Introduction to Wireless Sensor Network

Peter Scheuermann and Goce Trajcevski

Dept. of EECS

Northwestern University

A Database Primer

A leap in history

- A brief overview/review of databases (DBMS's)
  - Aren't they for payrolls, inventories, and transactions?
- Databases are about providing a declarative interface to data processing/management
  - Hides complexity and increases flexibility
- Programming sensors is hard—can databases help?
  - After all, it's all about data
  - But, as we will see, traditional databases don't work well in this setting (good for us: lots of research problems!)

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Two important questions

- What's the right interface?
  - Data model: How is data structured conceptually?
  - Query language: How do users specify data processing/management tasks?
- How do you support this interface efficiently?
  - Physical data organization: Store and index data in smart ways to speed up access
  - Query processing and optimization: Figure out the most efficient method to carry out a given task

A simplified example

- Data
  - Nodes are uniquely identified by their ids
  - They are deployed at fixed locations
  - Each node generates readings (e.g., light, temperature, humidity) from the environment periodically, over time
- Query
  - Find nodes in a rectangular region *D*, where the temperature reading at time *t* is higher than 40
- As a simplification, assume for now the base station has already collected all data

Without DBMS…

- Deployment configuration file
  - One node per line (*id*, *x*, *y*), sorted by *id*
- Data log file
  - Each line contains (*id*, *timestamp*, *light*, *temperature*, …), sorted by *timestamp*
- To answer the query, write a program
  - In configuration file, find ids in *D*, and remember them
  - Search log file for section for timestamp *t*
  - Scan the section for lines with qualified ids and temperature higher than 40

Tricks and Alternatives

- Indexes, e.g., on *t* and on *temperature*?
- Change evaluation order, e.g., find temperature readings higher than 40 first?
  - When does this work better?
- Best choice may not be known in advance
- Problems with imperative programming
  - Burden on programmer to figure out right tricks/alternatives
  - To keep up with runtime characteristics, you need to reprogram your apps constantly!

Physical data independence

- Apps should not need to worry about how data is physically organized
- Apps should work with a logical data model and a declarative query language
  - Specify what you want, not how to get it
  - Leave implementation and optimization to DBMS!

Relational data model

- A database is collection of relations (or tables)
- Each relation has a list of attributes (or columns)
- Each relation contains a set of tuples (or rows)

Nodes

id	*x*	*y*
N1	14.2	8.5
N2	7.1	-4.2
N3	-0.4	1.9
N4	3.1	-4.1
...	...	...

Key = {*id*}

Readings

id	*time*	*light*	*temp*	...
N1	1	3.14	26	...
N2	1	3.27	27	...
N3	1	2.97	26	...
...	...	...	...	...
N1	2	3.17	26	...
N2	2	2.99	25	...
N3	2	3.02	26	...
...	...	...	...	...

