CS 348 Lecture 12

Physical Data Organization Finish & Indices

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UNIVERSITY OF WATERLOO | DSG Data Systems Group

Announcements

- Assignment 3 past but still have until tomorrow midnight:
- Reading week: No lectures or OHs next week.

Outline For Today

1. Recap & Finish Physical File Organization Designs
   - Row-oriented Physical Design (Recap)
   - Colum-oriented Physical Design
   - Hybrid (PAX) Physical Design
   - Designs for Variable-length Fields
   - Designs for NULLs
2. Database Indices
   - 5 Index Designs in Increasing Level of Robustness
   - Using Indices In Practice

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Recall Potential Goals of Physical Data Design

1. Minimize I/O!
   i. Design files to pack records/columns into few number of pages
   ii. Keep related data close in storage devices!
   iii. Cache pages of data that is likely to be used
2. Maximize sequential reads from storage devices!
3. Simplicity/speed of accessing values
   - E.g., don't compress using a complex compression scheme

These are general guidelines and not necessarily independent.

Common Record and Page Layouts

1. Row-oriented
2. Column-oriented
3. Hybrid (PAX) Row & Column-oriented Fixed-length Values
4. Designs for Variable-length Values
5. Designs for NULL Values

Recap: Row-Oriented NSM Design

- Each page contains ~ H/T many rows and all fields of each row

Customer		
cid : int64 (8 bytes)	name : string (60 chars)	isGoldMember : bool (1 byte)

101	Alice Munro\0\0\0….\0	1	201	Carl Sagan\0\0\0…\0	0
103	Bob \0\0\0….\0	1	…	…	…

(Example Disk Page, e.g., in file customer.mkd)

- Note: because records are fixed length, can read any field with simple arithmetic (*not a consequence of NSM*)
  - E.g: 5th records name field at offsets: 4*(8+60+1) + 8 = 284 to 344

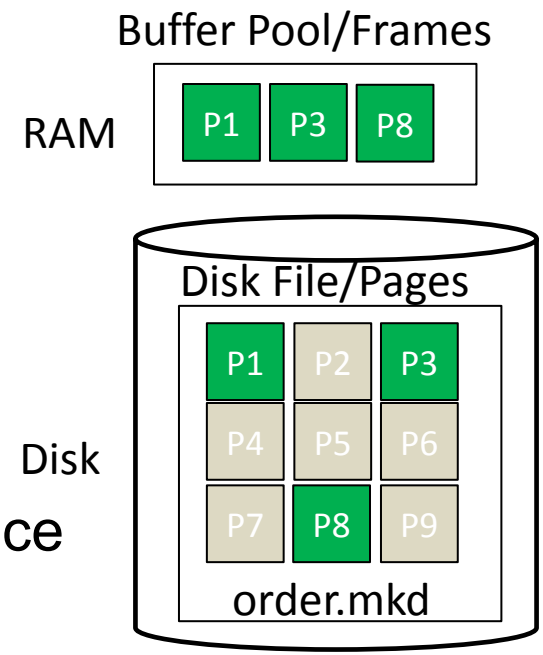
Recap: Pros/Cons of NSM

- Pro: Good for queries that access multiple or all fields of tuples
- Con: If queries access a single field, e.g., counting numGoldMembers, “effective read size” can be small
  - E.g. 1/69 bytes read is useful, in columnar storage you can do 69x less I/O to do the same count.
- Con: For some workloads higher # I/O => lower (buffer) cache utilization (next slide)

Recap: Buffer Manager & Ex Op/Storage Interface

- DBMSs have a *buffer manager* (BM) component that keeps a set of file pages in memory to reduce I/O.
- Goal of BM: keep pages that are likely to be accessed in memory
  - Implement a caching alg, e.g., Least-Recently Used (LRU)

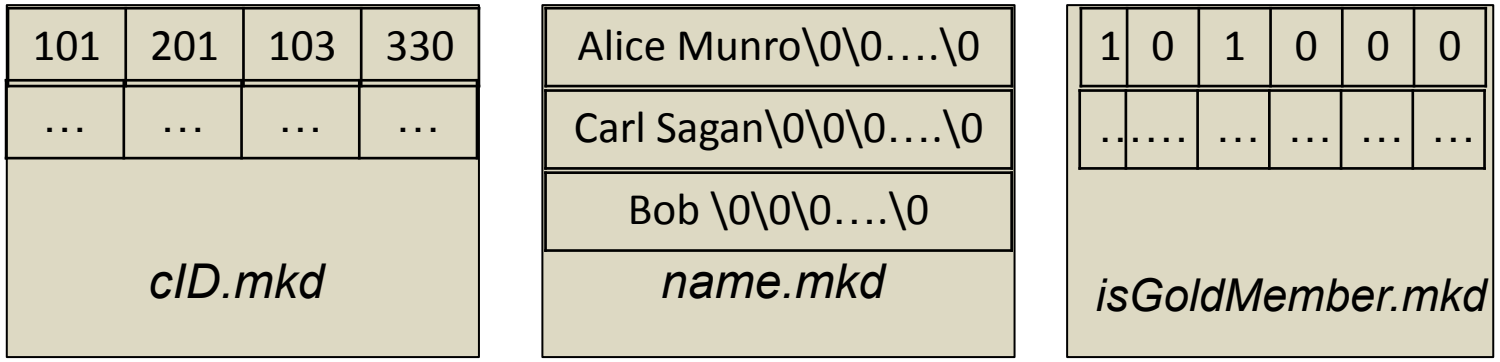
```
class DatabaseFileHandle : {
string filename; // e.g., order.mkd
int tupleLen; // e.g., 69
BufferManager bm;
void readRecord(Tuple* outTuple, recordID) {
   (pageIdx, offset)= calculatePageInfo(recordID)
   Frame* frame = bm.pinPage(pageIdx);
   memcpy(outTuple, frame>bytes[offset], tupleLen)
   bm.unpin(frame); }}
```



- Pin: put disk page into buffer pool until further notice
  - possibly evicts an existing page
- Unpin: can now remove the page from buffer pool if needed

Column-Oriented Storage Design

- One file for each field of table (~H/field-size rows worth of data):



- Pros: Good for queries that access few columns
  - Can reduce I/O significantly
  - Better sequential reads when pages are in memory

```
Select count(*)
from customer
where isGoldMember
```

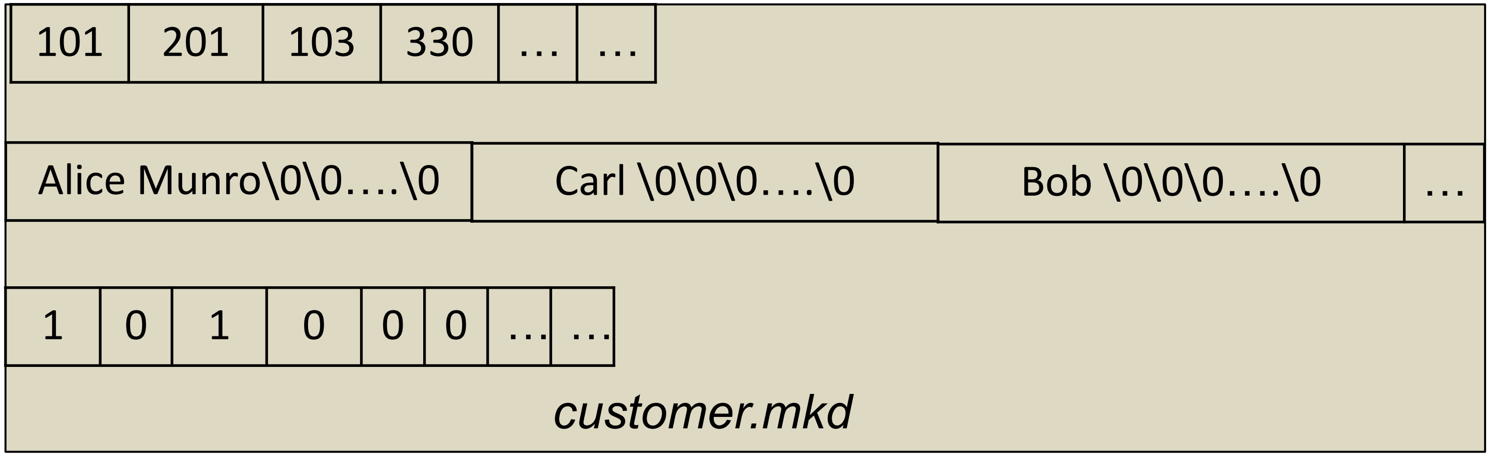
- Pros: Easier to apply compression because each page is very "homogenous"
- Cons: Bad for queries that access all columns (1 I/O in row-oriented storage could be done with # cols I/O).

PAX Hybrid Storage Design

- PAX: Partition Attributes Across (Ailamaki et al. VLDB 2001)
  - All fields of a row in the same page
  - But pages internally organized by columns


Weaving Relations for Cache Performance

Anastassia Ailamaki, David J. DeWitt, Mark D. Hill, Marios Skounakis



- Better sequential reads for queries that read a single column
- Gives the advantage of having all fields of a row in the same page
- But still more I/O than pure columnar storage for some queries

Outline For Today

1. High-level DBMS Architecture
2. Storage Manager and Physical File Organization Designs
   - Physical Operators/Storage Interface
   - Fundamental Property of Storage Devices & Potential Goals of Physical Design
   - Row-oriented Physical Design
   - Colum-oriented Physical Design
   - Hybrid (PAX) Physical Design
   - Designs for Variable-length Fields
   - Designs for NULLs

Variable-length Values

- Pages are often more complex than examples in these slides
- One complexity: variable-length fields
- Assume row-oriented NSM storage
- Approaches to encode var-length fields, e.g., var-len strings, in pages

1. Delimiters
2. Field Offsets
3. Pointers to Overflow Pages

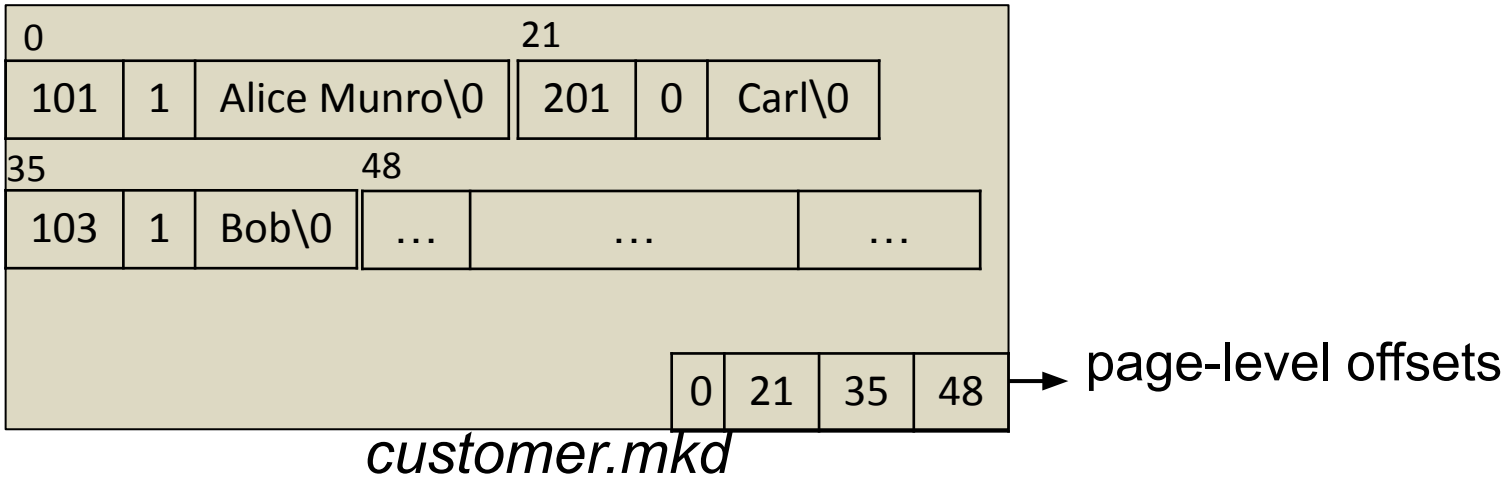
Both:

