Physical Data Organization and Indexing

Introduction to Databases

CompSci 316 Fall 2017

DUKE
COMPUTER SCIENCE

Announcements (Mon., Mar. 6)

- Homework #3 to be posted today
  - will be updated after each lecture

- Allocation of TA/UTA for each project has been done
  - see private piazza threads
  - use it for all communications
  - receive comments on the milestone report soon
  - keep working on the projects

Today:

- Finish physical organization
- Indexes

Recall: cost for DB = mostly I/O

- Reading from/writing to disk is a major source of cost

- It’s all about reducing I/O’s!

- Cache blocks from stable storage in memory
  - DBMS maintains a memory buffer pool of blocks
  - Reads/writes operate on these memory blocks
  - Dirty (updated) memory blocks are “flushed” back to stable storage

- Sequential I/O is much faster than random I/O
  - try to store records that are likely to be accessed together close to each other

Recall: different storage layouts

- Record layouts
  - how attributes are stored in a record
- Block layout
  - how records are stored in a block
  - block = unit of I/O
  - sometimes unit of I/O in terms of a “page”, and a block can contain multiple pages
  - basic idea remains the same

Recall: Record layout

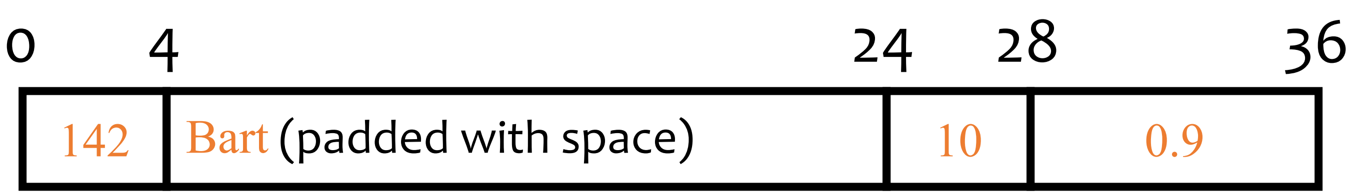
- Record = row or tuple in a table
  - “fixed format” dictated by table schema in relational databases

- Fixed-Length Records

- Variable-Length Records

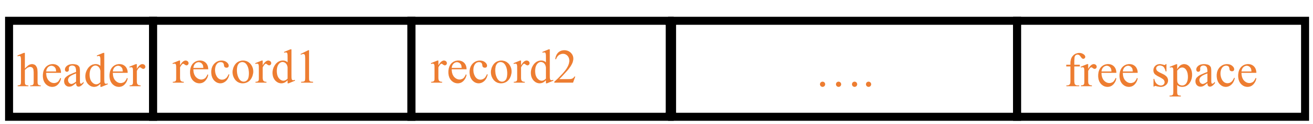
Fixed-length fields

- All field lengths and offsets are constant
  - Computed from schema, stored in the system catalog
- Common to start fields at locations multiple of 4 or 8
- Often record starts with a header
  - pointer to the schema
  - length of the record
  - timestamp for last read/write
  - pointers to the fields
- Example: CREATE TABLE User(uid INT, name CHAR(20), age INT, pop FLOAT);



Block layout for fixed length records

- Header may contain
  - links to some other "related" blocks, e.g. from overflow in indexes
  - information about the relation the block belongs to
  - directory for offset of each record
  - timestamp for last read/write
  - etc.

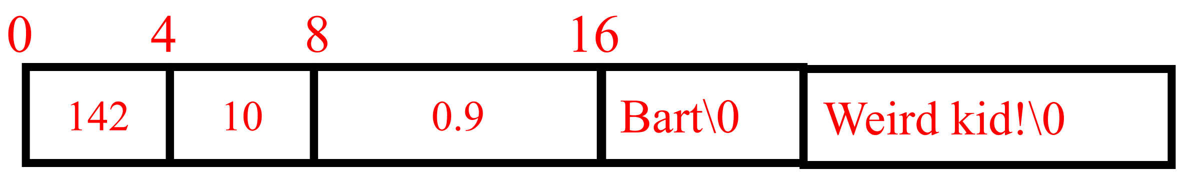


Variable Length Records - motivation

1. Data size may vary
   - address (up to 255 bytes, typically < 50 bytes), name
   - waste of space in fixed length
2. Repeating fields
   - e.g. pointers for a many-many relationship
   - the number of references may vary
3. Variable format records
   - do not know at the beginning (XML)
4. Enormous fields
   - like videos
   - recall BLOBs from Lecture 13

