CS 133: Databases

Fall 2019
Lec 5 – 09/17
Tree-based Indexes

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Goals for Today

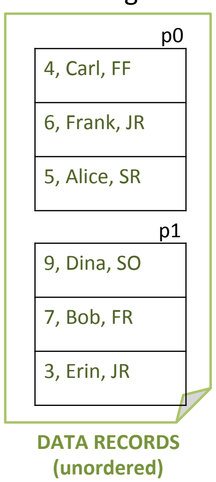
- Consider tradeoffs when choosing indexes
- Understand the difference and tradeoffs between **static** and **dynamic** tree-based indexes
- Learn the **algorithms** for search, insert, and delete for both types of tree indexes

Students(<u>**sid**</u>, name, class)

pi → "page *i*"

Example: Indexes

Student relation organized as a Heap:



In some (many?) systems, specifying `CLUSTERED` implies Alternative 1

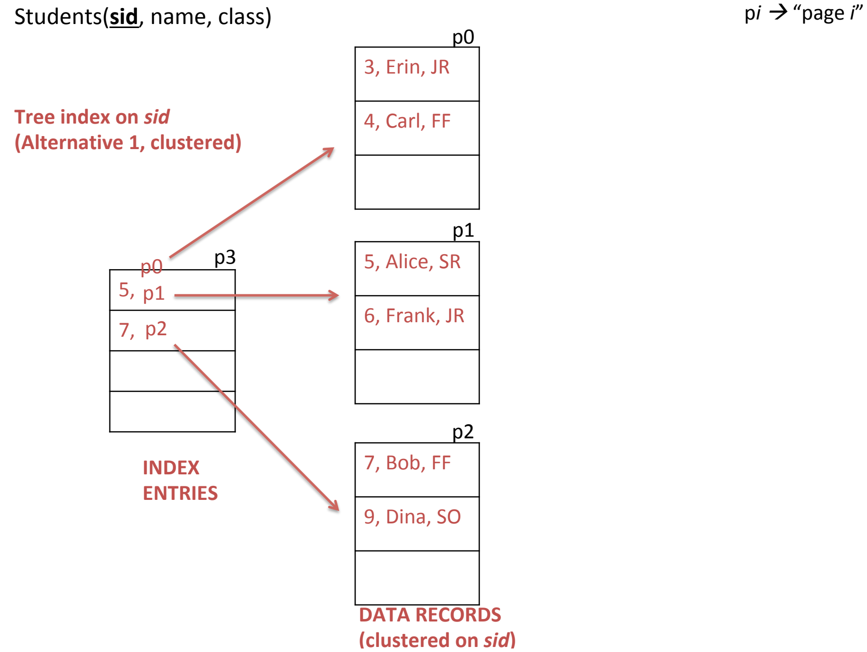
```
CREATE CLUSTERED index sidIndex
ON Students(sid)
USING B-tree;
```

`CREATE Index` syntax (and options) varies between DBMSs !!

(this is a canonical example)

Students(<u>**sid**</u>, name, class)

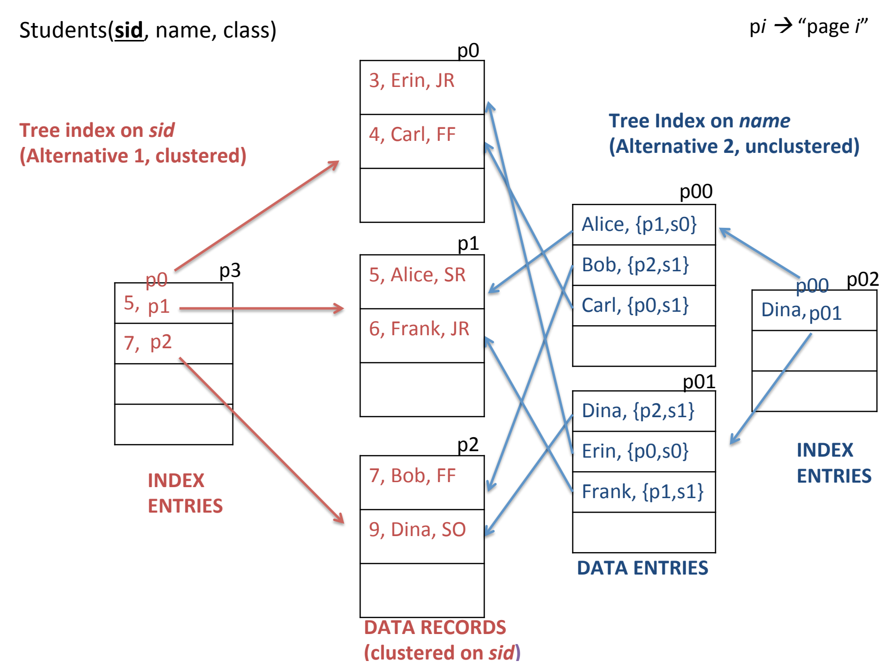
pi → "page *i*"