Key = {*id*, *time*}

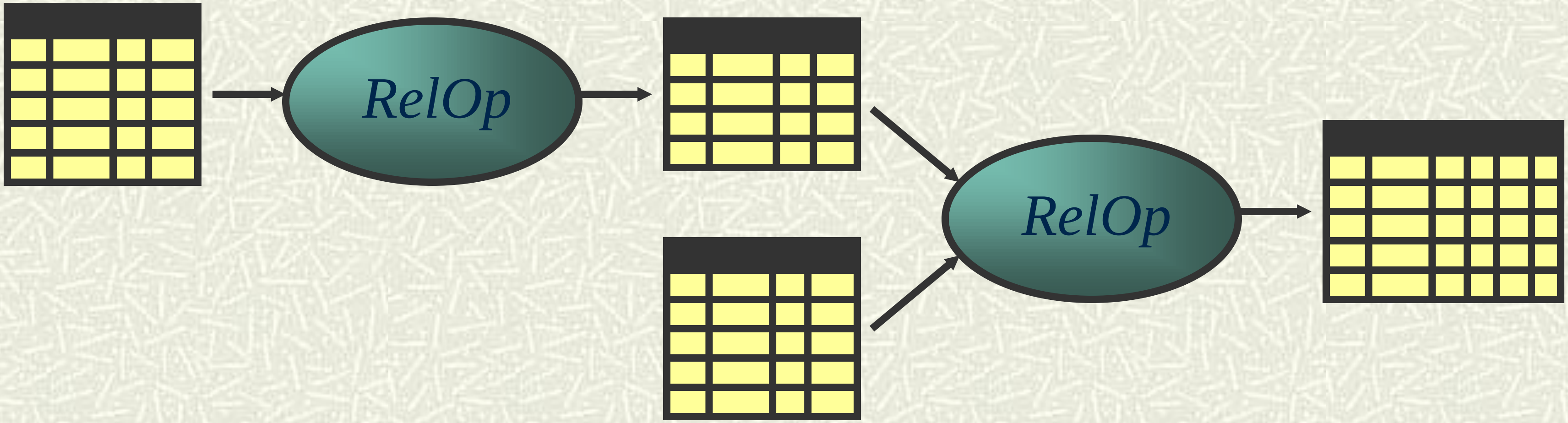
Key Constraint

- Two rules for Key constraints:
  - Two distinct tuples in a legal instance cannot have identical values in all columns of keys (unique)
  - No subset of the set of fields in a key is a unique identifier for a tuple (maximal)
  - Example:
    - No two nodes can have the same id
    - No two measurements can have the same id and time

CORE IDEA : Minimal subset of columns of the relation that uniquely identify the tuple.

Relational algebra

A language for querying relational databases based on operators:



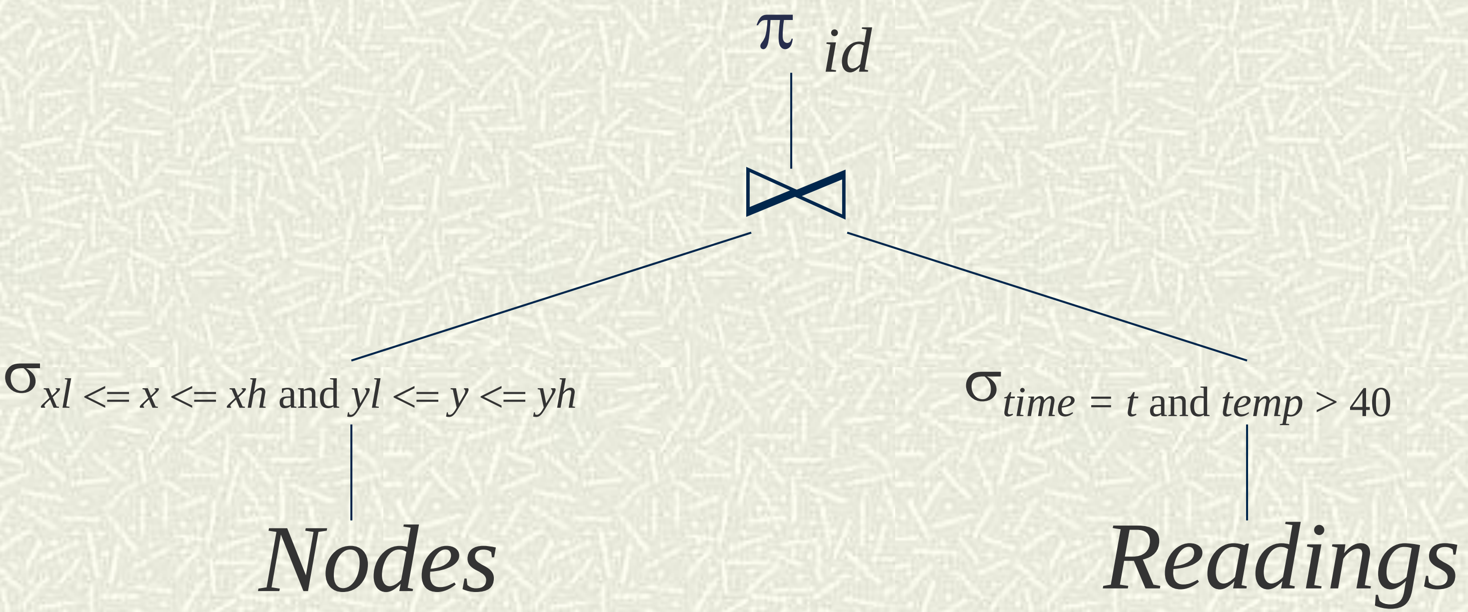
- Core set of operators: selection, projection, cross product, union, difference, and renaming
- Additional, derived operators: join, natural join, etc.
- Compose operators to make complex queries