(i) put first fixed-len fields and then var-len fields when encoding each row

(ii) require storing page-level offset of each row

Delimiter Approach

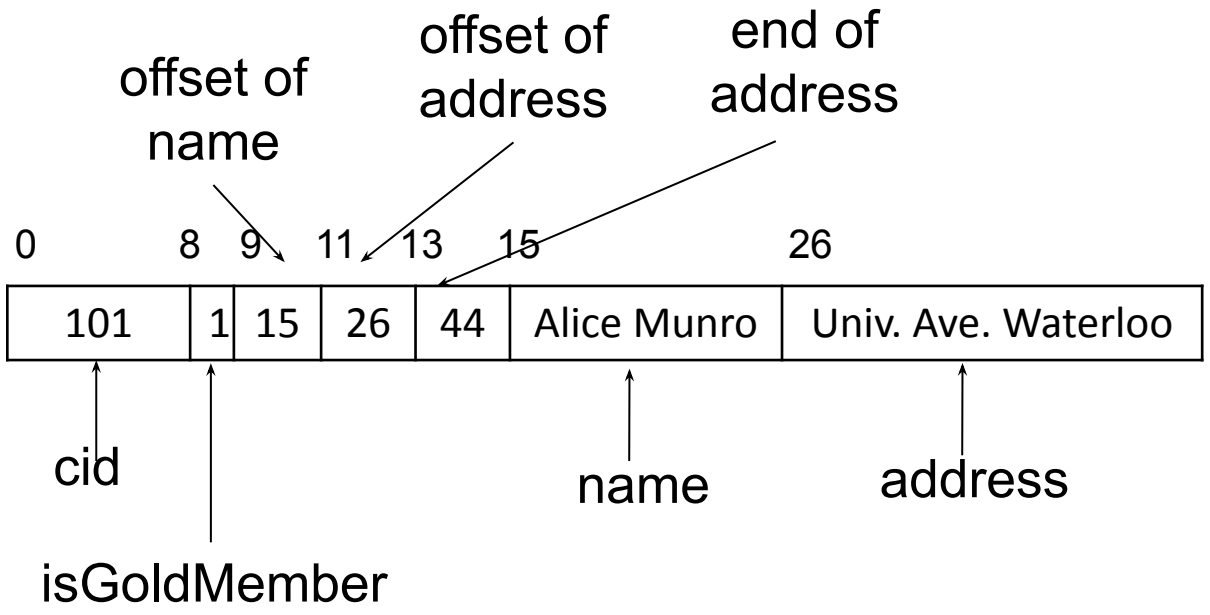
- Example Delimiter: \0 character



- Why are page offsets at the end and fields in the beginning of pages?
  - Can grow them separately without sliding data within pages.
- Advantage of storing fixed-len fields and then var-len fields:
  - Can read fixed-len fields w/ page-level offsets +arithmetic
  - e.g., isGoldMember of rowID 2: offset[2] + 8 = 35+8=43.
  - no need to scan over var-len fields

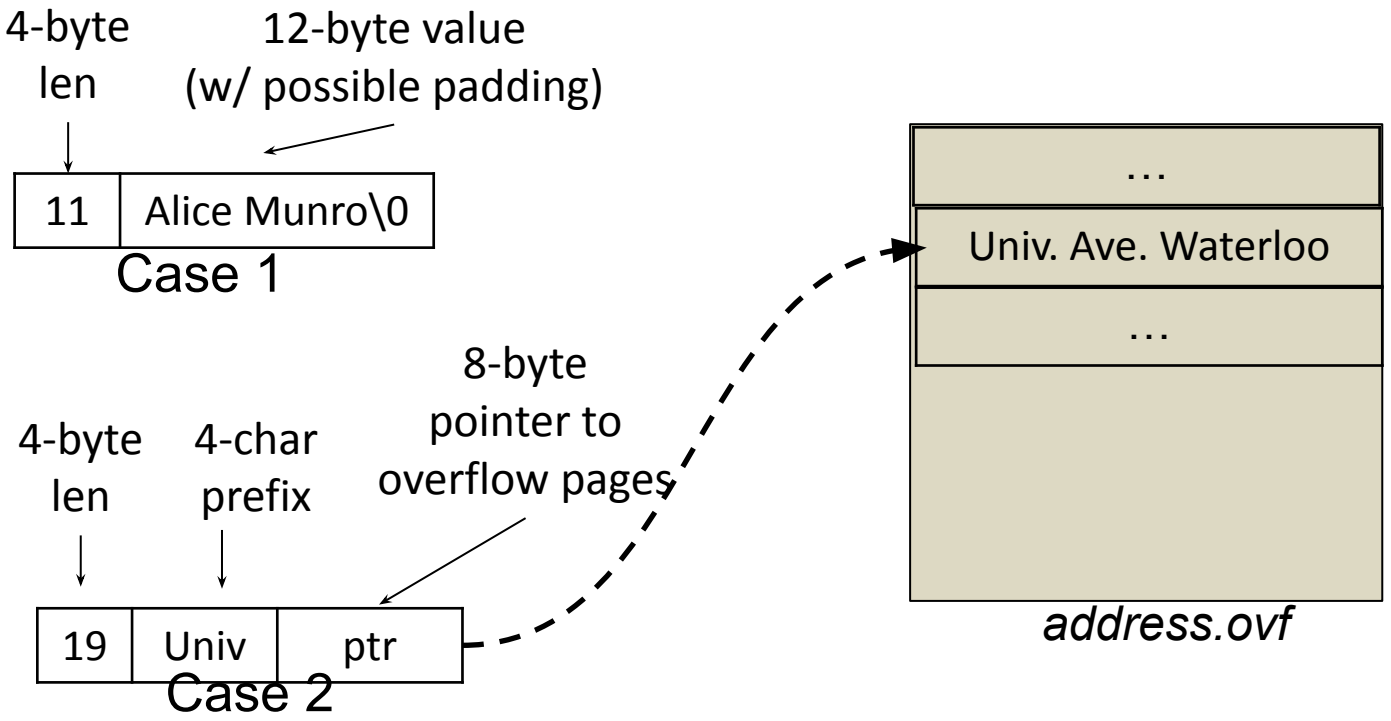
Field Offsets Approach

- Suppose there is a second var-len field called address
- Page structure stays same except each row would be encoded as:



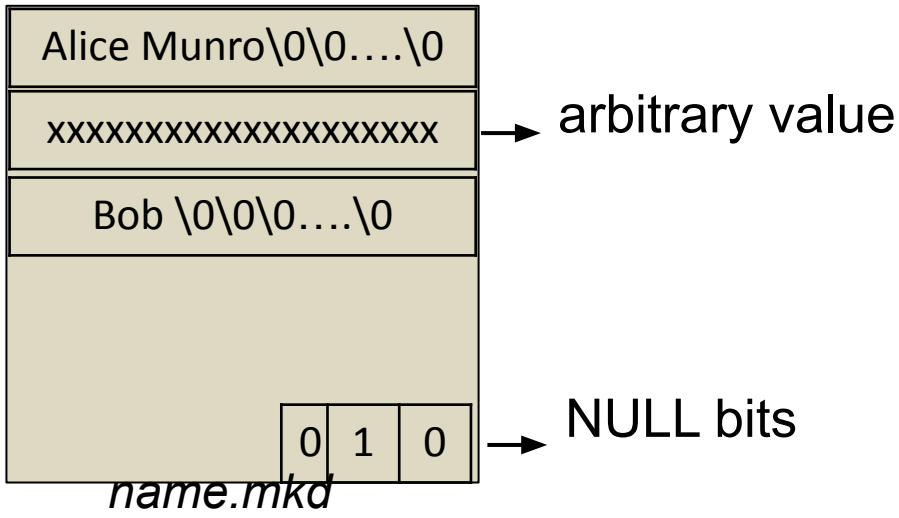
Overflow Pages

- Keep variable length fields, in particular strings, fixed length
- Any overflow points to separate overflow pages
- E.g., Strings in Graphflow (originally by Thomas Neumann)
  - 16 bytes fixed part with 2 possible cases
  - Pro: original pages are simpler; Con: More I/O for reading large strings



NULL Values

- Several possible approaches. E.g:
  - Store special NULL values for each data type as regular values
    - E.g.: -2^63 for 8-byte int
  - Store NULL bits in the page
    - Assume columnar storage and (fixed-len) name can be NULL
    - 1 means NULL 0 means NULL
  - Other alternatives may be possible



Summary of Physical Data Design Alternatives

- High-level: row-oriented vs columnar but row-oriented can be hybrid (PAX)
- Variable-length fields and fields that can be NULL require more sophisticated design
- For any physical design we showed, other alternatives are possible
- In practice physical design is principled art!
- Many tradeoff, choices, and complications exist:
  - Deletions of tuples (can leave gaps in pages or shift tuples)
  - Fields larger than page sizes
  - Tuple versions (some systems, e.g., Postgres, support multiple version of tuples so users can keep track of how each record changed)
  - Compression
  - Some crazy ideas put rows from multiple tables into same pages
  - Many other designs

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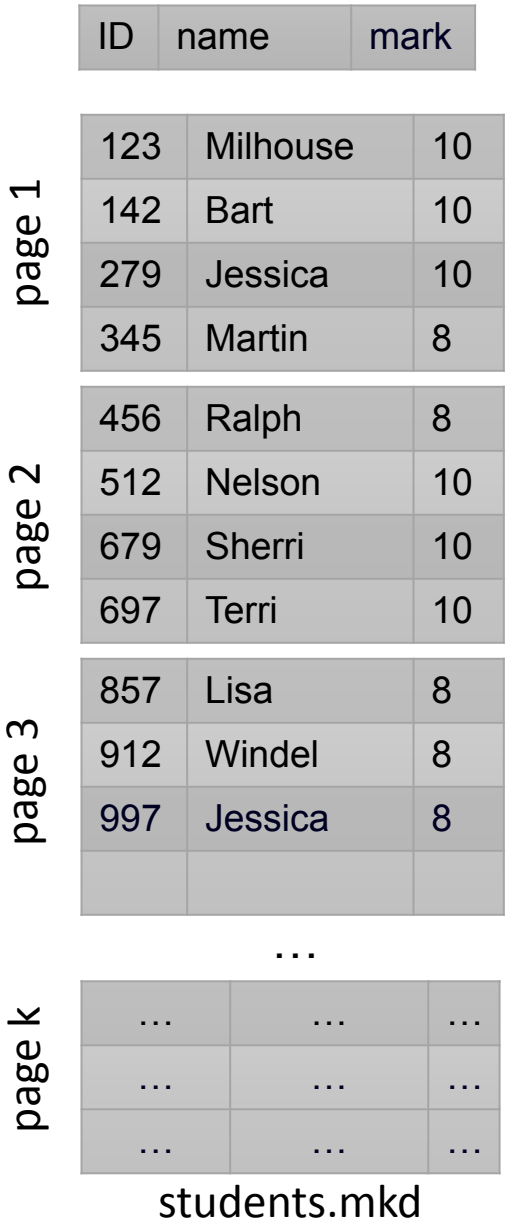
Functionality of Indices (1)

- Indices are the primary mechanism to
  1. *retrieve records quickly*
  2. *search records in sort order*

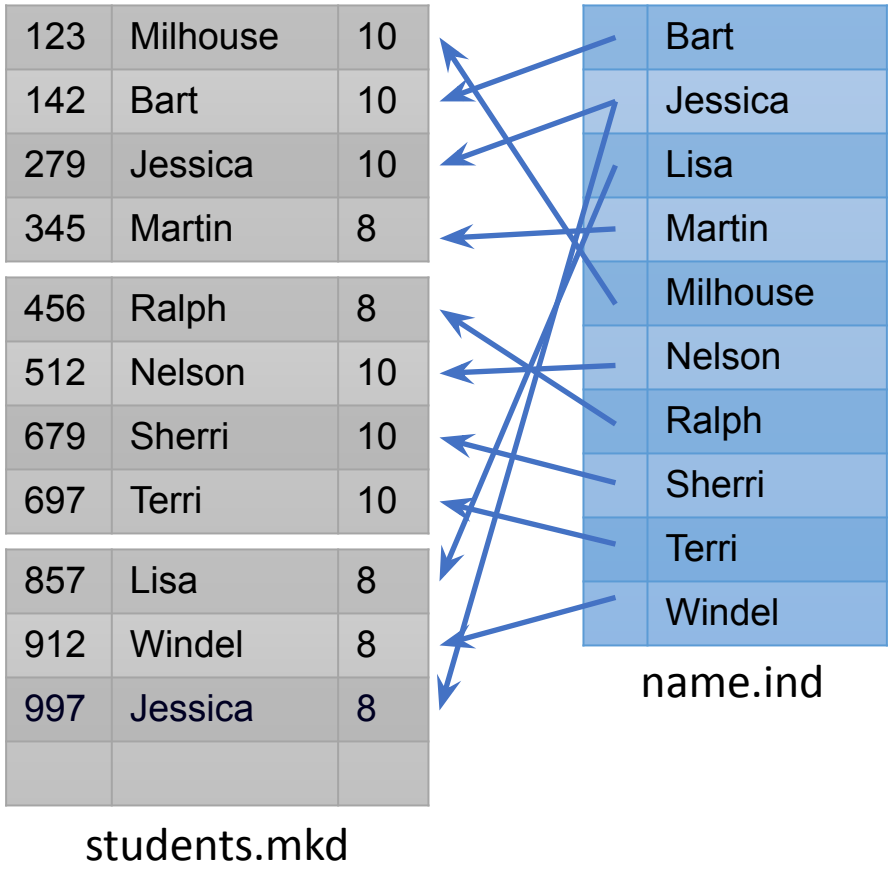
```
SELECT * FROM Students WHERE ID = 912;
SELECT * FROM Students WHERE ID > 100;
```

- Default way to find records:: sequential scans
  - Read each page and each record
  - Can be very slow for large tables
  - If a file sorted on some columns:
    - Can now do binary search
    - Key Question: How to do this efficiently?



Functionality of Indices (2)

- Indices: are persistent data structures that are stored along with table files that allow fast search.
- An example of a simple index: can be much smaller than the original table.