Suppose want index on name too!

- Cross off which options are not possible for the new index (given our existing Alt 1 tree index on `sid`)

- ~~Clustered~~
- Unclustered
- Tree-based
- Hash-based
- ~~Alt 1 (data entries are data records)~~
- Alt 2 (data entries are pairs of key → record id)
- Alt 3 (data entries are pairs of key → {record ids})



Exercise 2: Discuss with a Neighbor

1. What are the implications if Erin changes her name to TheAwesomeErin?

```
UPDATE Students
SET name = "TheAwesomeErin"
WHERE sid=3;
```

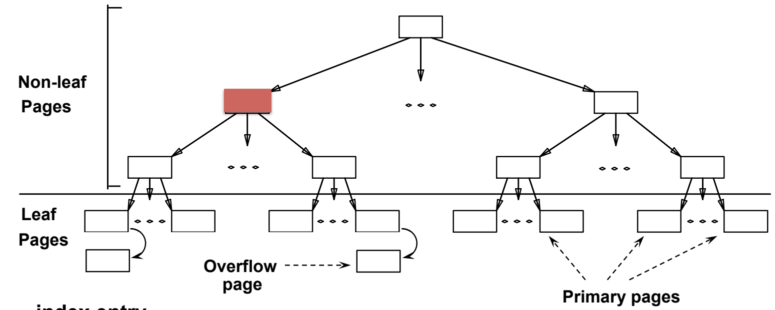
2. Now consider adding two new students, and suppose we want to keep our clustered file completely sorted.

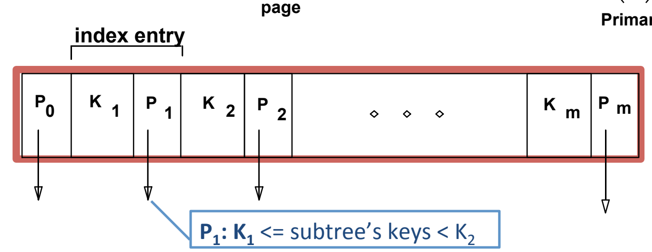
   Contrast the implications in these two scenarios:
   - Scenario 1: Adding two students with `sids` 1 and 2
   - Scenario 2: Adding two students with `sids` 10 and 11

Tree Indexes:
Indexed Sequential Access Method

- ISAM is an old-fashioned idea
  - B+ trees are usually better, as we'll see
    - Though not *always*
- But, it's a good place to start
  - Simpler than B+ tree, but many of the same ideas
- Summary
  - **Don't** brag about being an ISAM expert
  - **Do** understand how they work, and tradeoffs with B+ trees

ISAM Tree Format

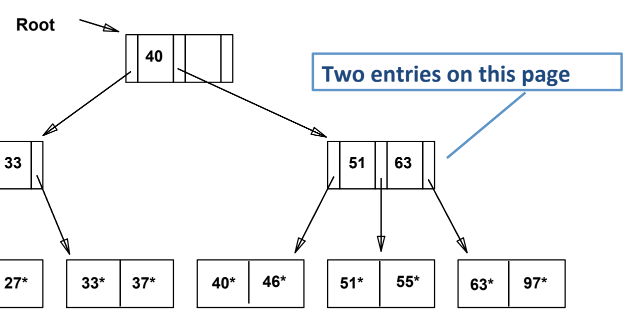




Pointer P_i points to sub-tree with search keys K, K_i <= K < K_{i+1}

Example ISAM Tree

- *Index entries*: <search key value, page id> they direct search to data entries *in leaves.*
- Example where each node can hold 2 entries