Relational algebra operators

- Selection: $\sigma_p R$
  - Return only rows that satisfy selection condition *p*
- Projection: $\pi_C R$
  - Return all rows, but only with columns in *C (eliminate duplicates !)*
- Cross product: $R \times S$
  - For every pair of rows from *R* and *S*, return the concatenation
- Union and difference: $R \cup S$ and $R - S$
- Rename: $\rho_S R$, $\rho_{(A1, A2, \ldots)} R$ or $\rho_{S(A1, A2, \ldots)} R$
  - Rename a table and/or its columns
- Join: $R \bowtie_p S = \sigma_p (R \times S)$
- Natural join: $R \bowtie S$
  - Equate common columns and keep one in output

Example query

- *Given:*
  - *Nodes*(<u>*id*</u>, *x*, *y*), *Readings*(<u>*id*</u>, <u>*time*</u>, *light*, *temp*, …)
- Find nodes in rectangular region *D*(*xl*, *yl*, *xh*, *yh*), where temperature at time *t* is higher than 40



SQL

- Structured Query Language: standard language spoken by most commercial DBMS

- Simplest form:

  SELECT $A_1, A_2, \ldots, A_n$
  FROM $R_1, R_2, \ldots, R_m$
  WHERE *condition*;

  - A_i's can be expressions in general
  - Same as $\pi_{A_1, A_2, \ldots, A_n}(\sigma_{condition}(R_1 \times R_2 \times \ldots \times R_m))$
    - Except SQL preserves duplicates
  - Also called an SPJ (select-project-join) query

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Same query in SQL

- *Nodes*(*id*, *x*, *y*), *Readings*(*id*, *time*, *light*, *temp*, …)
- Find nodes in rectangular region *D*(*xl*, *yl*, *xh*, *yh*), where temperature at time *t* is higher than 40

```
SELECT Nodes.id
FROM Nodes, Readings
WHERE xl <= x AND x <= xh
  AND yl <= y AND y <= yh
  AND time = t
  AND temp > 40
  AND Nodes.id = Readings.id;
```

Compare this with an imperative program!

More SQL features

SELECT [DISTINCT] *list_of_output_exprs*
FROM *list_of_tables*
WHERE *where_condition*
GROUP BY *list_of_group_by_columns*
HAVING *having_condition*
ORDER BY *list_of_order_by_columns*

Operational semantics

- FROM: take the cross product of *list_of_tables*
- WHERE: apply $\sigma_{where\_ondition}$
- GROUP BY: group result tuples according to *list_of_group_by_columns*
- HAVING: apply $\sigma_{having\_condition}$ to groups
- SELECT: evaluate *list_of_output_exprs* for each output group
- DISTINCT: eliminate duplicates in output
- ORDER BY: sort output by *list_of_order_by_columns*

Aggregation example

- *Nodes(id, x, y), Readings(id, time, light, temp, …)*
- Average light over time, by nodes
  - SELECT id, AVG(light) FROM Readings GROUP BY id;

Compute GROUP BY: group rows according to the values of GROUP BY columns

id	time	light	temp	...
N1	1	3.14	26	...
N2	1	3.27	27	...
N3	1	2.97	26	...
N1	2	3.17	26	...
N2	2	2.99	25	...
N3	2	3.02	26	...

id	time	light	temp	...
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Compute SELECT for each group

id	avg_light
N1	3.155
N2	3.13
N3	2.995

Summary of the relational interface

- How is data structured conceptually?
  - Simple tables (no order by design!)
  - Rows "linked" by key values
- How do users specify data processing/management tasks?
  - Relational algebra: data flow of operators
  - SQL: easier to write; even more declarative

☞ Next: How do we support this interface efficiently?

