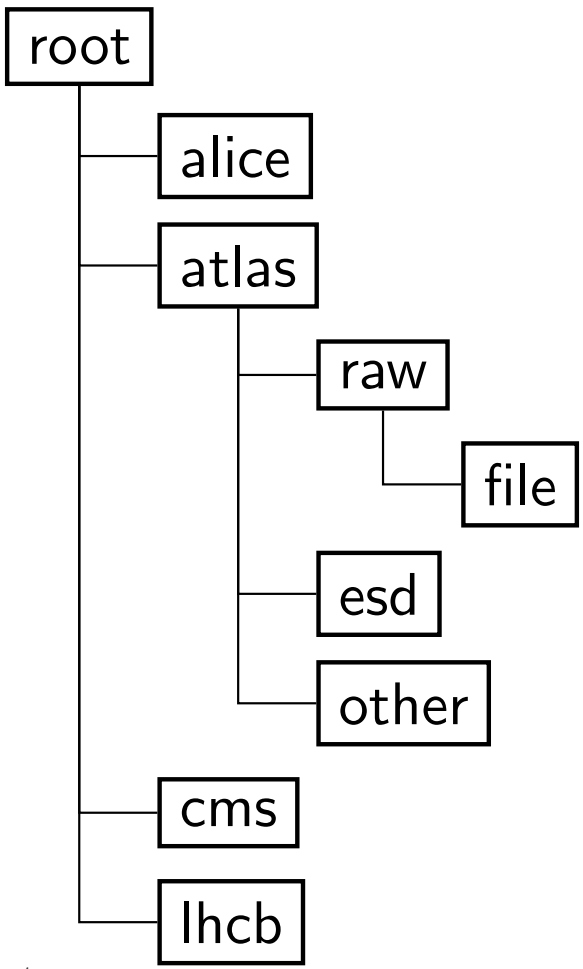
But...

- tree scanning is needed to check for the dirty flag !
- actually, special structures like bit map indexes can help speeding it up

Some partial solutions - root bottleneck

Path indexing

- keep an index of full paths and their locations



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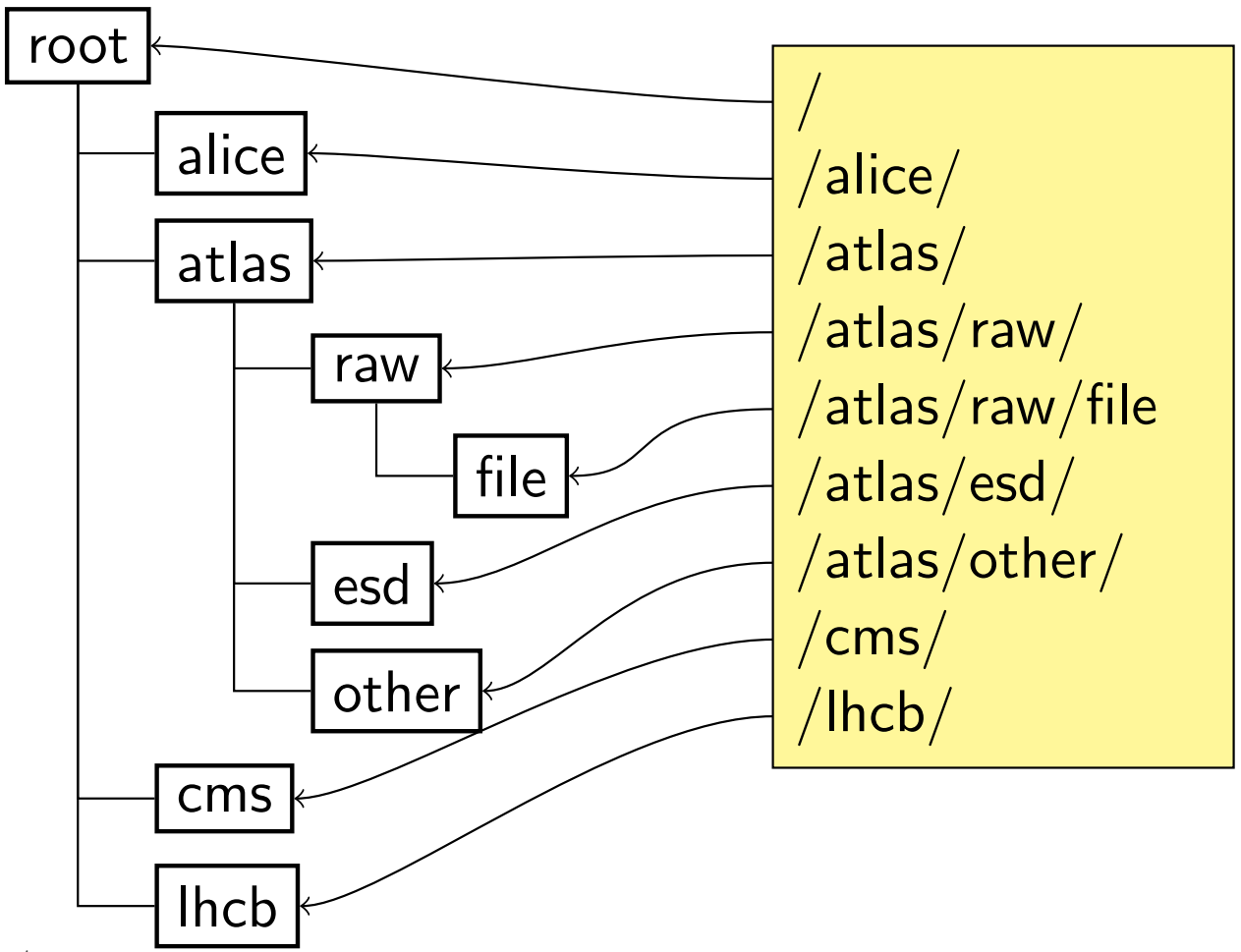