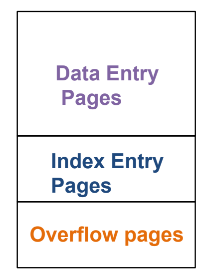
ISAM has a STATIC Index Structure

Index File creation:

1. Allocate leaf pages sequentially
2. Sort records by search key
3. Allocate and fill index entry pages

(now the structure is ready for use)

4. Allocate overflow pages as needed



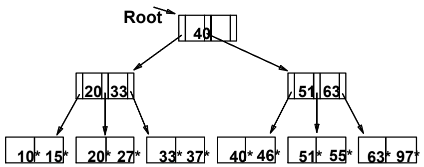
ISAM File Layout

Static tree structure: *inserts/deletes affect only leaf nodes of tree.*

ISAM Operation Summary

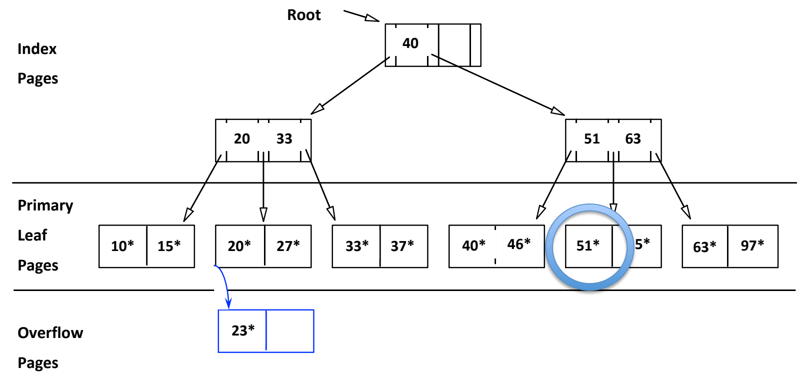
- *Search*: Start at root; use key comparisons to find leaf
  N = # leaf pages
  F = # entries/page **+ 1** (i.e., fan-out)
  Cost = $\log_F N + 1$

No need for "next-leaf-page" pointers (Why?)



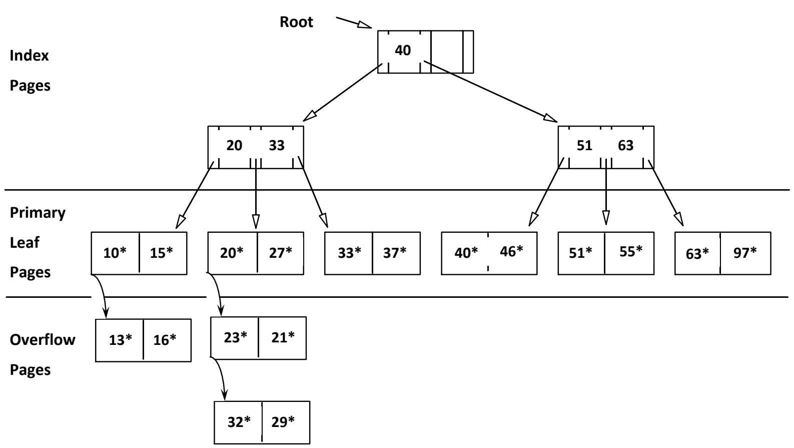
- *Insert*:
  - Search for leaf that data entry belongs to, and put it there.
  - Create overflow page if necessary. Sorting in overflow possible but *not usually done*.
- *Delete*:
  - Search for leaf; remove from leaf;
  - If an overflow page becomes empty, can de-allocate

Example: Insert 23*, Delete 51*



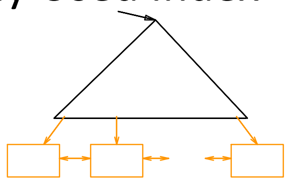
After deletion 51 will still appear in index levels, but not in leaf!

Exercise: (3) on worksheet
Insert 21*, 13*, 16*, 32*, 29*



B+ Tree: The Most Widely Used Index

Insert/delete at $\log_F N$ cost;
keep tree *height-balanced*.