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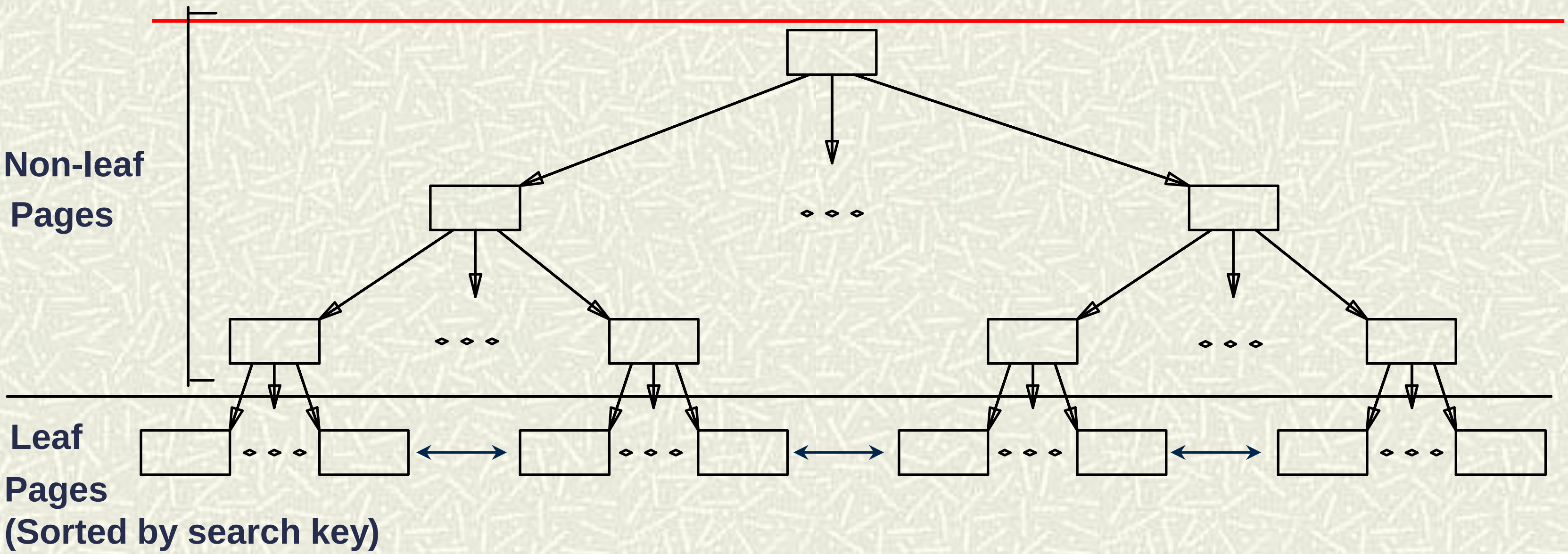
Physical data organization

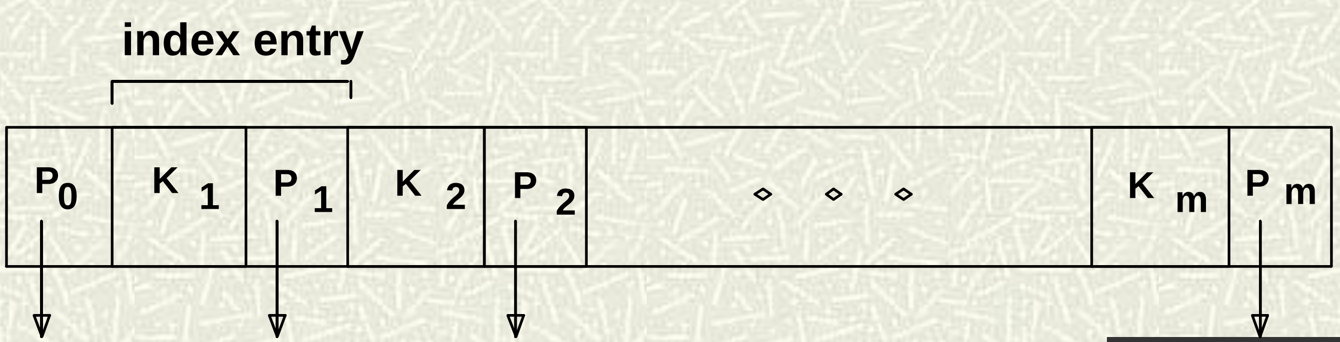
- Lay out data in various ways, e.g.:
  - Store *Nodes* hashed by *id*
  - Store *Readings* sorted by *time, id*
- Use auxiliary data structures
  - Index data to provide alternative access paths, e.g.:
    - R-tree index on *Nodes*(*x, y*)
    - B-tree index on *Readings*(*light*)
  - Materialize views of data, e.g.:
    - All temperatures higher than 40