Naïve Approach for Keeping a Table Sorted

- Sorting: primary technique to find things & data quickly!
- Once a file is sorted, we can do binary search on the pages of the file.
- How to keep a relation file in sorted order (e.g., students.mkd)?
- Assume a sequence of insertions. 2 records/page. Sort on ID
- Simple/naïve approach: Shift-based (index-less) sorting

Naïve Approach for Keeping a Table Sorted

Next Insertion

857	Lisa	8

PAGES

Naïve Approach for Keeping a Table Sorted

Next Insertion

512	Nelson	10

PAGES

857	Lisa	8

pg 1

Naïve Approach for Keeping a Table Sorted

Next Insertion

279	Jessica	10

PAGES

512	Nelson	10
857	Lisa	8

pg 1

Naïve Approach for Keeping a Table Sorted

Next Insertion

912	Windel	8

PAGES

pg 1

279	Jessica	10
512	Nelson	10

pg 2

857	Lisa	8

Naïve Approach for Keeping a Table Sorted

Next Insertion

345	Martin	8

PAGES

pg 1

279	Jessica	10
512	Nelson	10

pg 2

857	Lisa	8
912	Windel	8

Naïve Approach for Keeping a Table Sorted

Next Insertion

697	Terri	10

PAGES

279	Jessica	10	pg 1
345	Martin	8	
512	Nelson	10	pg 2
857	Lisa	8	
912	Windel	8	pg 3

Naïve Approach for Keeping a Table Sorted

Next Insertion

123	Milhouse	10

PAGES

279	Jessica	10	pg 1
345	Martin	8	
512	Nelson	10	pg 2
697	Terri	10	
857	Lisa	8	pg 3
912	Windel	8	

Naïve Approach for Keeping a Table Sorted

Next Insertion

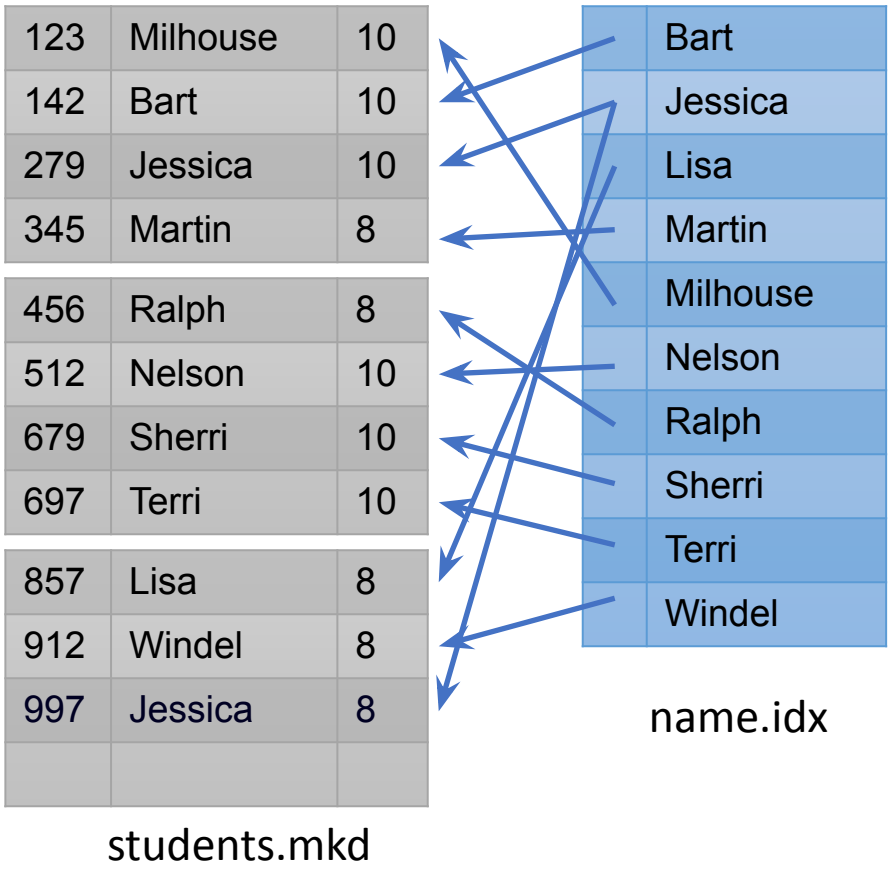
PAGES

123	Milhouse	10	pg 1
279	Jessica	10	
345	Martin	8	pg 2
512	Nelson	10	
697	Terri	10	pg 3
857	Lisa	8	
912	Windel	8	pg 4

- Pro: Very simple to implement
- Con: Each insertion could require up to 2xb many I/Os (to read and right pages) if the table has b pages.
  - Will not scale. Not practical.

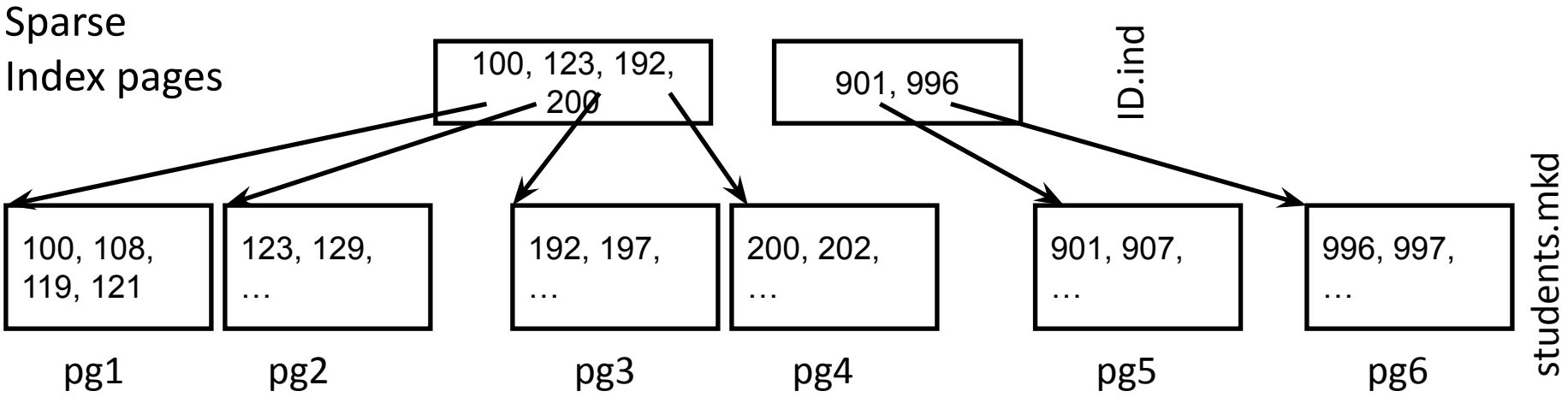
2nd Approach: Single-level Dense Index

- Lookup: find the record in index & follow pointer (page & offset)
- If index file is disk-based:
  - Con: Same problem as naïve solution
  - Pro: But at a smaller scale b/c the index is smaller (a projection).
- If index is in memory:
  - Pro: Optimal I/O. Only store the record in the relation file but no sorting (called unclustered index)
  - Con: Index cannot get very large.



3rd Approach: Single-level Sparse Index w/ Overflows

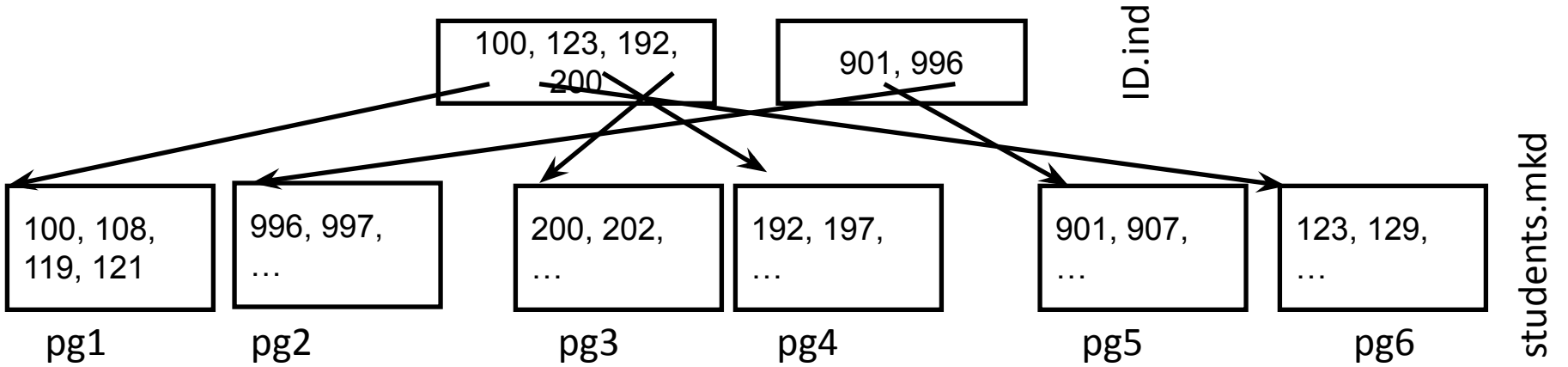
- Suppose the sort column keys have a relatively stable domain and the table is not expected to grow significantly.
- Can do an initial sort upon data ingestion and keep a sparse-index
- Below: Just showing the sort column not entire rows
- Lookup: Find page, follow pointer, scan page (& overflow pages (soon))



- Need the data pages sorted (called clustered index)
- Advantage over dense index: much smaller (can be a few orders of magn.)
- Insertions require chaining & deletions can lead to empty pages (soon)

Note on Clustered Indices

- When a relation file has a clustered index, i.e., when pages are sorted, we do not necessarily need the pages to be sorted.
- If a file has b pages, as long as we can recover the full sort order with b I/Os (ignoring I/Os to read the sparse index), we get similar benefits
- Below design will have similar performance as previous slide if we read pages sequentially through sparse index

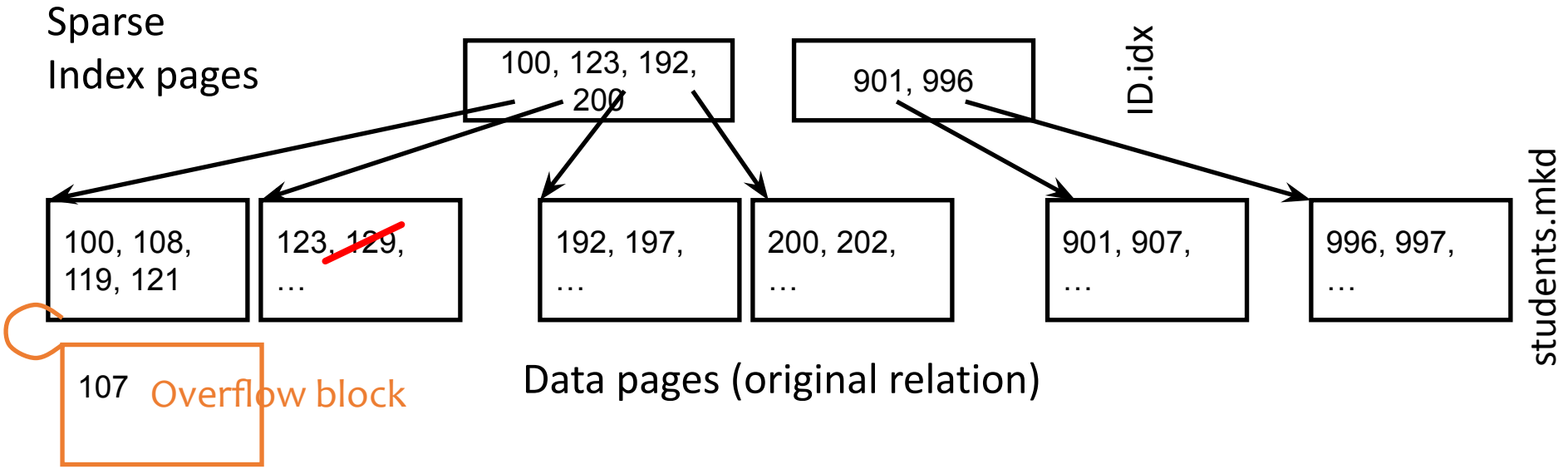


3rd Approach: Single-level Sparse Index w/ Overflows

- Handing Insertions

Example: insert tuple with key 107

Example: delete tuple with key 129



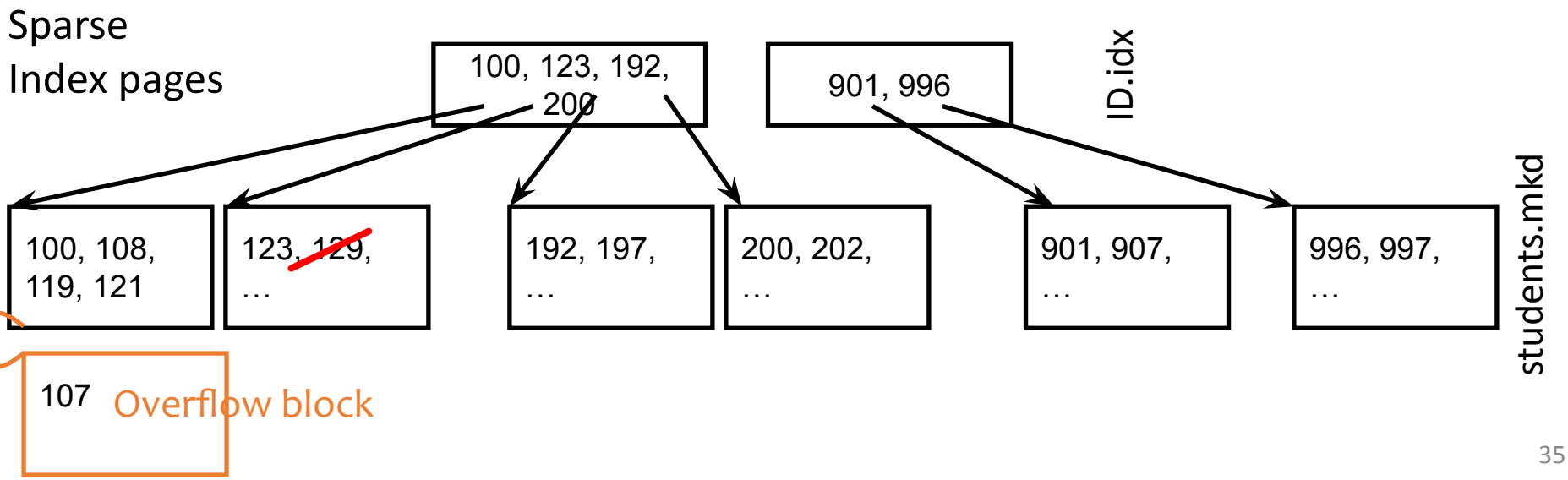
- Overflow chains and empty data blocks degrade performance
  - If there is significant *data distribution skew*: records can go into one long chain, so lookups require scanning all data in worst-case.