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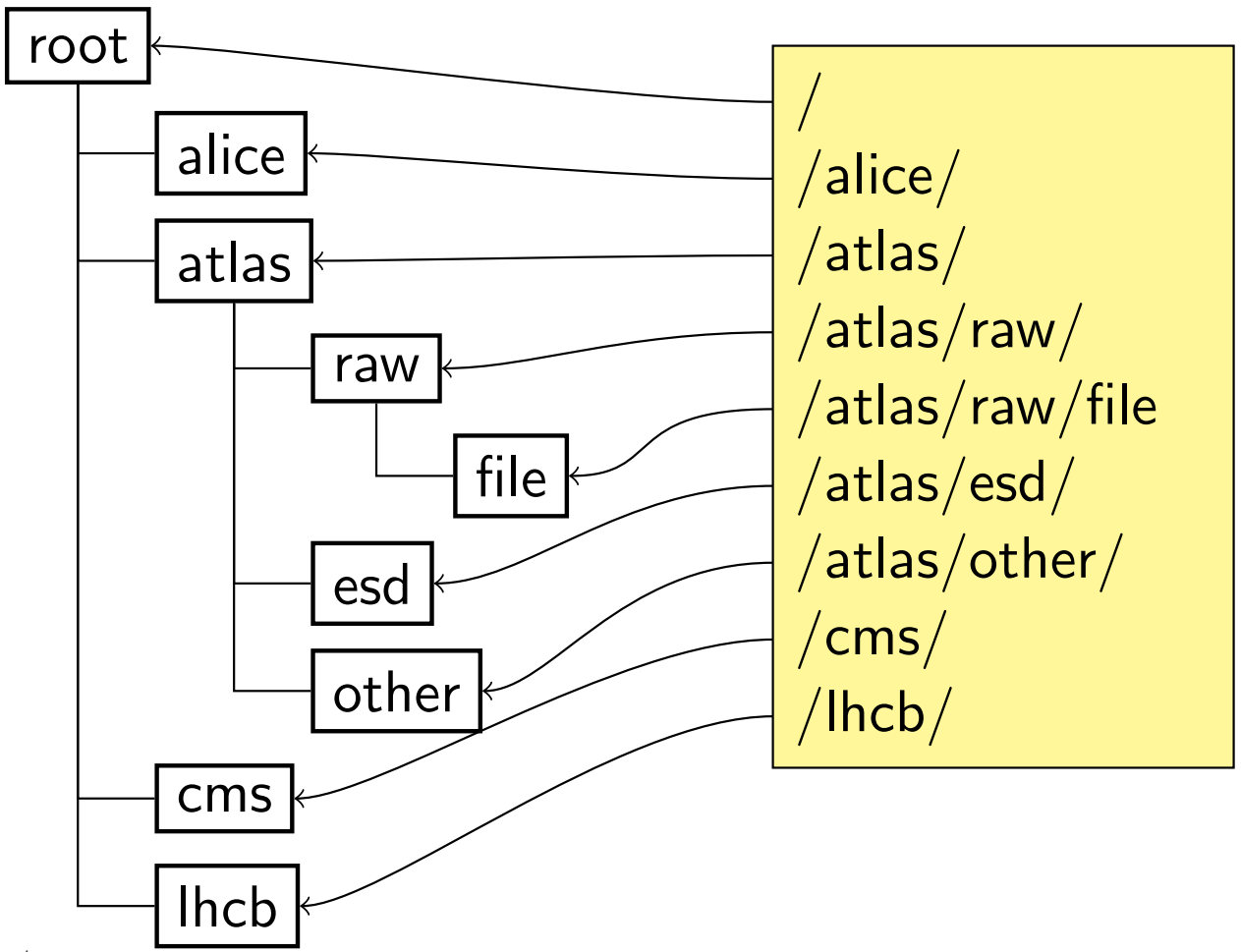