      SELECT id, time, temperature FROM Readings WHERE temperature > 40;
  - Basic trade-off?

B+ Tree Indexes

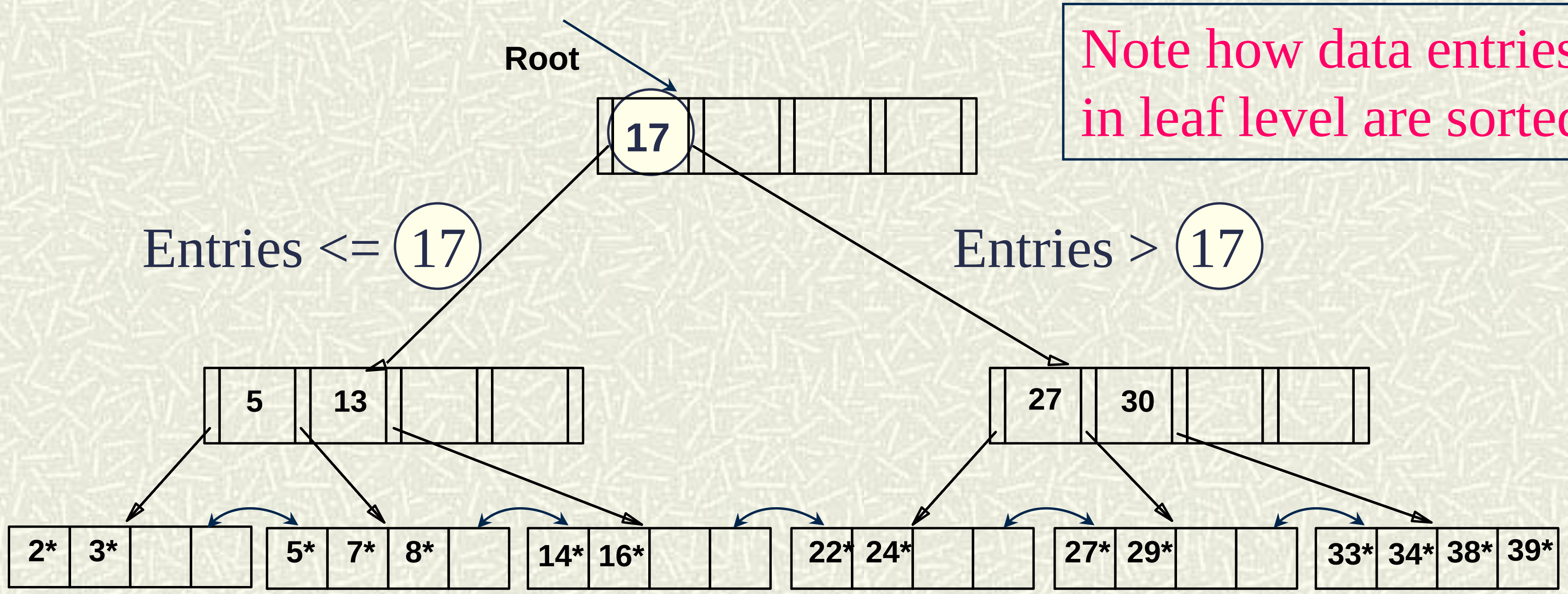


- Index leaf pages contain *data entries*, and are chained (prev & next)
- Index non-leaf pages have *index entries;* only used to direct searches:



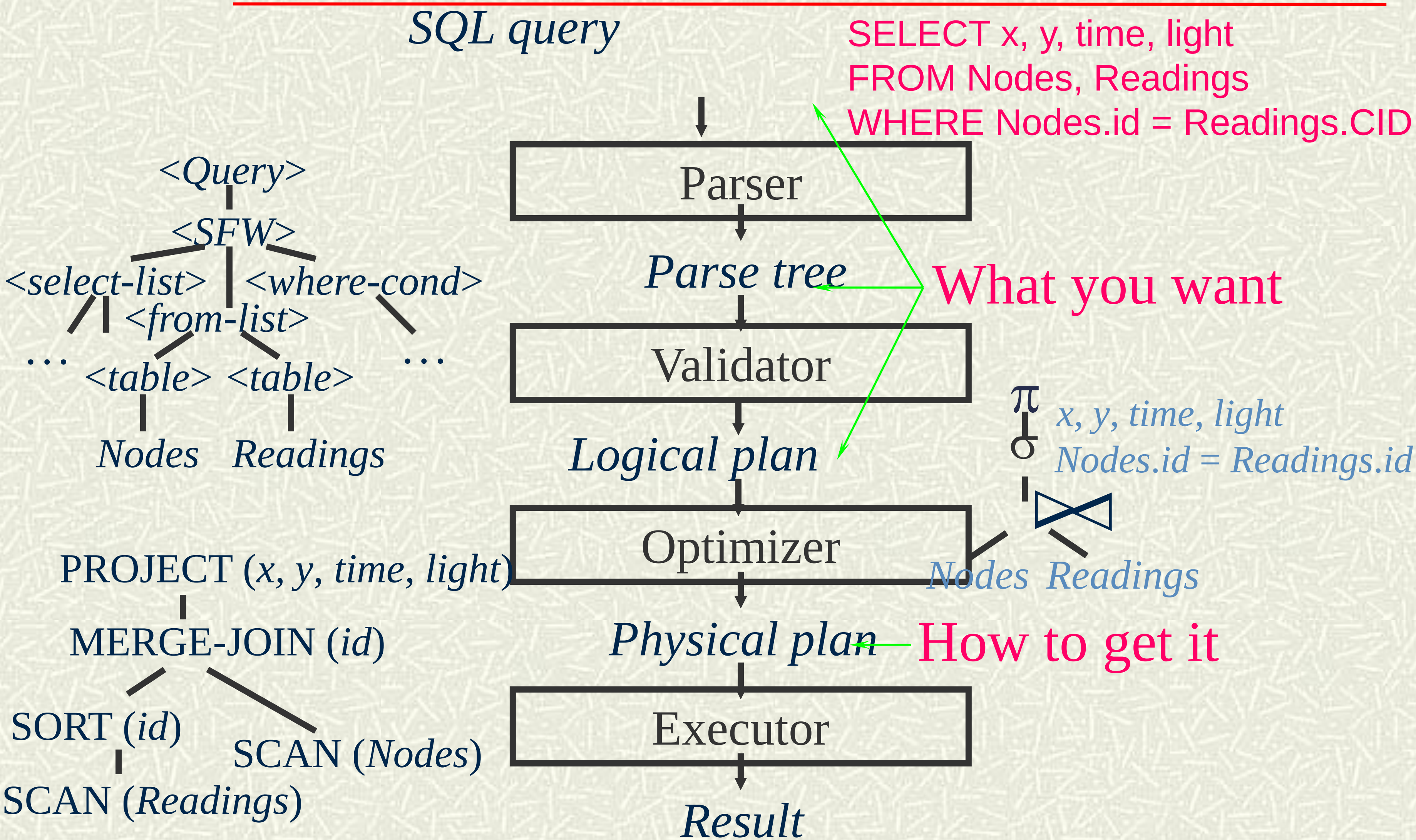
Example B+ Tree

Note how data entries in leaf level are sorted



- Find: 29*? 28*? All > 15* and < 30*
- Insert/delete: Find data entry in leaf, then change it.