3rd Approach: Single-level Sparse Index w/ Overflows

- Pros: Index size smaller than dense index (1 key/ptr in index per page), so can be larger
- Cons:
  - Can still become very large (GBs) for large tables.
  - Need overflows, which is not robust, if table grows significantly over time (e.g., most pages can become overflows, leading to large scans)
  - Can lead to empty pages (but less of an issue in practice)

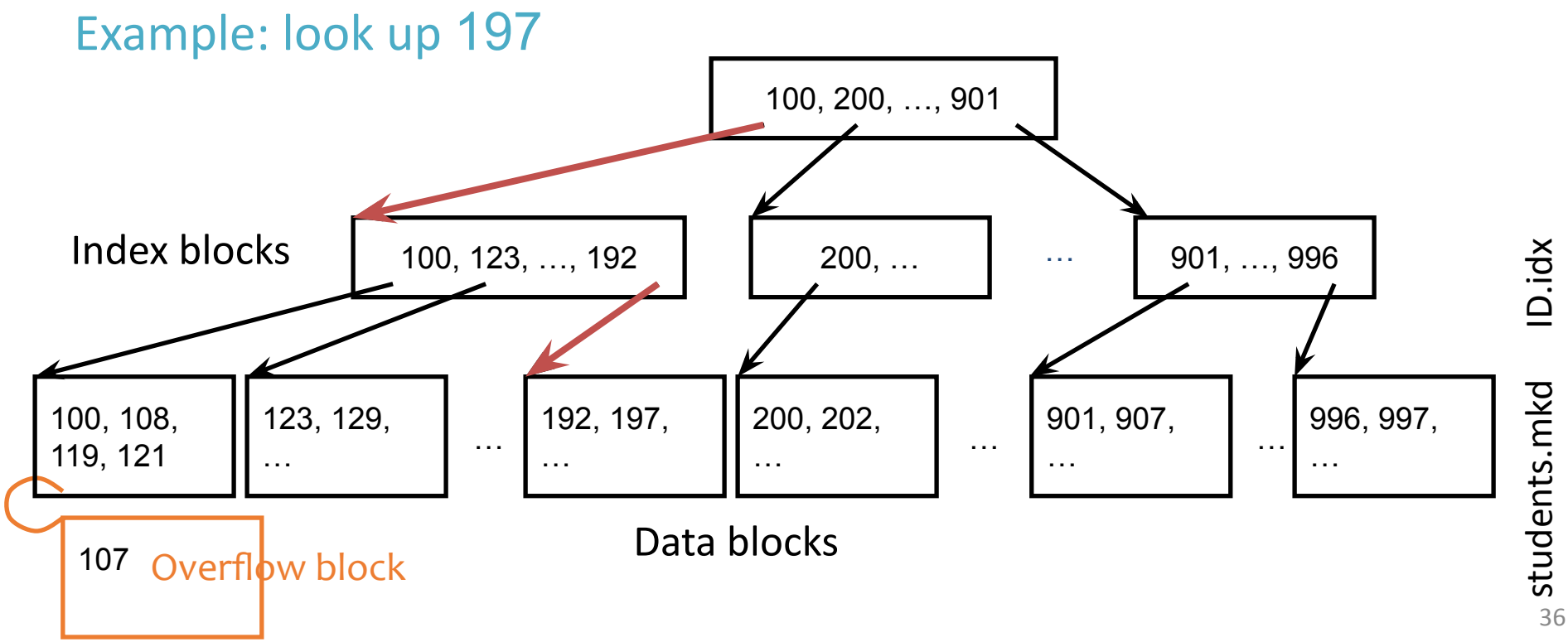
Address w/ multi-level indices

Address w/ splitting/merging



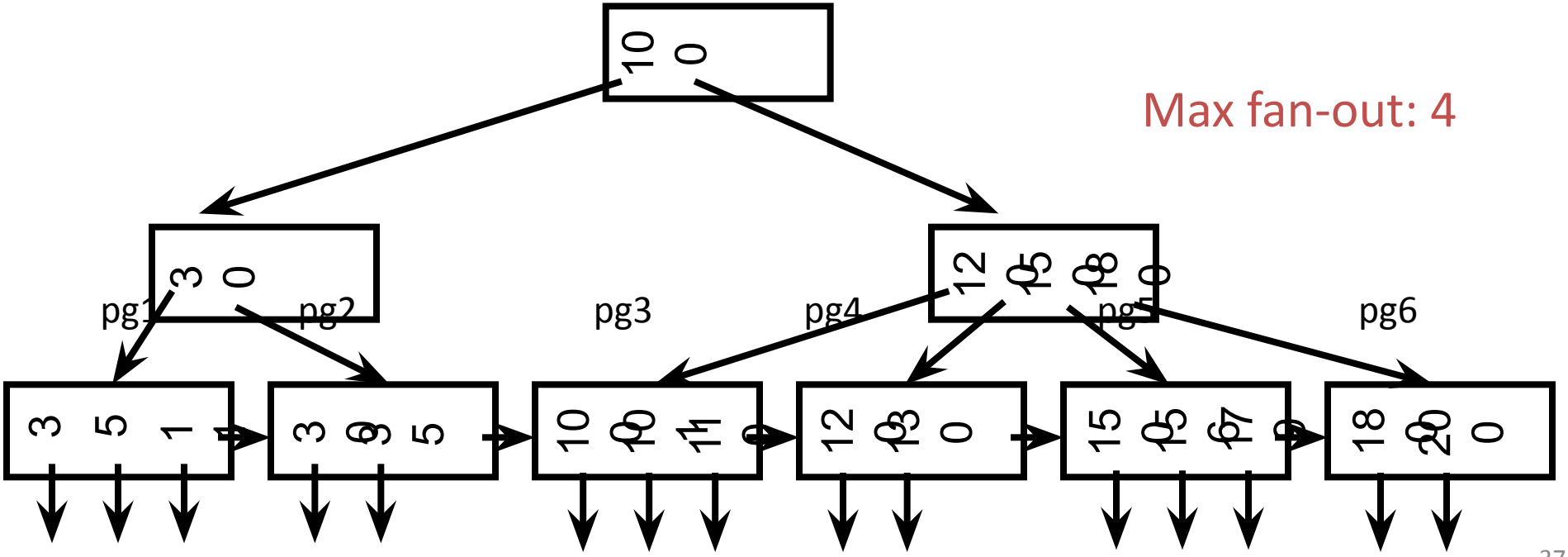
4th Approach: Multi-level Indices

- If an index is too large, can put other layers of sparse indices on the index
- Forms a tree and allows the system to keep higher-level indices in memory
  - Cand do depth-1 many I/Os in lookups (ignoring overflows)

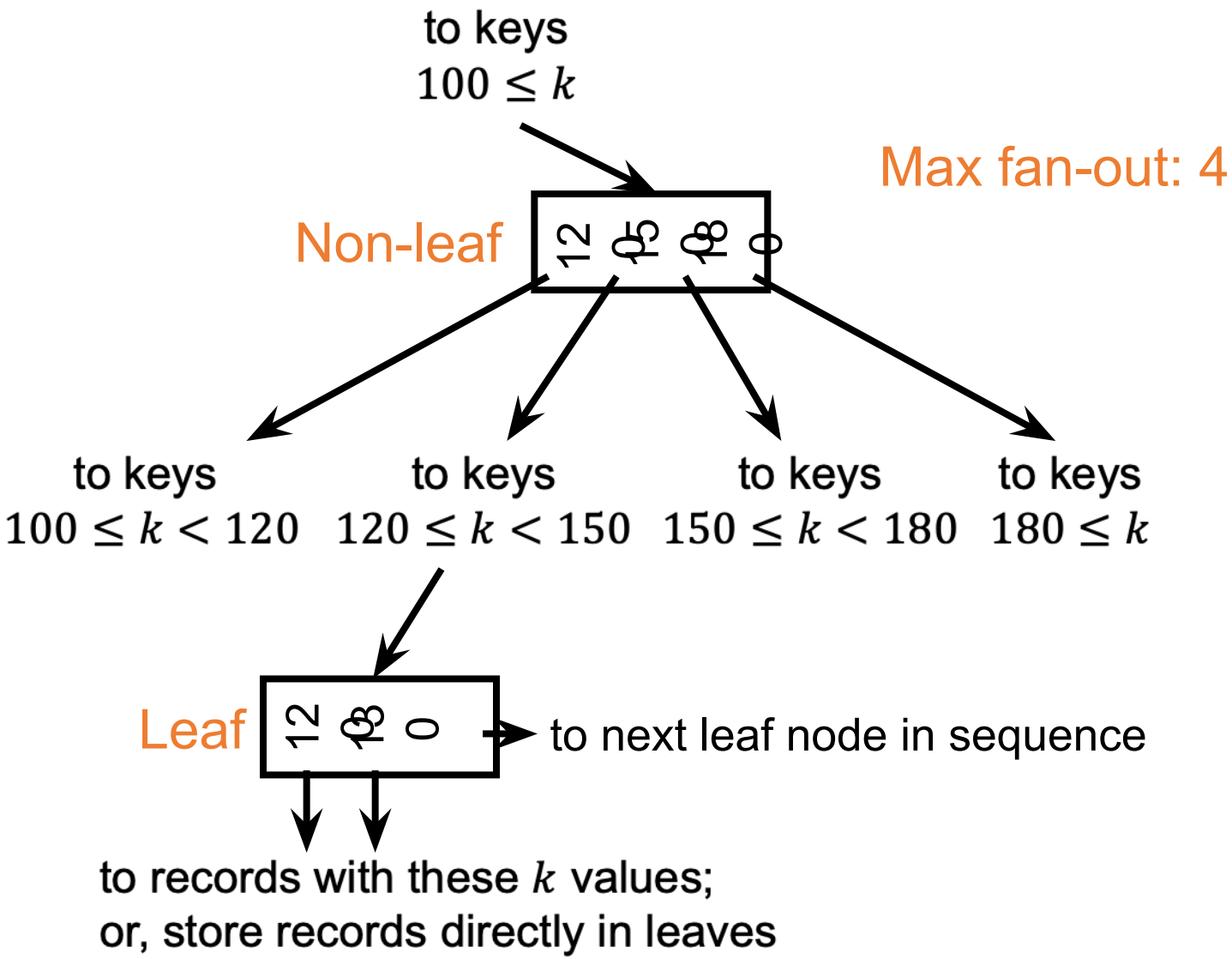


5th Approach: B/B+ Tree Indices

- Multi-level sparse indices on a first level of pages that is either:
  - actual relation pages (if clustered)
  - dense index on the relation pages (works for clustered or unclustered)
  - leaf level consists of *chained pages*
- Forms a k-ary balanced tree
- Instead of overflow pages uses splitting and merging of pages at any layer