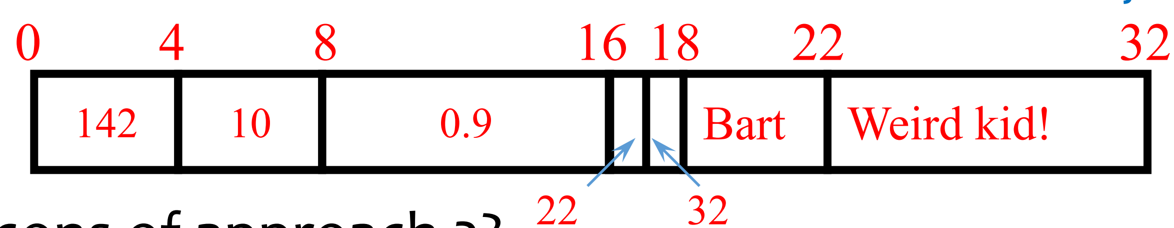
Variable-length records

- Put all variable-length fields at the end after all fixed length fields (why?)
- Example: CREATE TABLE User(uid INT,
  name VARCHAR(20), age INT, pop FLOAT,
  comment VARCHAR(100));
- Approach 1: use field delimiters ('\0' okay?)



- Approach 2: use an offset array

why no pointer to Bart?



- Pros/cons of approach 2?
  - (-) Update is messy if it changes the length of a field – may not fit in the block
  - (+) direct access to i-th field, efficient storage of nulls

Specific approaches

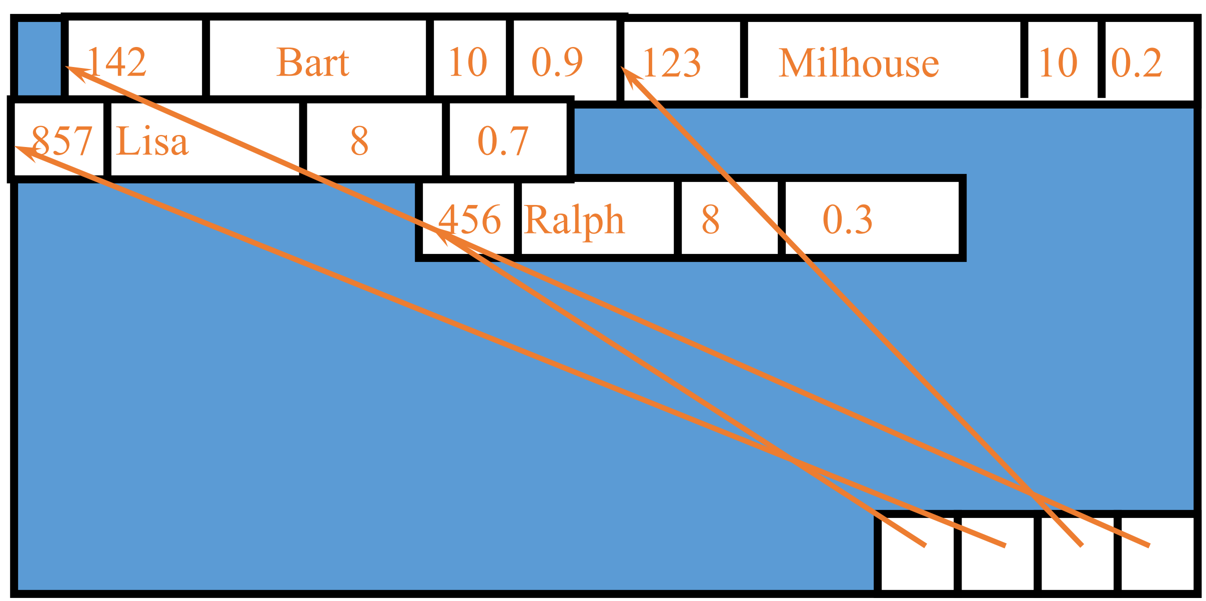
- NSM:
  - N-ary storage model
  - Standard row-major order
- PAX:
  - Partition Attributes Across
  - (if you are interested, see this: http://www.pdl.cmu.edu/PDL-FTP/Database/pax.pdf)
- Column store
  - Store records in column-major order