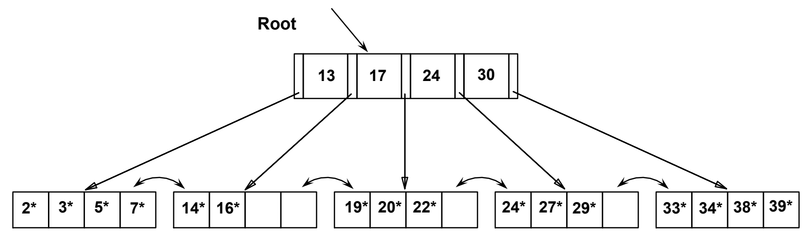


- Each node (except for root) contains *m entries:* d <= *m* <= 2d entries.
- "d" is called the *order* of the tree.
  (so maintain 50% min occupancy)
- Supports equality and range-searches efficiently.

*As in ISAM, all searches go from root to leaves, but structure is **dynamic**.*

Example B+ Tree

- Search begins at root page, and key comparisons direct it to a leaf (as in ISAM)
- Search for 5*, 15*, all data entries >= 24* ...



Based on the search for 15, we know it is not in the tree!*

B+Tree Insertions and Deletions

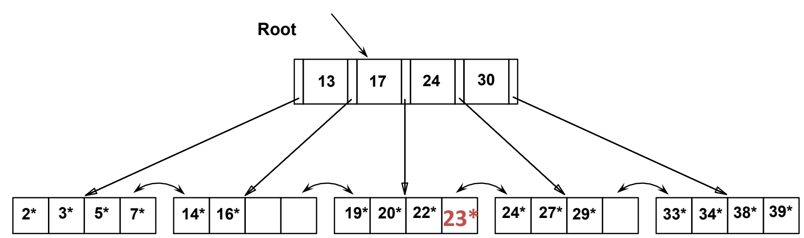
- Important goals for tree modification:

  1. Maintain **balanced** nature of tree!
     (non-leaf pages at least half-full)

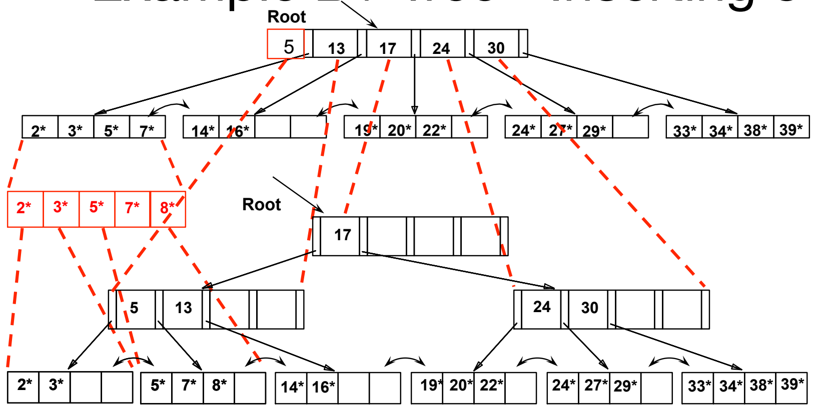
  2. Maintain **correctness** of pointers

  3. *Only leaf pages contain data entries*

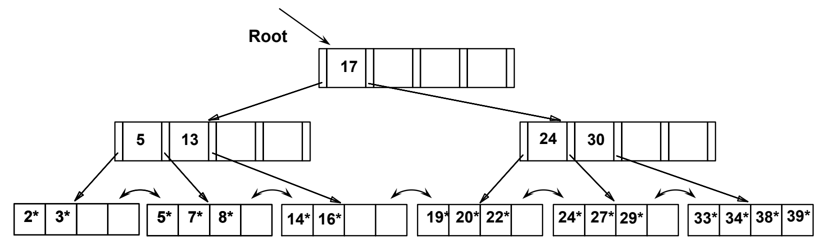
Example B+ Tree – Inserting 23*



Example B+ Tree - Inserting 8*



Example B+ Tree - Inserting 8*



Notice that root was split, leading to increase in height.