Sample B$^+$-tree Nodes



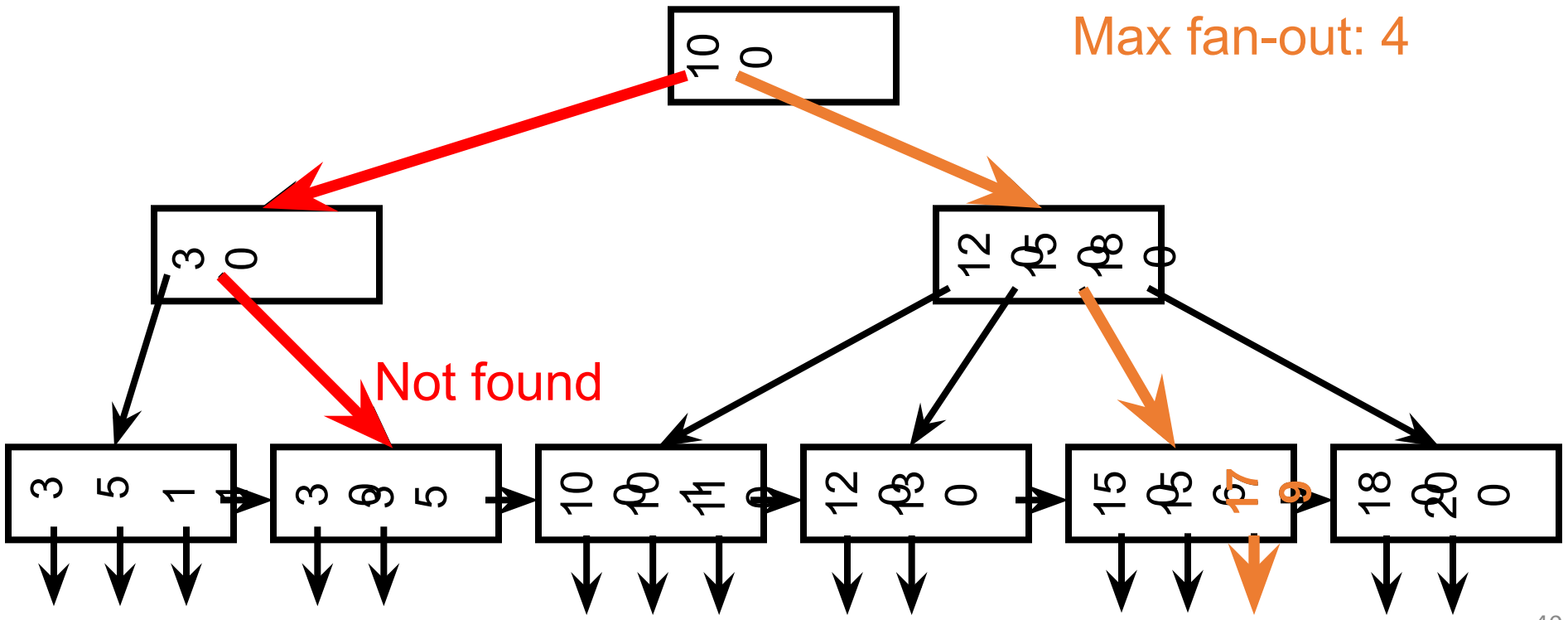
B^+-tree Balancing Properties

- 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	$f-1$	$\lfloor f/2 \rfloor$	$\lfloor f/2 \rfloor$

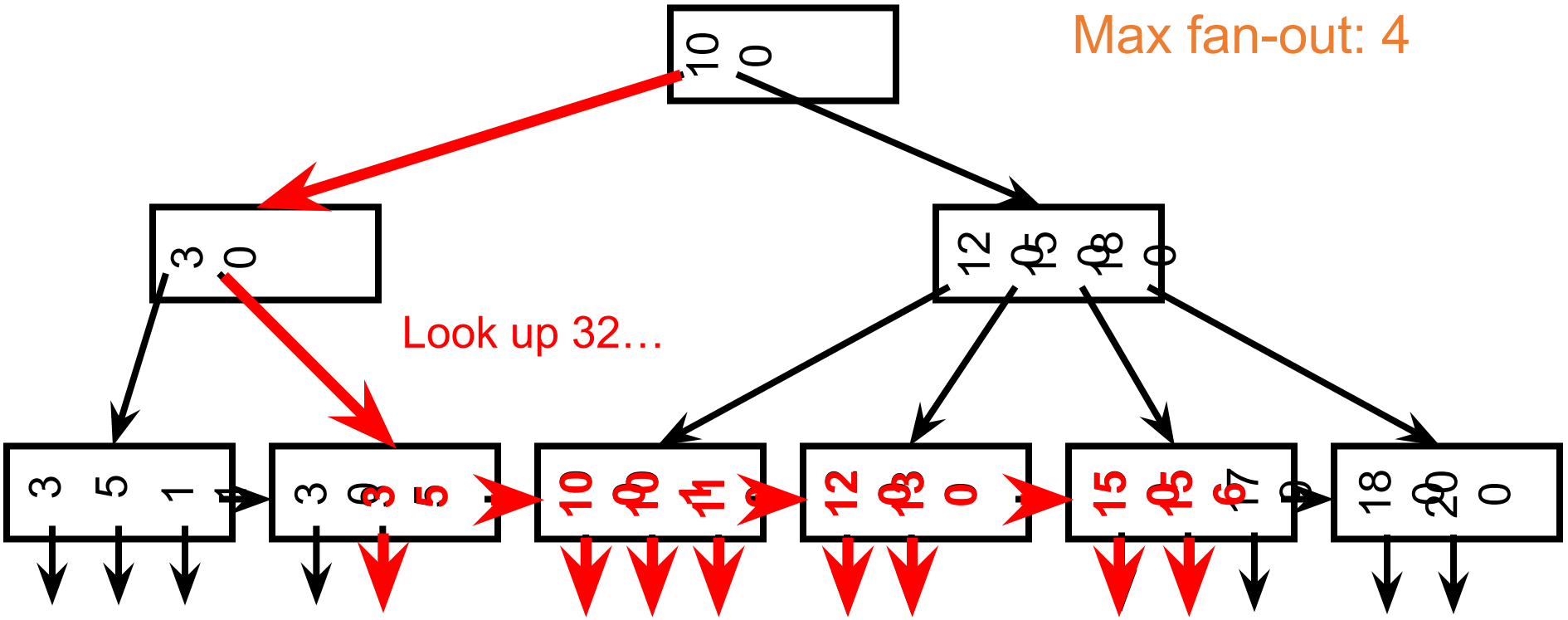
Lookups

```
SELECT * FROM R WHERE k = 179;
SELECT * FROM R WHERE k = 32;
```