NSM

- Store records from the beginning of each block
- Use a directory at the end of each block
  - To locate records and manage free space
  - Necessary for variable-length records

Why store data and directory at two different ends?

So both can grow easily!



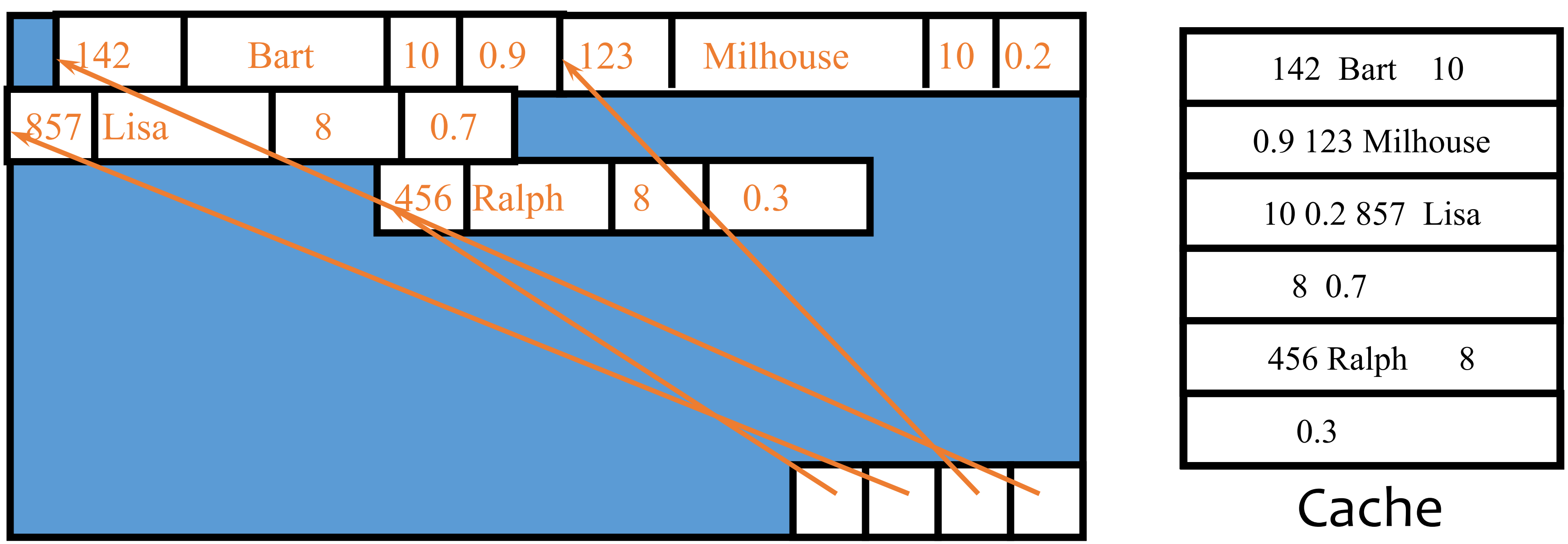
Options

- Reorganize after every update/delete to avoid fragmentation (gaps between records)
  - Need to rewrite half of the block on average

- A special case: What if records are fixed-length?
  - Option 1: reorganize after delete
    - Only need to move one record
    - Need a pointer to the beginning of free space
  - Option 2: do not reorganize after update
    - Need a bitmap indicating which slots are in use