Query processing and optimization



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Database Parameters

- |R|, |S| = Number of pages in relations R and S respectively
- ||R||, ||S|| = Number of tuples in relations R and S respectively
- K= no. of tuples per page
- JS = Join Selectivity Factor
  - JS = $||R \bowtie S|| / (||R||*||S||)$
- V(A, R) = number of distinct values that appear in relation R for attribute A

Estimating the Selectivity of Selection and Join

- σ = Selection selectivity factor of relation R
  - $\sigma_{(A = value)} = 1 / V(A, R)$
  - $\sigma_{(A>value)} = (max(A) – value) / (max(A)-min(A))$
    - Max(A) (Min(A)) is the largest (smallest) value of A in R
- $||R \bowtie S|| = min (||R||x||S|| / V(A, R), ||R||x||S|| / V(A, S))$
- For each tuple $t \in R$ there are on the average $||S|| / V(A, S)$ tuples in S matching it

Join Techniques: R ⋈ S

- Nested-loop Join Algorithm

  For each block b_r in R do /* read blocks*/

  For each block b_s in S do

  For each tuple $r \in b_r$ do

  For each tuple $s \in b_s$ do

  if r.a = s.b then output $r \cup s$

- Cost of Method

  T_R = Number of Reads = |R| + |R|*|S|

  T_W = Number of Writes = [J_s*||R||*||S|| / K]

  Cost can be lowered if index is available on R and / or S

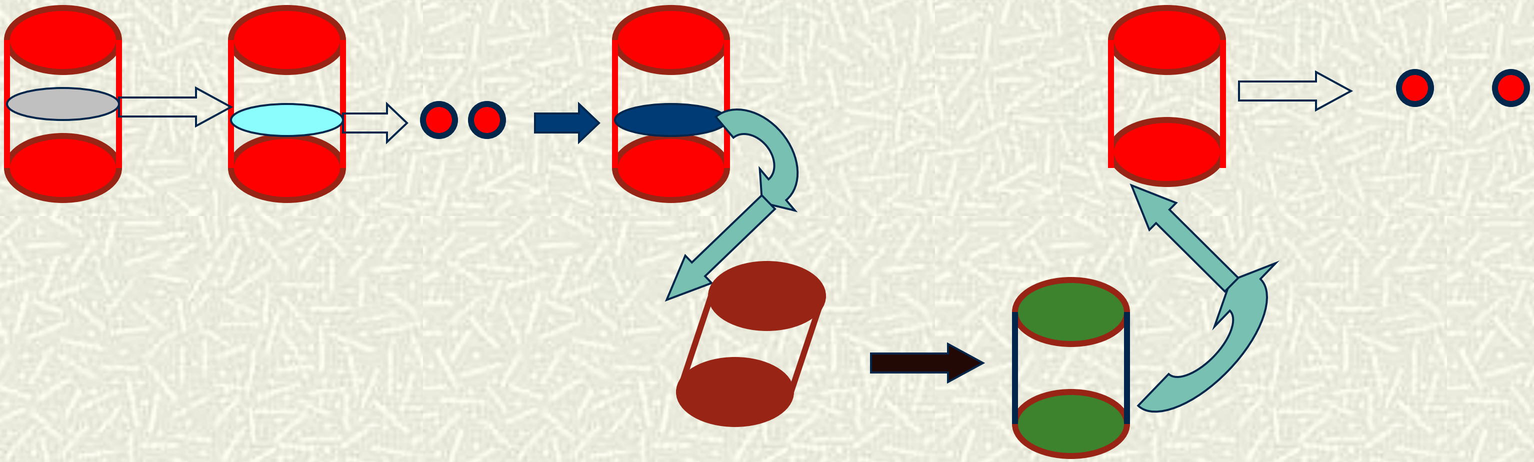
Physical plan operators

- One logical plan operator can be implemented in many different ways (physical plan operators)
- Example: $R \bowtie_{R.A = S.B} S$
  - Nested-loop join: for each tuple of *R*, and for each tuple of *S*, join
  - Index nested-loop join: for each tuple of *R*, use the index on *S*.*B* to find joining *S* tuples
  - Sort-merge join: sort *R* by *R*.*A*, sort *S* by *S*.*B*, and merge-join
  - Hash join: partition *R* and *S* by hashing *R*.*A* and *S*.*B*, and join corresponding partitions
  - And many more…