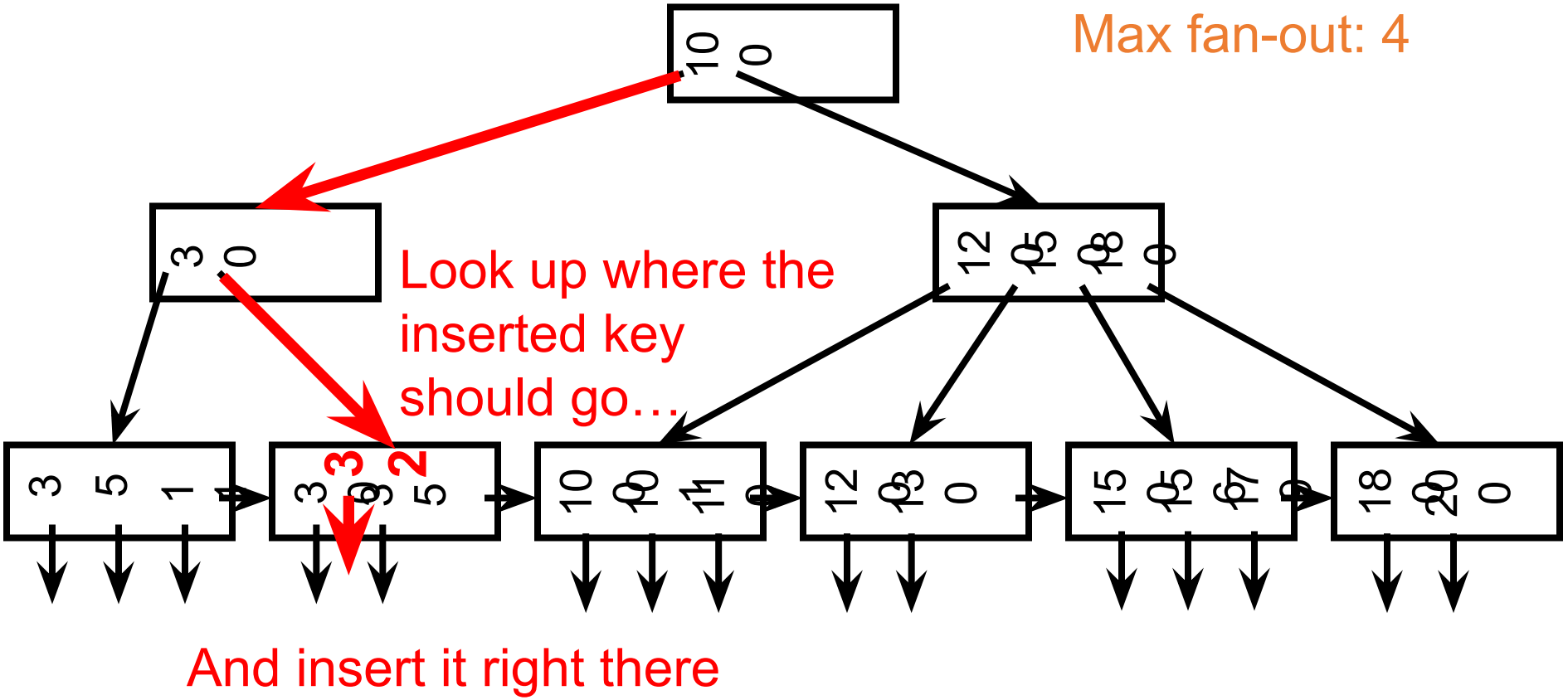
Range Query

- `SELECT * FROM R WHERE k > 32 AND k < 179;`



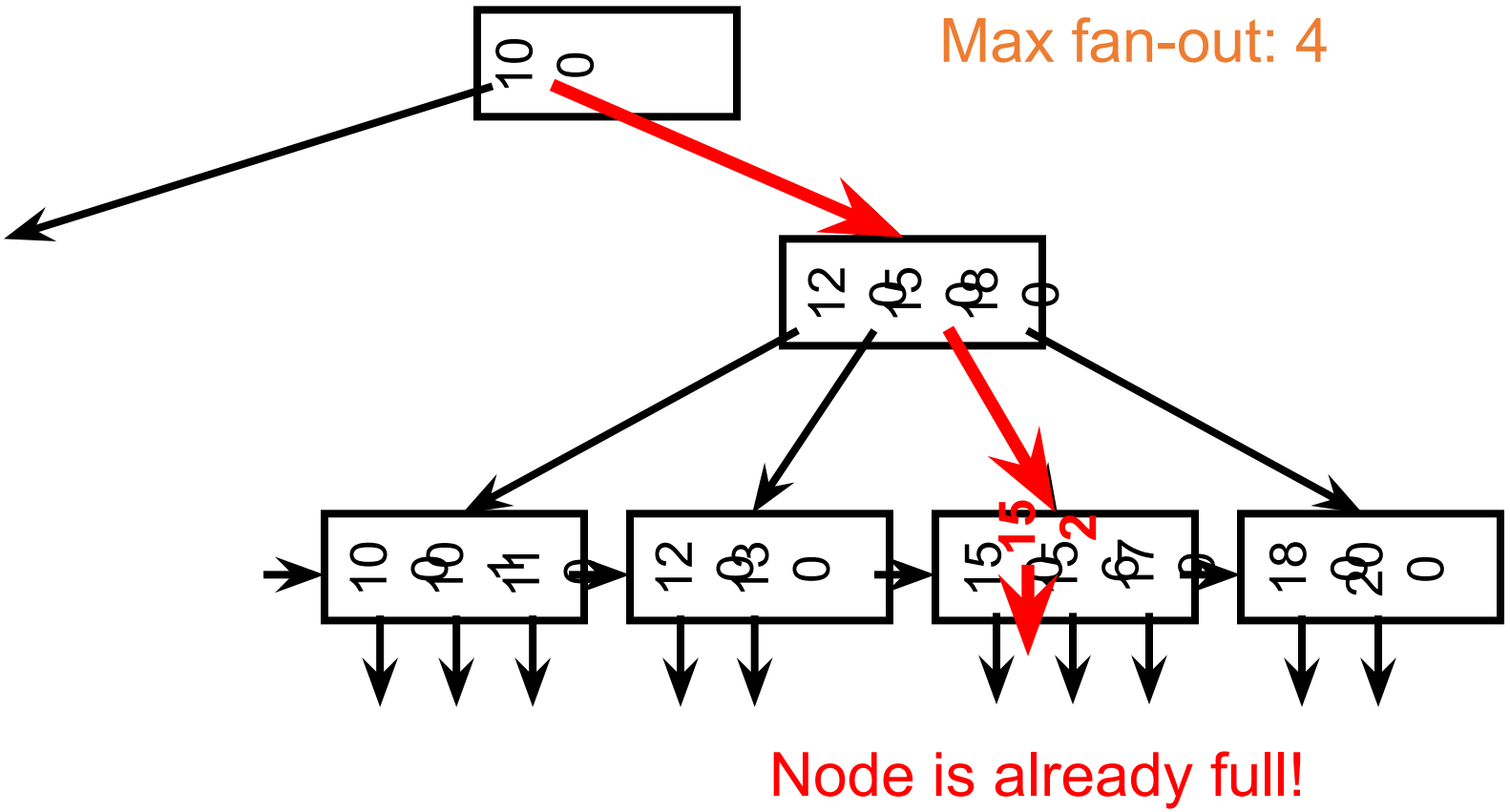
Insertion

- Insert a record with search key value 32

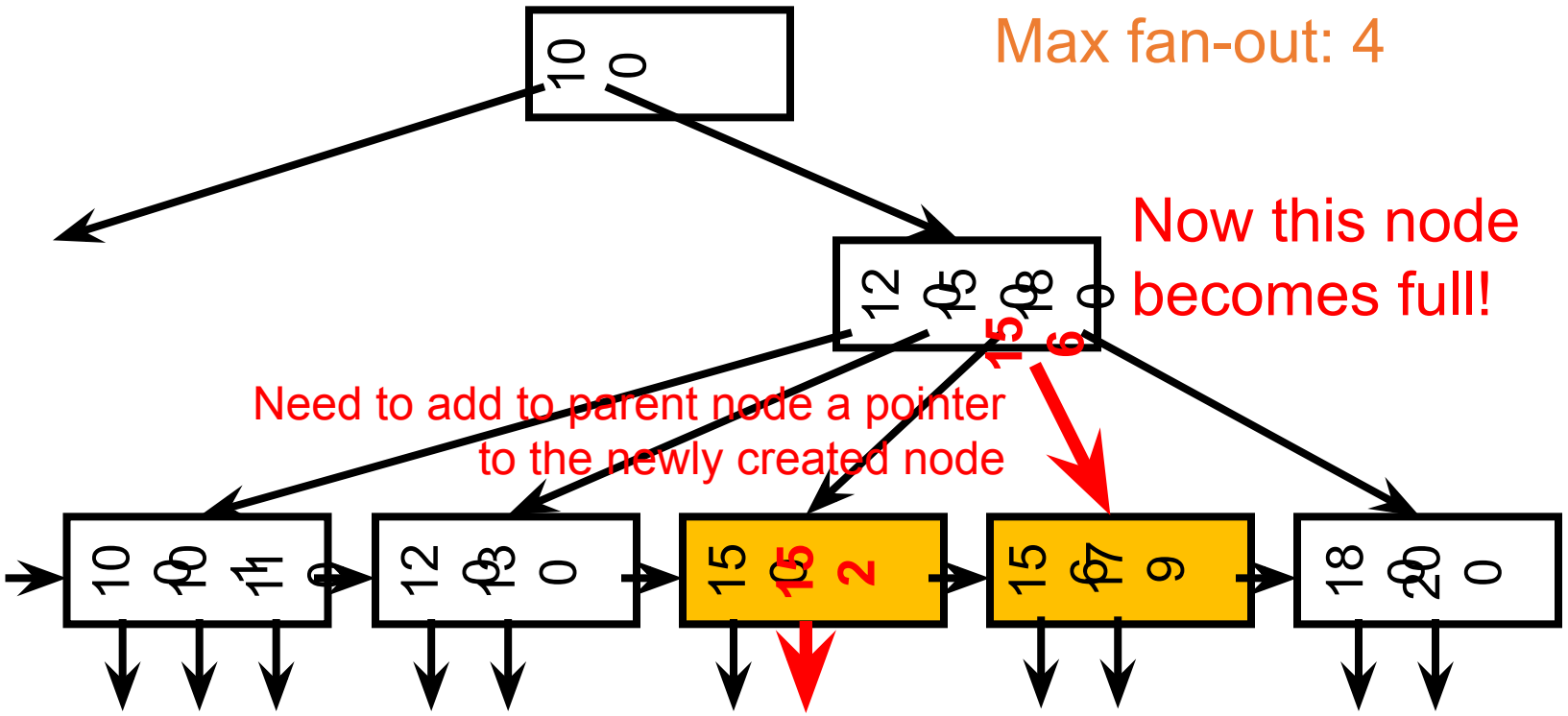


Another Insertion Example

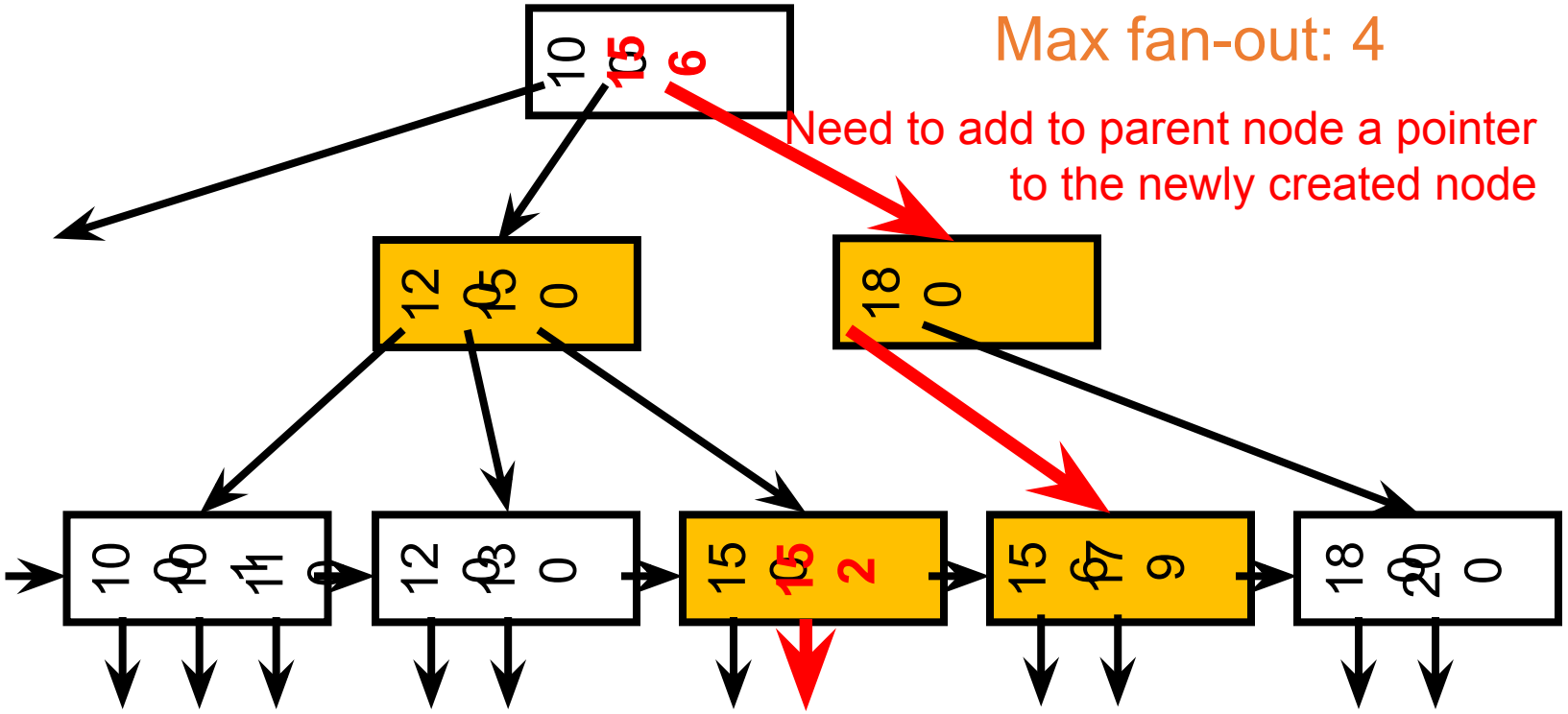
- Insert a record with search key value 152



Node Splitting



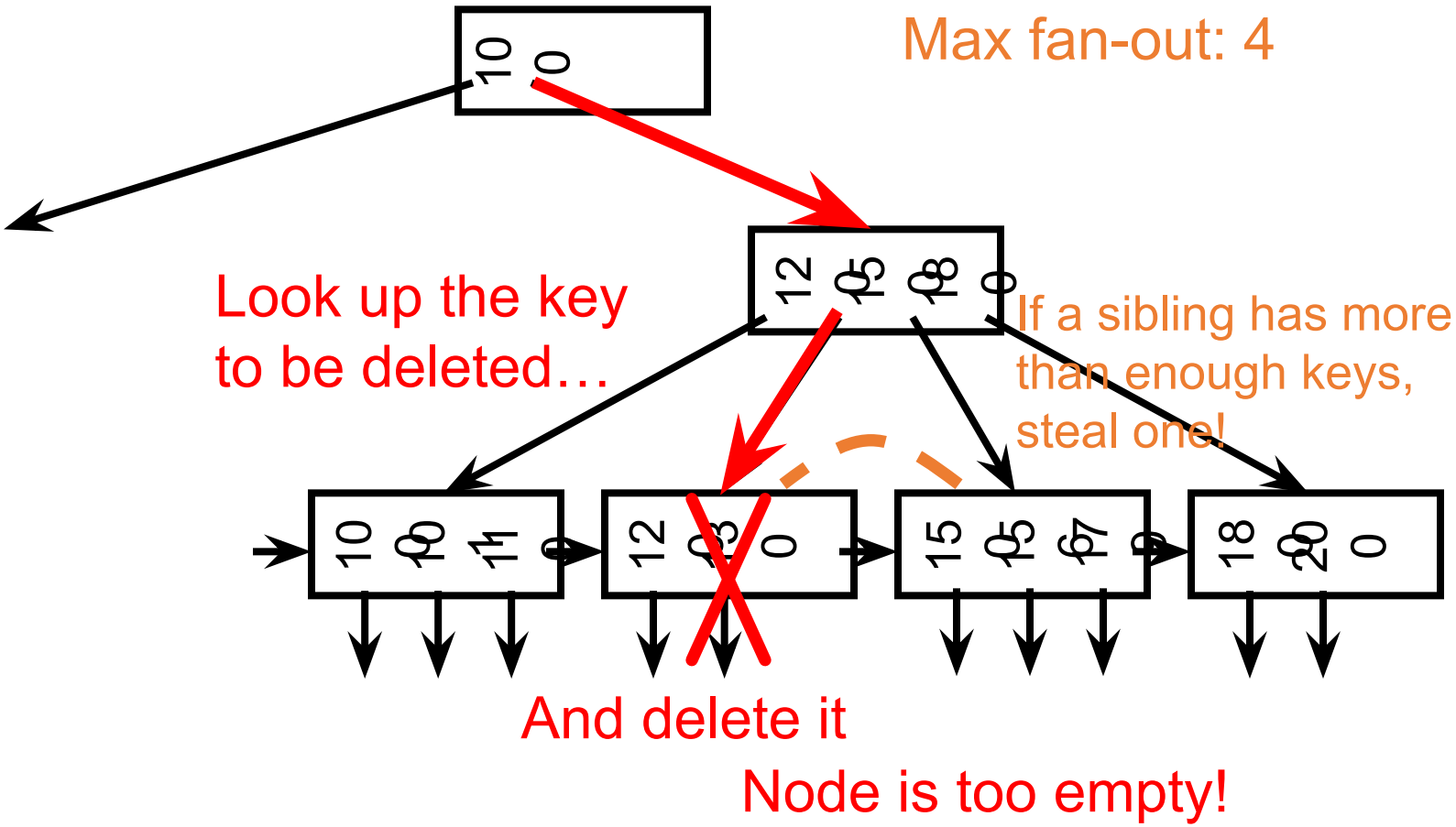
More Node Splitting



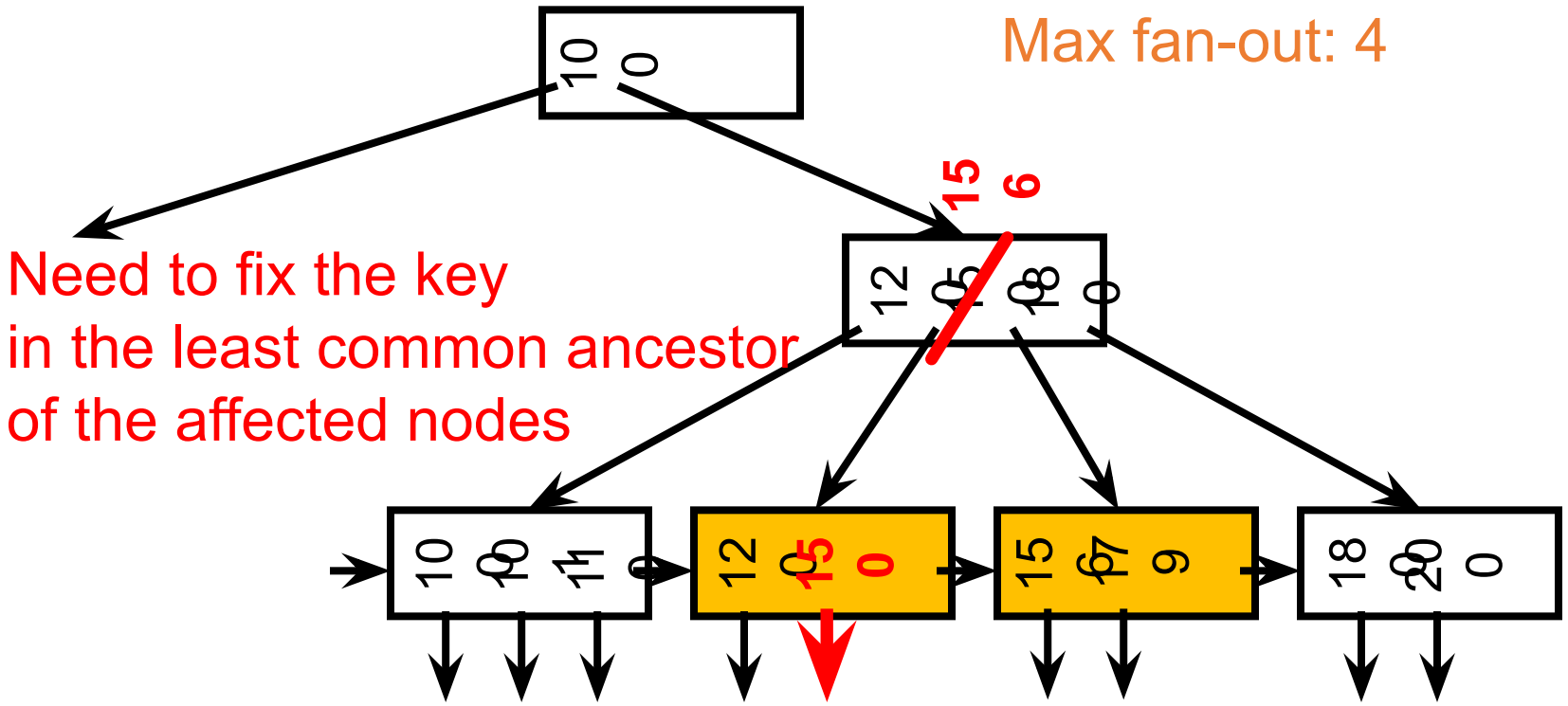
- In the worst case, node splitting can "propagate" all the way up to the root of the tree (not illustrated here)
  - Splitting the root introduces a new root of fan-out 2 and causes the tree to grow "up" by one level (this is why roots can have < f/2-1 keys)