But...

- just think of a rename of atlas into titan...

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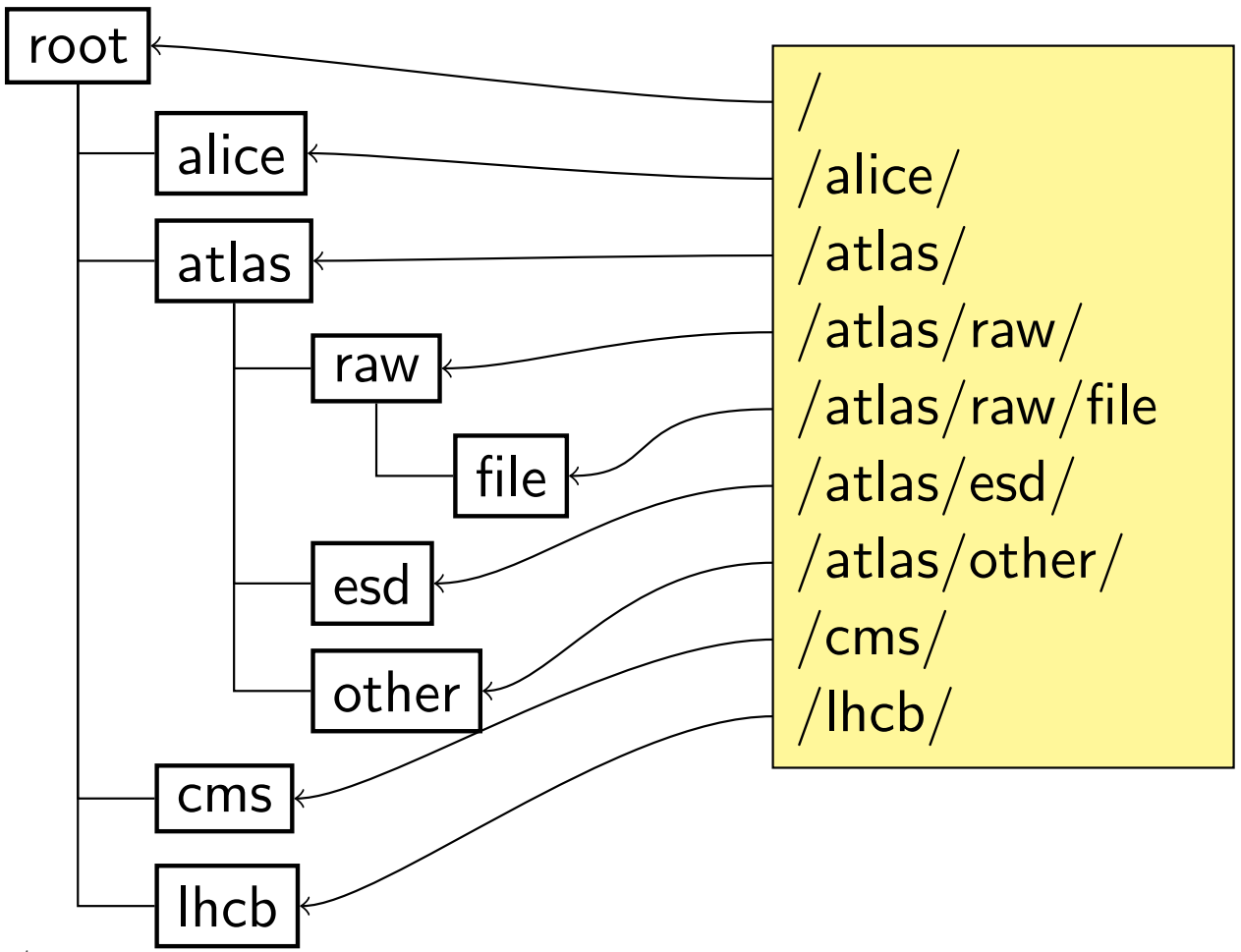