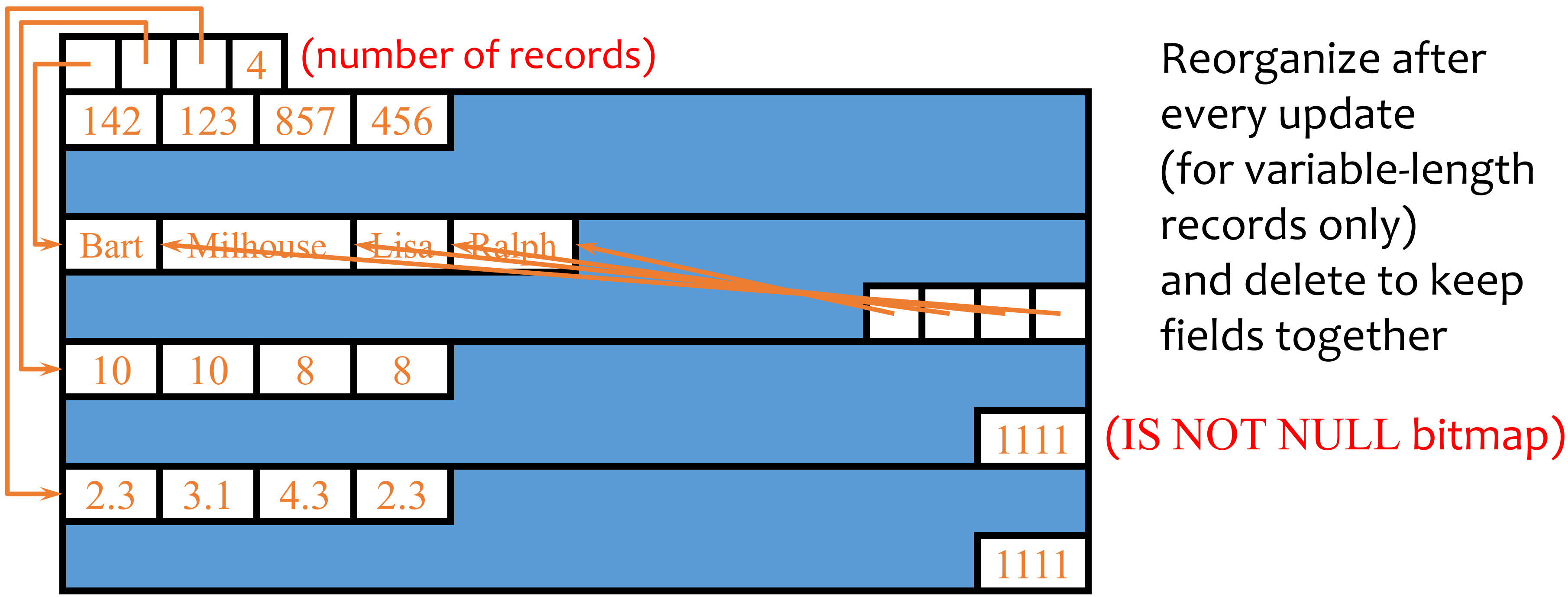
Cache behavior of NSM

- Query: SELECT uid FROM User WHERE pop > 0.8;
- Assumptions: no index, and cache line size < record size
- Lots of cache misses
  - loads unnecessary attributes
  - uid and pop are not close enough by memory standards



PAX

- Most queries only access a few columns
- Cluster values of the same columns in each block
  - When a particular column of a row is brought into the cache, the same column of the next row is brought in together



Reorganize after every update (for variable-length records only) and delete to keep fields together

Beyond block layout: column stores

- The other extreme: store tables by columns instead of rows
- PAX affects data layout within a single page
  - e.g. one relation can store NSM, other PAX
  - or first do vertical partitioning, then use PAX for storing
- Advantages (and disadvantages) of PAX are magnified
  - Not only better cache performance, but also fewer I/O's for queries involving many rows but few columns
  - Aggressive compression to further reduce I/O's
- More disruptive changes to the DBMS architecture are required than PAX
  - Not only storage, but also query execution and optimization

Summary

- Storage hierarchy
  - Why I/O's dominate the cost of database operations
- Disk
  - Steps in completing a disk access
  - Sequential versus random accesses
- Record layout
  - Handling variable-length fields
  - Handling NULL
  - Handling modifications
- Block layout
  - NSM: the traditional layout (row store)
  - PAX: a layout that tries to improve cache performance
- Column store: NSM transposed, beyond blocks

Index

What are indexes for?