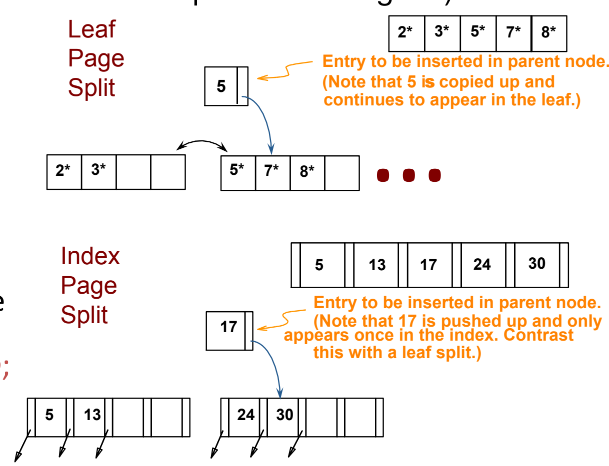
B+Tree: Inserting a Data Entry

- Find correct leaf *L.*
- Put data entry into *L*.
  - If *L* has enough space, *done*!
  - Else, must *split* *L (into L and a new node L2)*
    - Redistribute entries evenly, **copy up** middle key.
    - Insert index entry pointing to *L2* into parent of *L*.
- This can happen recursively
  - To split index node, redistribute entries evenly, but **push up** middle key. (Contrast with leaf splits.)
- Splits "grow" tree; root split increases height.
  - Tree growth: gets *wider* or *one level taller at top.*

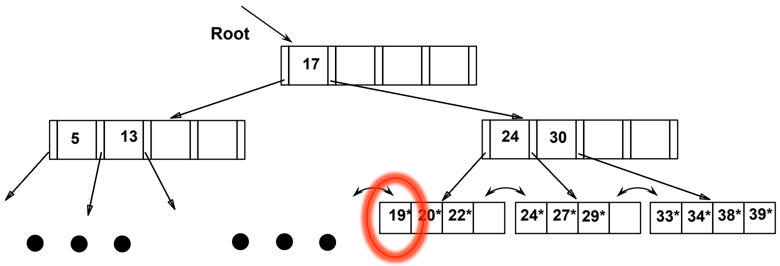
Leaf vs. Index Page Split

(from previous example of inserting "8")

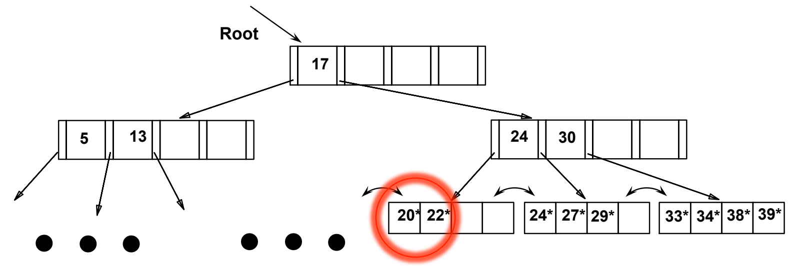
- Minimum occupancy is guaranteed in both leaf and index page splits
- Note difference between *copy-up* and *push-up;*