But...

- just think of a rename of atlas into titan...

Ideas

- use redirections, dirty flags, ...

Some partial solutions - conclusion

→ very high complexity

no scalable solution on the market so far

Radical change : flat namespaces

The idea

- drop the hierarchy
- only have a sea of objects with a unique identifier
- forbid object modifications (only appends)
- forbid renames
  - or implement them as copy + drop

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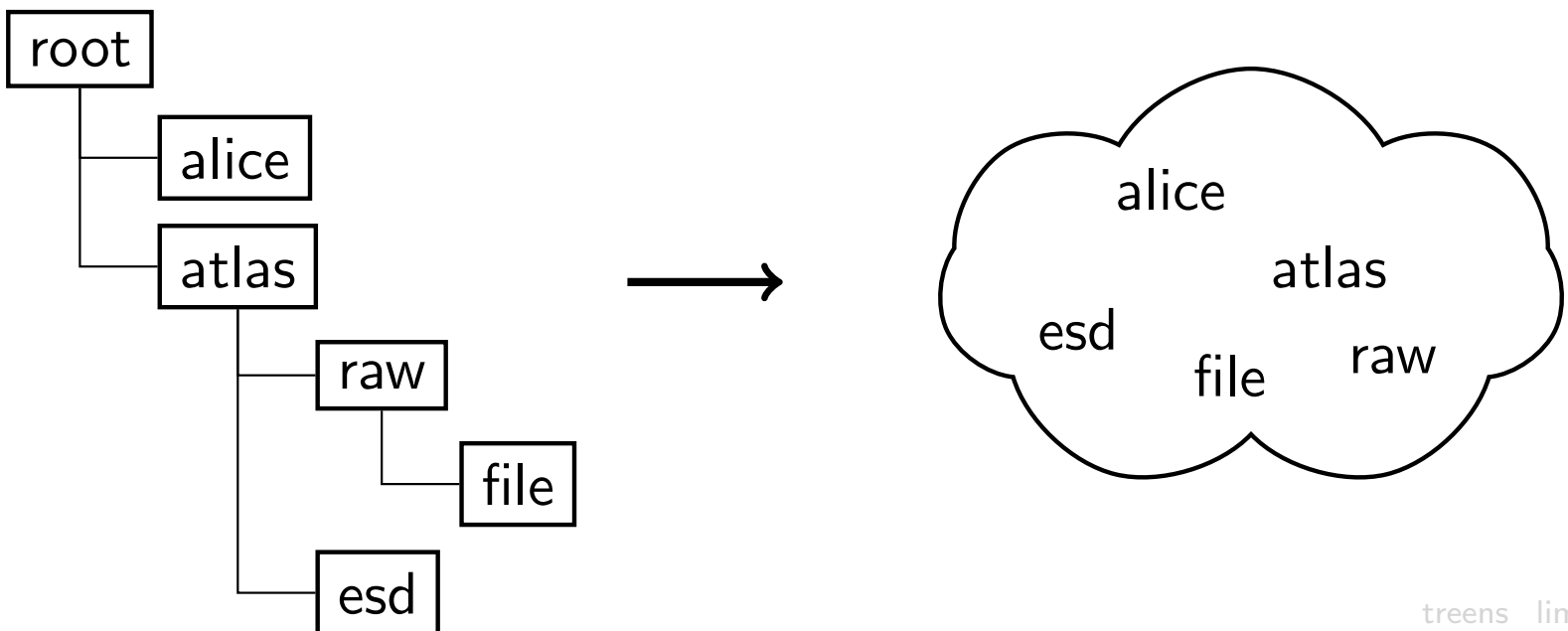