- Given a value, locate the record(s) with this value

  SELECT * FROM *R* WHERE *A* = *value*;

  SELECT * FROM *R*, *S* WHERE *R*.*A* = *S*.*B*;

- Find data by other search criteria, e.g.
  - Range search

    SELECT * FROM *R* WHERE *A* > *value*;
  - Keyword search

Focus of this lecture

Index classification

- Dense vs. Sparse
- Clustered vs. unclustered
- Primary vs. Secondary
- Tree-based vs. Hash-based
  - we will only do tree indexes in 316

- Discussion on structure of indexes and pages : on whiteboard

Dense and sparse indexes

- Dense: one index entry for each search key value
  - One entry may “point” to multiple records (e.g., two users named Jessica)
- Sparse: one index entry for each block
  - Records must be clustered according to the search key

Dense versus sparse indexes

- Index size
  - Sparse index is smaller
- Requirement on records
  - Records must be clustered for sparse index
- Lookup
  - Sparse index is smaller and may fit in memory
  - Dense index can directly tell if a record exists
- Update
  - Easier for sparse index

Clustered vs. Unclustered Indexes

- CREATE INDEX UserPopIndex ON User(pop);
- What happens if multiple records with the same value of “pop”?
- Clustered:
  - records with the same pop value are physically stored close to each other
  - access one page, access many records with the same pop
- Unclustered
  - no such guarantee
  - may need to access a page for each record
- At most one clustered index in each relation

Primary and secondary indexes

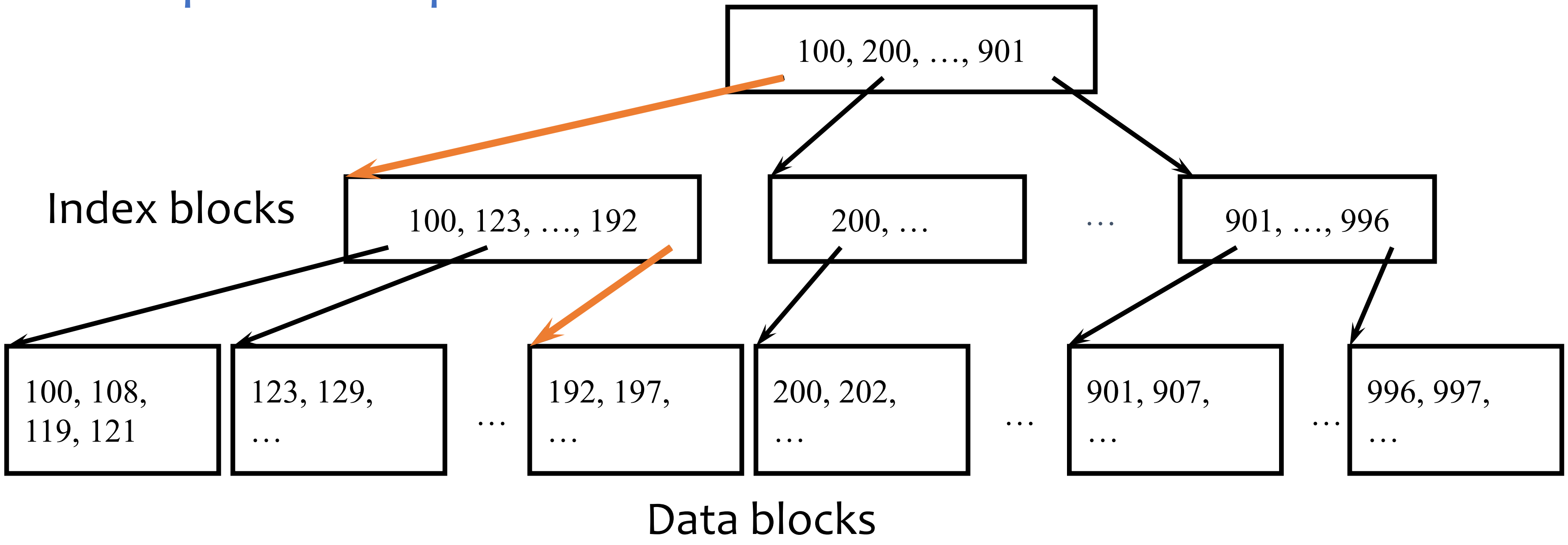
- Primary index
  - Created for the primary key of a table
  - Records are usually clustered by the primary key
  - Can be sparse, usually clustered
- Secondary index
  - Usually dense and unclustered
- SQL
  - PRIMARY KEY declaration automatically creates a primary index, UNIQUE key automatically creates a secondary index
  - Additional secondary index can be created on non-key attribute(s):
    CREATE INDEX UserPopIndex ON User(pop);