Deletions

- Delete a record with search key value 130



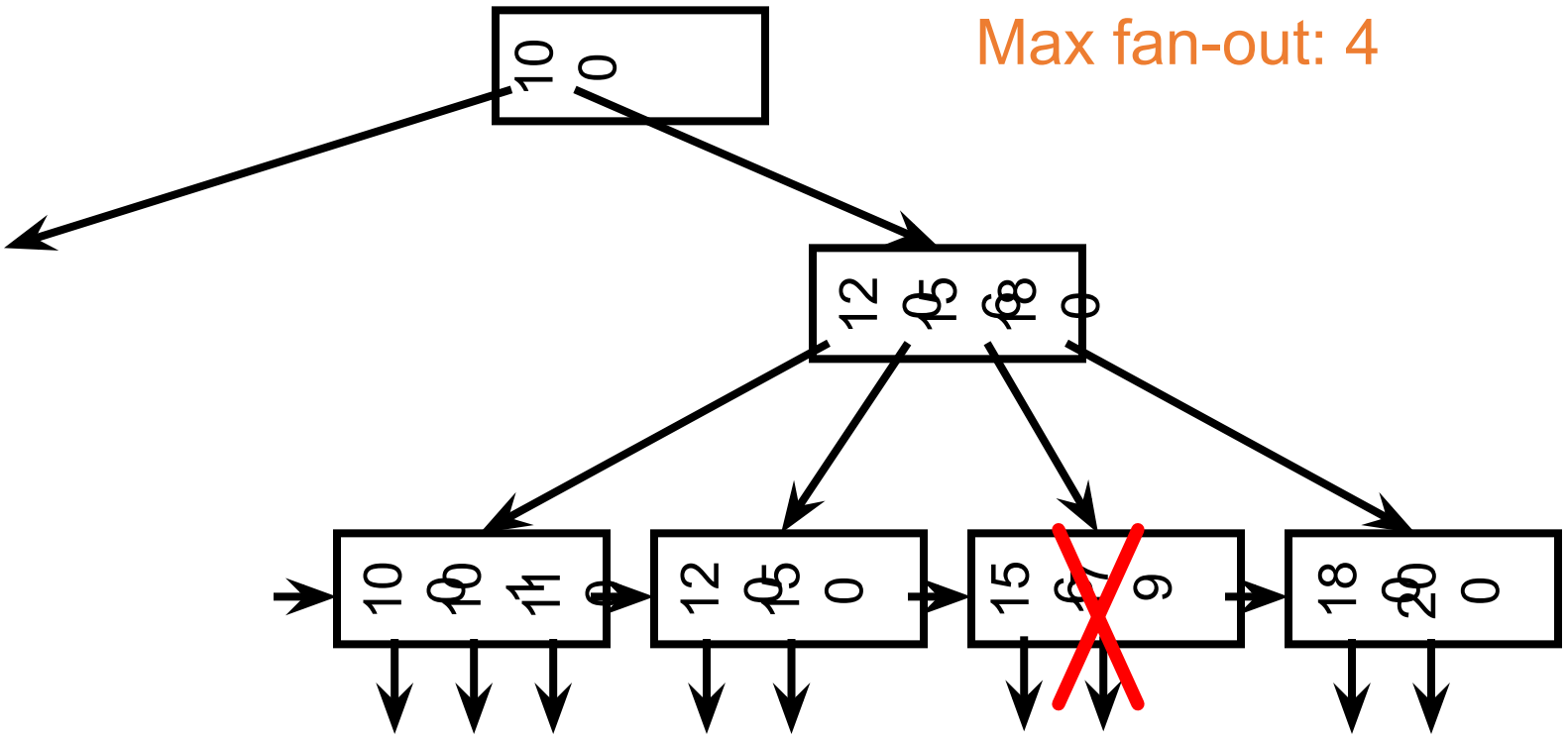
Stealing From a Sibling Node



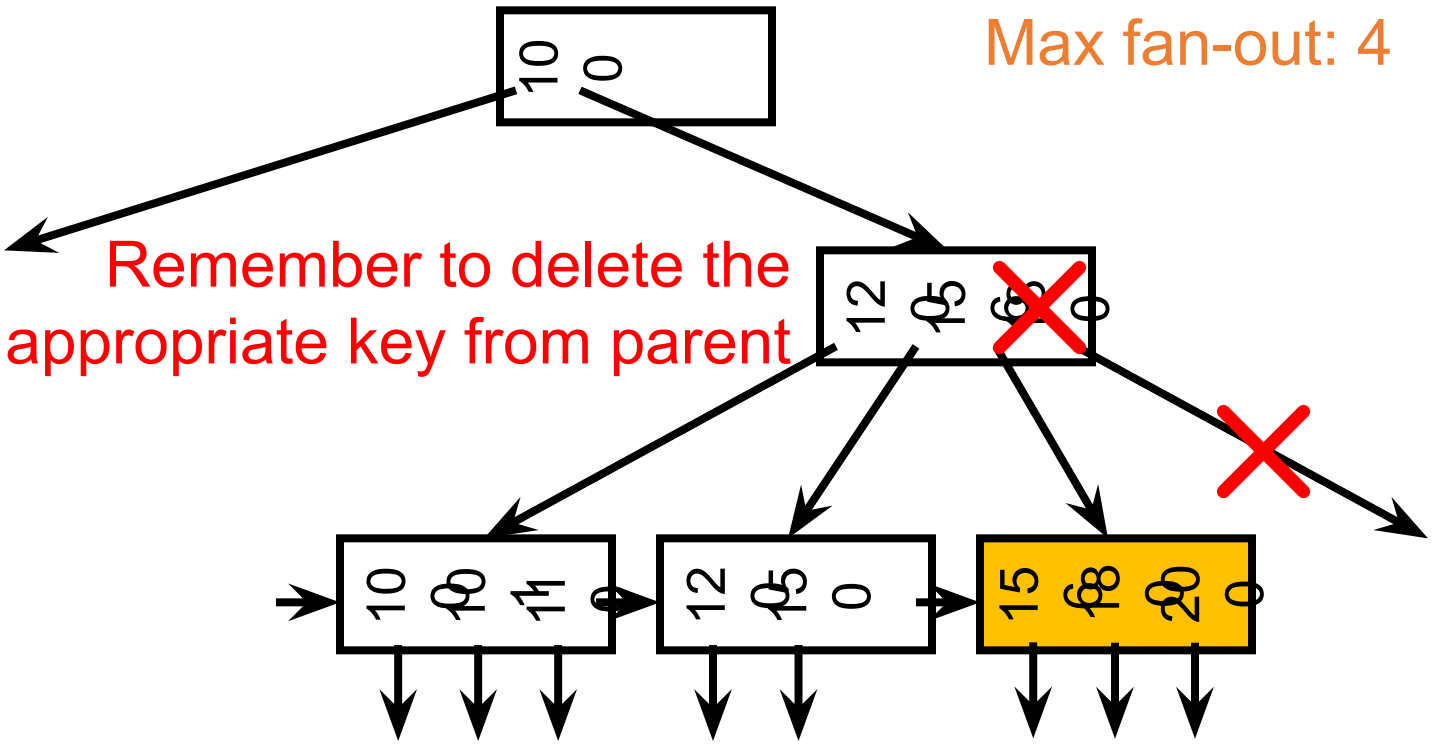
- If you are hacker, encourage you to implement the deletion subroutine of an external B+ tree. Quite challenging!

Another Deletion Example

- Delete a record with search key value 179



Merging



- Deletion can “propagate” all the way up to the root of the tree (not illustrated here)
  - When the root becomes empty, the tree “shrinks” by one level

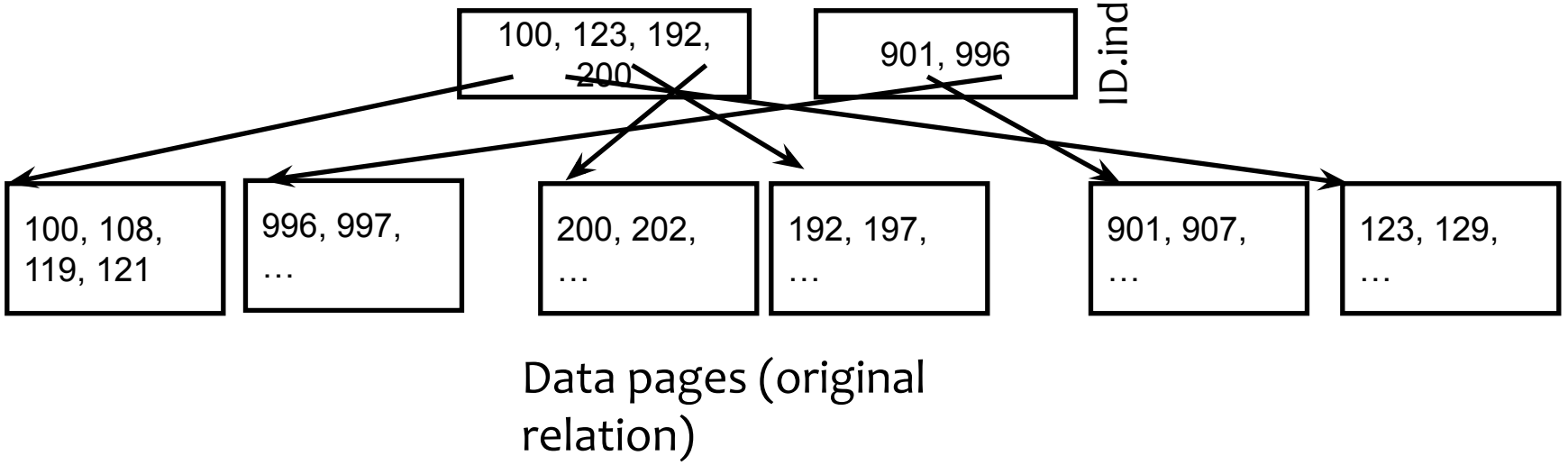
Performance analysis of B$^+$-tree

- How many I/O's are required for each operation?
  - h, the height of the tree
  - Plus one or two to manipulate actual records
  - Plus $O(h)$ for reorganization (rare if f is large)
  - Minus one if we cache the root in memory

- How big is h?
  - Roughly $\log_{\text{fanout}} N$, where N is the number of records
  - Fan-out is typically large (in hundreds)—many keys and pointers can fit into one block
  - A 4-level B$^+$-tree is enough for many tables (e..g, if f=200, then you can accommodate 1.6B rows)

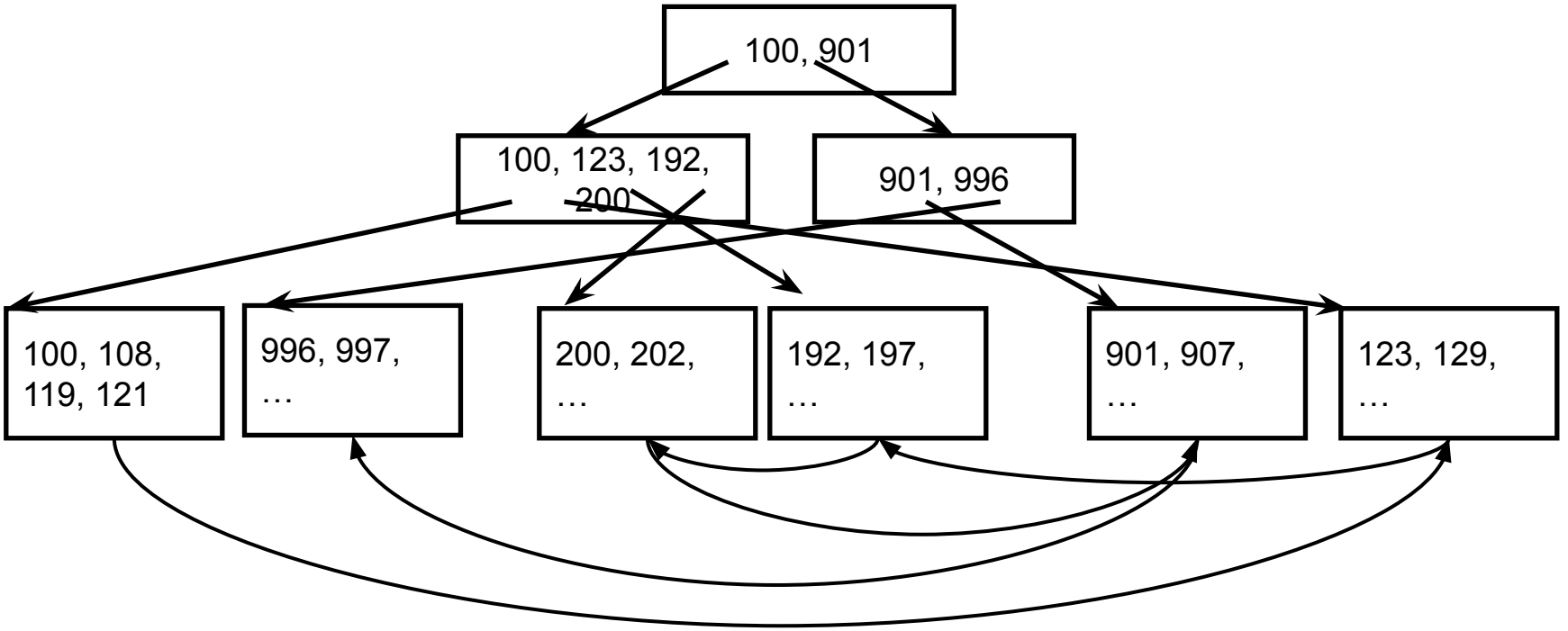
How to Keep A Table Sorted?