Radical change : flat namespaces

Infinitely scalable namespace

- client can hash the entry path
- and connect accordingly to the right server

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Infinitely scalable namespace

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- and connect accordingly to the right server

You lose

- data management aspect, left to user
- listing facilities
  - can be implemented in a Map/Reduce way

About hashing on the client

Large systems are dynamic

- i.e. they change over time
  - adding/removing hardware
  - changing network topology
- data may need to be rebalanced (see later)
- the client hashing algorithm needs to deal with that

About hashing on the client

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CRUSH : the ceph's hash

- achieves pseudo-random but deterministic data distribution
- supports replication and erasure coding (see later)
- taking into account storage structure (machines, racks, rows, ...)
- minimizing the data movements in case of cluster modifications

Stateful interfaces

The traditional POSIX interface for I/O

Based on file descriptors

```
int open(const char *pathname, int flags);
int socket(int domain, int type, int protocol);
int connect(int sockfd,
            const struct sockaddr *addr,
            socklen_t addrlen);
ssize_t read(int fd, void *buf, size_t count);
ssize_t write(int fd,
              const void *buf, size_t count);
off_t lseek(int fd, off_t offset, int whence);
int close (int fd);
int stat(const char *pathname, struct stat *buf);
DIR *opendir(const char *name);
struct dirent *readdir(DIR *dirp);
int closedir(DIR *dirp);
```

Key features and their consequences

hierarchical namespace

- can be a limitation

strong coherency

- last writer wins, metadata updated
- not suited for distributed environment, out of order concurrent writes
- lack of explicit atomicity
- metadata maintenance (e.g. last access time) is costly

file oriented

- no bulk interfaces for metadata
- stateful, requires server to maintain a state per client
  - e.g. opendir / readdir

Limitations of stateful interfaces

Server resources

- any stateful client call means allocation of server resources
- these resources will accumulate with the number of clients
- limiting single server scalability

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Parallelization issues

- multiple servers in parallel would need to share resources
  - which creates a single point of faillure and a possible contention
- alternatively you can dedicate servers to clients
  - but you lose server fail over
  - and load balancing

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Practically stateful interfaces do not scale

Stateless interfaces

Approach

- each client request must bring enough information to complete it without context
- simply the state is stored on the client

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Example of listing

- stateful

```
DIR *opendir(const char *name);
struct dirent *readdir(DIR *dirp);
int closedir(DIR *dirp);
```

- stateless

```
struct dirent *readdir(const char *name);
struct dirent *readdir(struct dirent* current);
```

- providing you have a strict order defined

Conclusion

Conclusion

Key messages of the day

- Choose well your data format
- Think twice before compressing
- Value your metadata
- Think stateless for scalability