ISAM

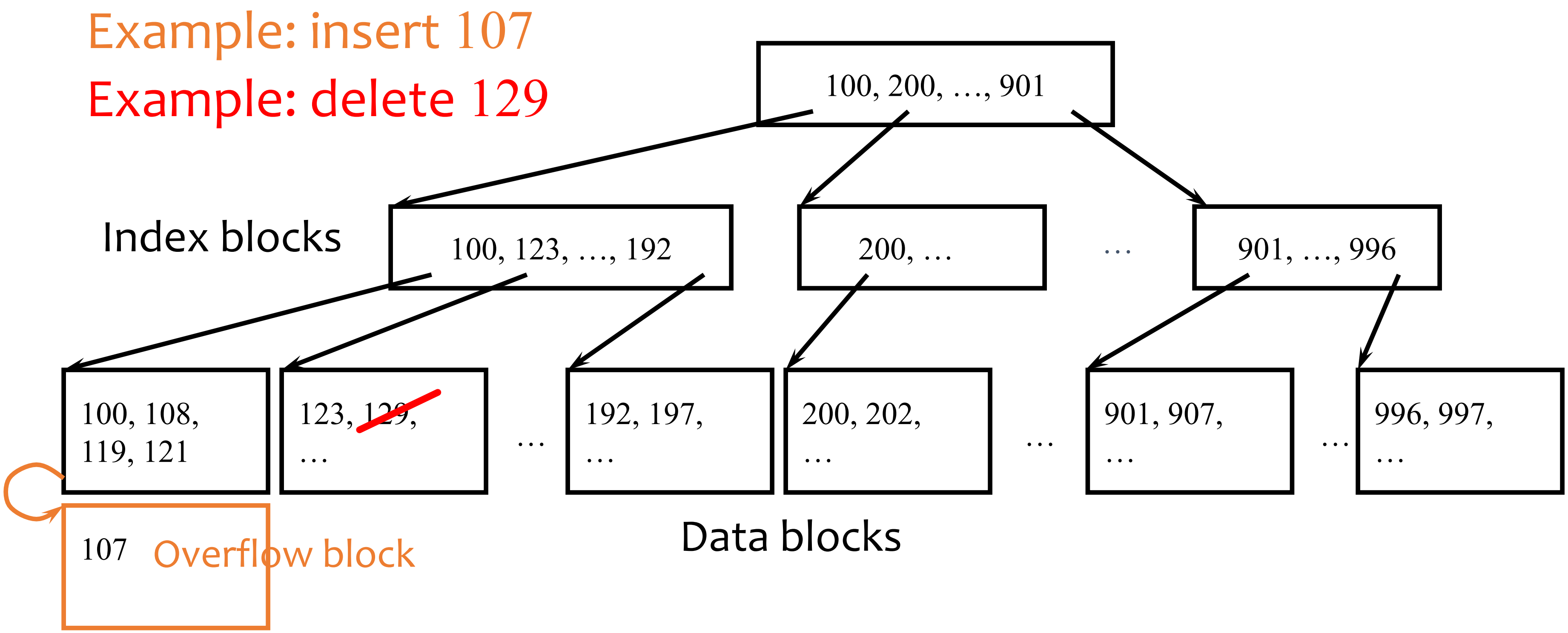
- What if an index is still too big?
  - Put a another (sparse) index on top of that!