- Recall this key question
- Recall further note on clustered indices and page order.



How to Keep A Table Sorted?

- Recall this key question
- Recall further note on clustered indices and page order.
- Again assume leaf nodes are tuples
- Many RDBMSs use “B+ tree files” to store the tables, i.e., entire file is a B+ tree index, with leaf nodes storing tuples (instead of pointers to tuples)



Difference Between B and B+ Tree

- B-tree stores pointers to records or records in non-leaf nodes too
- Pro: These records can be accessed with fewer I/O's
- Cons:
  - Storing more data in nodes decrease fan-out and increases h
  - Records in leaves require more I/O's to access
  - Vast majority of the records live in leaves!

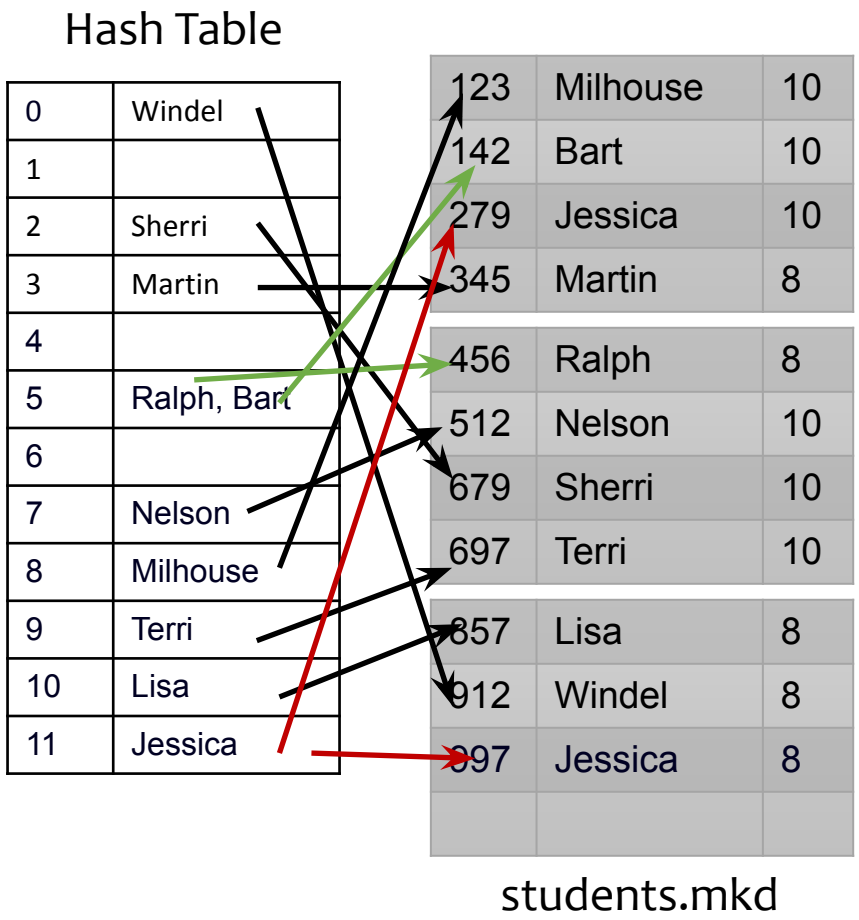
What Does B Stand For?

- No one really knows!
- But Edward M. McCreight, co-inventor with Rudolf Bayer, has a video that says:
  - They never resolved what B is but they had in mind:
  - Boeing, Bayer, and Balance

Other Common Indices

- 2 Classes of Indices Overall

1. Tree-based: can do both lookups and range queries
   - B/B+ Trees, R Trees, Radix Tree
2. Hash-based
   - Can only do look ups. Cannot do range queries.
   - In practice: handle collisions
3. Many other indices: bitmap indices, probabilistic indices, suffix arrays, GiST or Inverted Index for different applications and data types.



Outline For Today

1. Recap & Finish Physical File Organization Designs
   - Row-oriented Physical Design (Recap)
   - Colum-oriented Physical Design
   - Hybrid (PAX) Physical Design
   - Designs for Variable-length Fields
   - Designs for NULLs
2. Database Indices
   - 5 Index Designs in Increasing Level of Robustness
   - Using Indices In Practice

Using Indices In Practice (1)

- Indices can be defined on one ore more attributes:
  - CREATE INDEX NameIndex ON User(Lastname,Firstname);
  - I.e., B+'s keys are (Lastname, Firstname) pairs and tuples are sorted first by LastName and then Firstname.
  - This index would be useful for these queries:

```
select * from User where Lastname = 'Smith'
select * from User where Lastname = 'Smith' and Firstname='John'
```

  - But not this query:

```
select * from User where Firstname='John'
```

- Many systems use indices by default on the primary key
- Many systems use indices to implement UNIQUE constraints

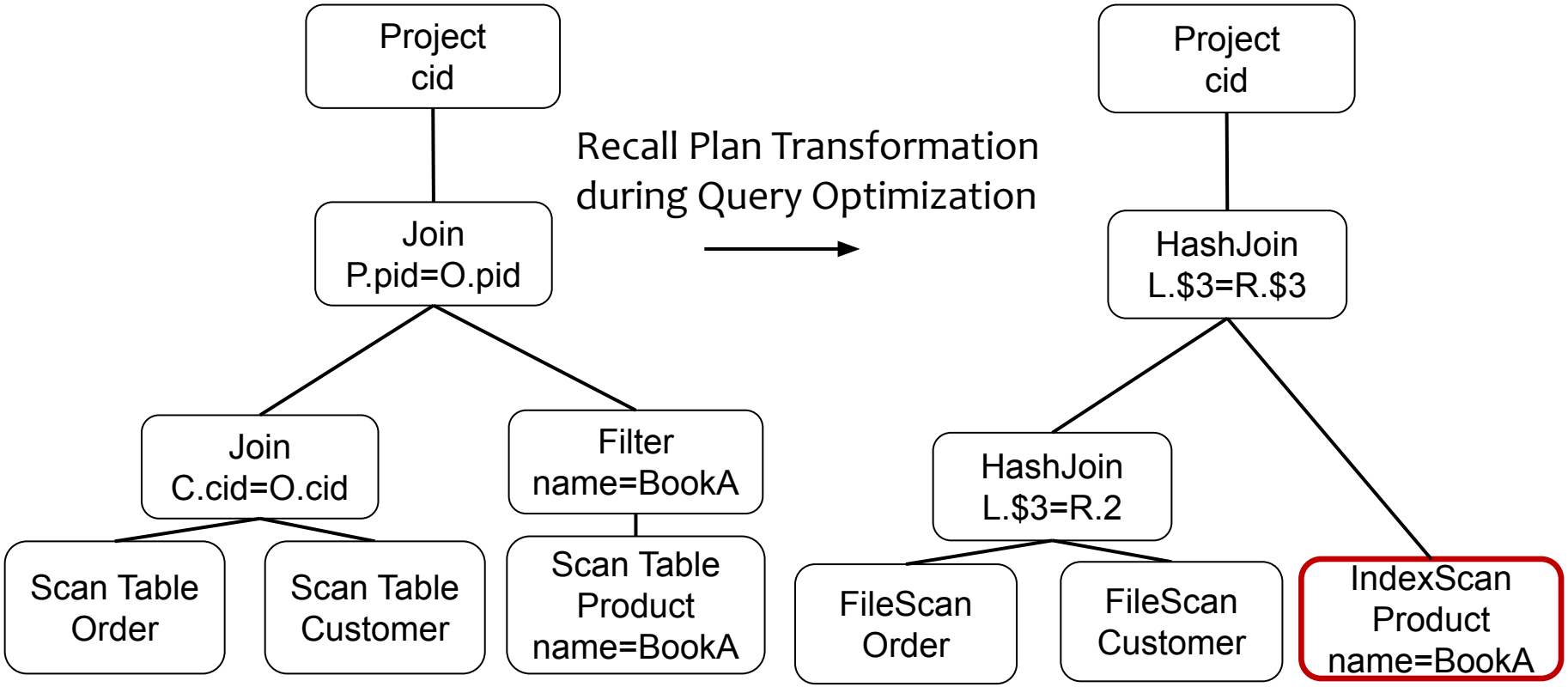
```
CREATE TABLE Students(
    studentID int,
    sinNumber varchar(16) UNIQUE
    PRIMARY KEY (studentID))
```

Will create 2 B+ indices:

1) on studentID;
2) 2) on sinNumber

Using Indices In Practice (2)

- Users only create indices. They do not refer to indices in queries.
- Pro: Some user queries will get much faster
  - B/c RDBMSs use indices during query evaluation
  - Ex: IndexScan operators, or IndexMergeJoin (in Oracle) or IndexNestedLoopJoin etc.



Using Indices In Practice (3)

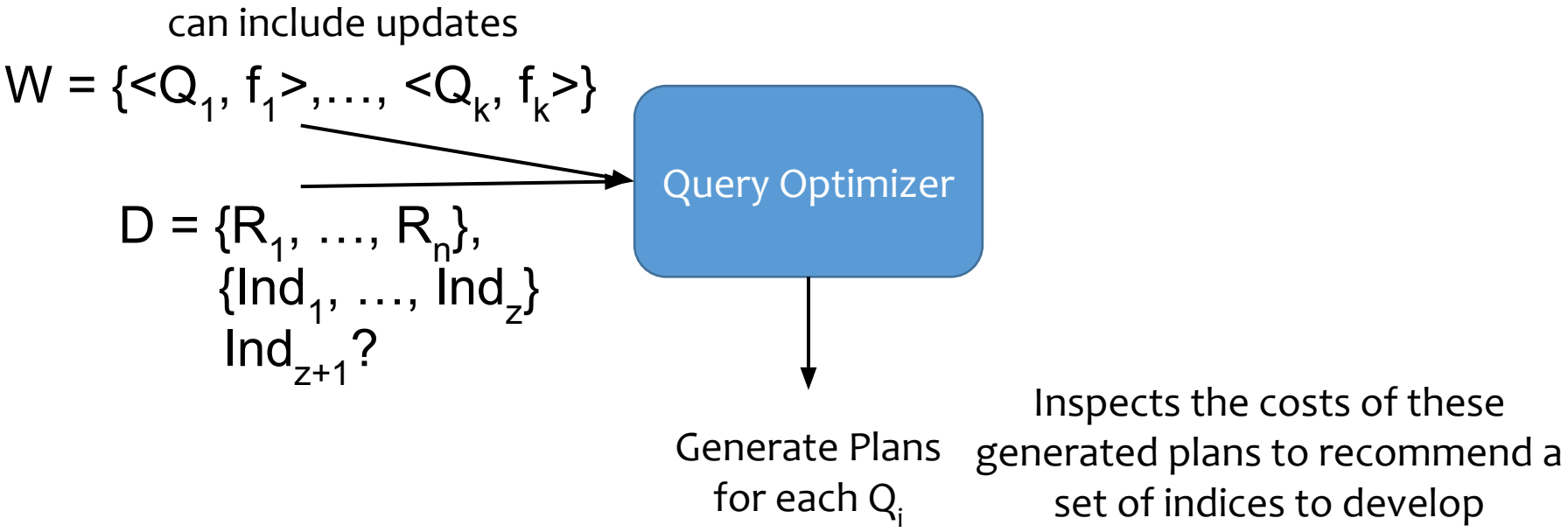
- Con: Updates will get slower because indices need to be maintained
- Q: How should users pick indices given a workload W (i.e., the set of queries an application asks and their frequencies)
- General Guideline:
  - Profile slow queries. Check if they have =, <, ≤, >, ≥ predicates

```
SELECT * FROM R WHERE A = value;
SELECT * FROM R WHERE A = value AND B = 27;
SELECT * FROM R, S WHERE R.A = S.C;
SELECT * FROM S WHERE D > 50;
```

  - E.g., above indices on R.A, R.A and R.B multicolumn, S.C, S.D are possible indices that can speed queries
  - But one should weigh these benefits against slow downs due to updates

Using Indices In Practice (4)

- Many RDBMSs have “Physical Design Advisor” (PDA) tool
- Input: Database D (w/ existing indices), workload W
- Output: A set of recommended indices
- Internally PDA does a “what if” analysis:
  - Uses Query Optimizer & inspects the estimated runtimes/costs of plans the system would use for queries in W with & without additional indices



The Halloween Problem: An Interesting Note On Challenging Problems a DBMS has to solve

- Story from the early days of System R:

```
UPDATE Payroll
SET salary = salary * 1.1
WHERE salary >= 100000;
```

  - There is a B^+-tree index on *Payroll*(*salary*)
  - The update never stopped (why?)
- Why?
- How could you try to solve this if you implemented System R.