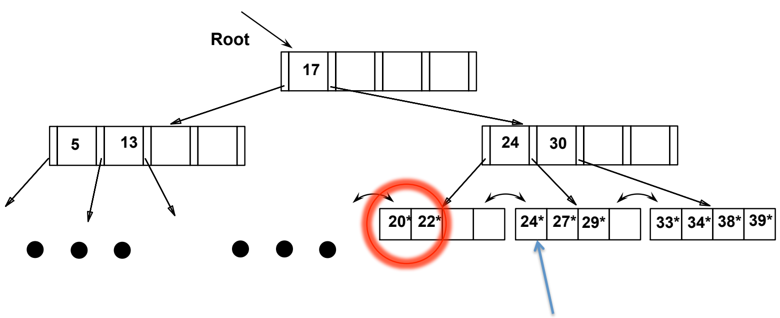
Example Tree - Delete 19*



Example Tree - Delete 19*



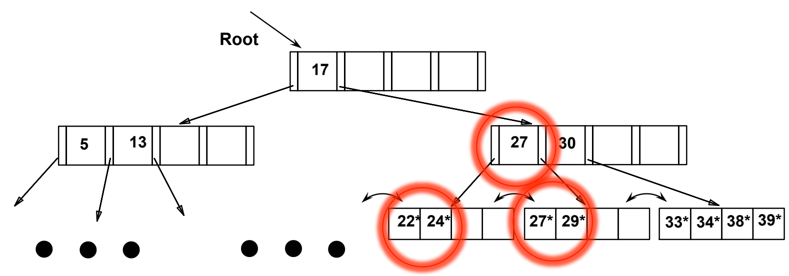
Example Tree – Now, Delete 20*



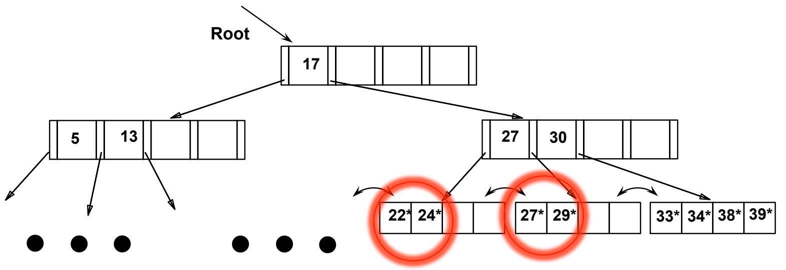
Under-occupancy!
Need to re-distribute.

Take from sibling

Example Tree – Delete 20*



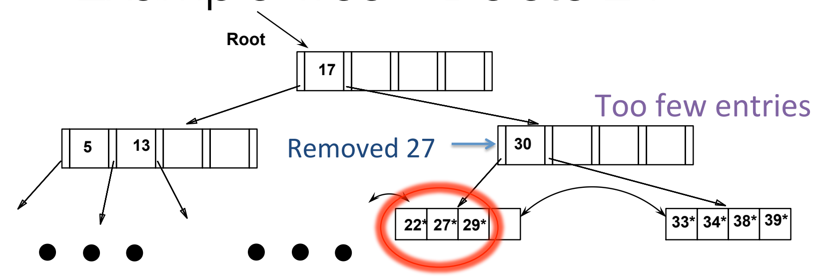
Example Tree – Then Delete 24*



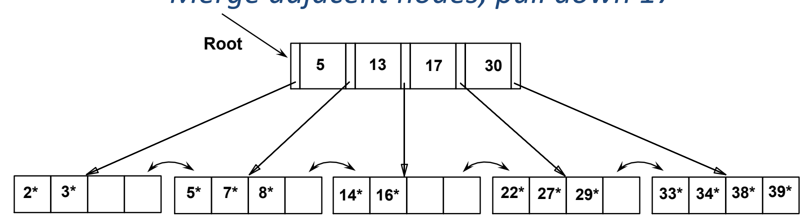
Too few entries!

Can't redistribute, Must merge…

Example Tree – Delete 24*



Merge adjacent nodes, pull down 17



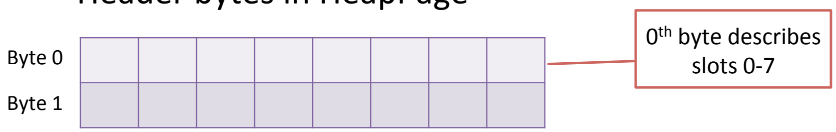
B+ Tree: Deleting a Data Entry

- Find correct leaf L.
- Remove the entry.
  - If L is at least half-full, *done!*
  - If L has only d-1 entries,
    - Try to re-distribute, borrowing from *sibling (adjacent node with same parent as L).*
    - If re-distribution fails, *merge* *L* and sibling.
- If merge occurred:
  - If merging leaf pages must delete entry (pointing to *L* or sibling) from parent of *L*.
  - Else if merging non-leaf pages, must pull down parent entry
- Merge could propagate to root, decreasing height.

Be sure to update the "differentiating entry" between the two siblings

HeapPages in SimpleDb

- Bits are just bits (zeroes and ones)
  - The software we write **imposes meaning** on them
  - E.g., 00000110
    - could mean the number 6
    - could mean slots 1,2 in a heap page are occupied!
  - Note how we read the bits from right to left
    - I.e., the *least significant bit* is the right-most bit
- Header bytes in HeapPage



SimpleDb HeapPage

- Example: Slot 10's bit would be in the second byte (byte 1)
  - Generally, slot *i* in byte `floor( i / 8 )`
  - (other ways of computing this too)
- Bitwise operators!
  - <<, &
  - Check if a bit is 0:
    `headerByte & (1 << headerBit) == 0`

Java Exceptions

- So far in Lab 1:
  - Possibly seen `java.lang.NullPointerException` !!
  - Followed documentation to *throw* exceptions, e.g., `throw new DbException();`
- Coming up:
  - May need to *catch* exceptions, e.g., `catch (IOException e) {…}`
  - In general, poor design (and hides bugs!) to catch multiple exceptions just by one `catch` clause that catches the parent class `Exception`