☞ISAM (Index Sequential Access Method), more or less

Example: look up 197



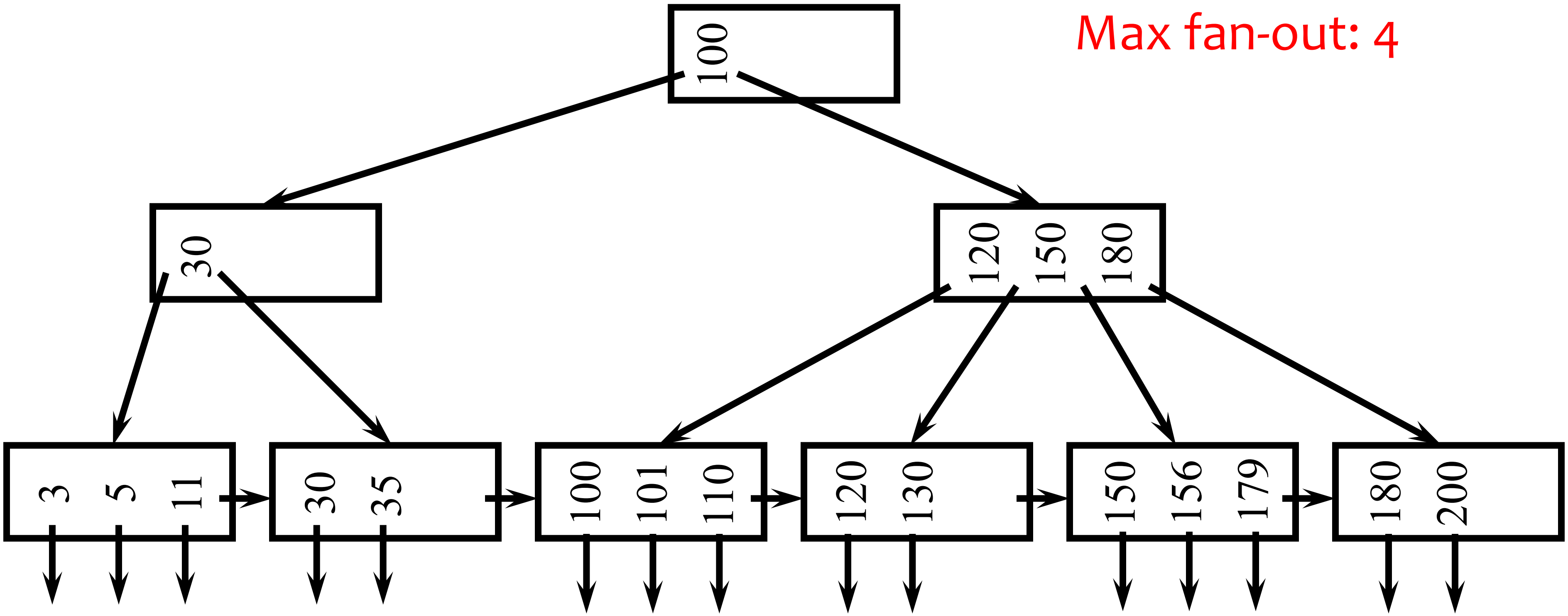
Updates with ISAM



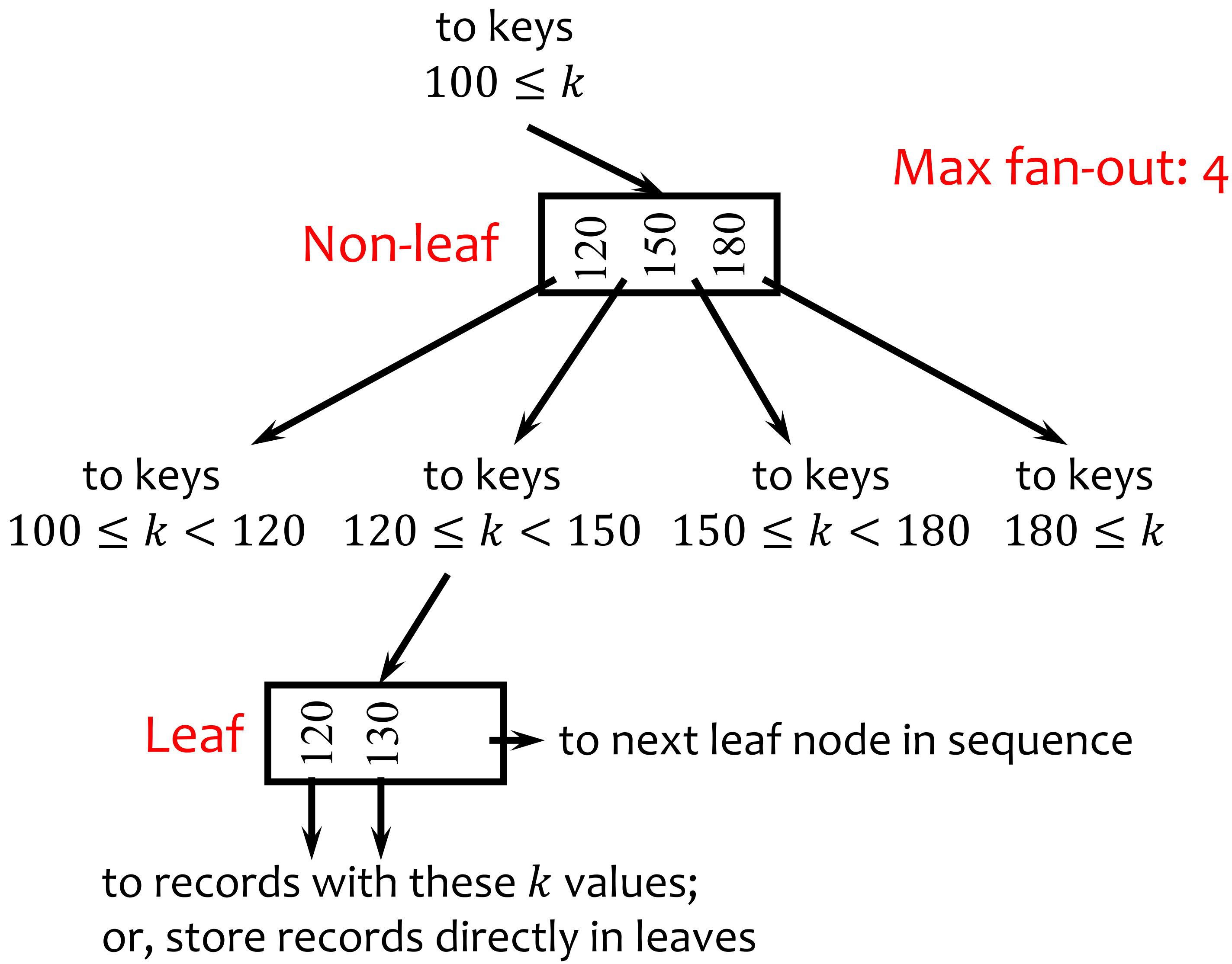
- Overflow chains and empty data blocks degrade performance
  - Worst case: most records go into one long chain, so lookups require scanning all data!

B⁺-tree

- A hierarchy of nodes with intervals
- Balanced (more or less): good performance guarantee
- Disk-based: one node per block; large fan-out



Sample B+-tree nodes



B^+-tree balancing properties

- Height constraint: all leaves at the same lowest level
- Fan-out constraint: all nodes at least half full (except root)

	Max # pointers	Max # keys	Min # active pointers	Min # keys
Non-leaf	f	$f-1$	$\lceil f/2 \rceil$	$\lceil f/2 \rceil - 1$
Root	f	$f-1$	2	1
Leaf	f	$f-1$	$\lfloor f/2 \rfloor$	$\lfloor f/2 \rfloor$

End of lecture 14
B+-tree to be continued in Lecture 15