Query optimization

- One query, many alternative physical plans
  - With different access methods, join order, join methods, etc.
  - With dramatically different costs too!
- Query optimization
  - Enumerate candidate plans
    - Query rewrite: transform queries or query plans into equivalent ones
  - Estimate costs of plans
    - Estimate result sizes using statistics such as histograms
  - Pick a plan with reasonably low cost
    - Dynamic programming
    - Randomized search

Active Databases



ECA = Basic Paradigm of the Reactive Behavior:

Triggers (Active Rules)

ON *EVENT*
IF *CONDITION*
THEN *ACTION*

} **seemingly straightforward, but incorporates an interplay of many *semantic dimensions***

Example of Triggers Execution

Assume that the Average Salary of the employees in a given enterprise should not exceed 65,000.

The *Database Modifications* that could cause
a change of the value(s) of the Average Salary are:
-Insertions; (of new employees with high salary)
-Deletions; (deletions of employees with low salary
-Update of the salaries of current employees

An example of the SQL statement specifying a trigger that would automatically correct the database state (if needed) after an *UPDATE* has been executed is:

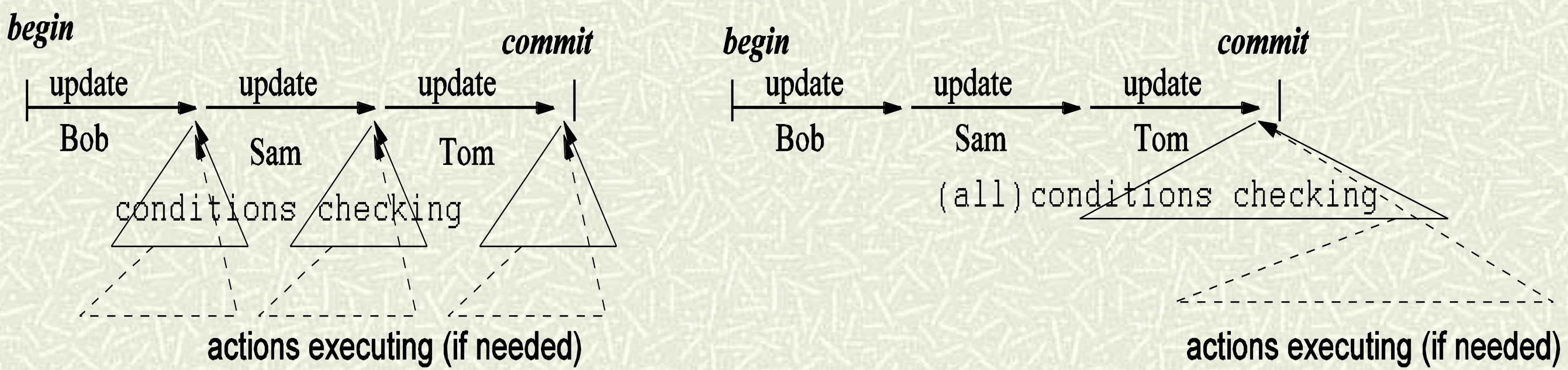
```
CREATE TRIGGER Update-Salary-Check
        ON UPDATE OF Employee.Salary
        IF (SELECT AVG Employee.Salary) > 65,000
        UPDATE Employee
                SET Employee.Salary = 0.95*Employee.Salary
```

Example of Triggers Execution

Assume that it was decided to increase the salary of every employee in the “Maintenance” department by 10%. Following is the SQL statement:

```
UPDATE Employee
        SET Employee.Salary = 1.10*Employee.Salary
        WHERE Employee.Department = ‘Maintenance’
```

Assume that there are 3 employees: Bob, Sam and Tom.
Below is an example of two execution scenarios:



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Back to sensor data processing…

- Does data really live in a few big, flat tables?
- Are data signals or symbols?
- Is SQL really enough?
- What would an index look like?
- What would a physical plan look like?
- How would the optimizer define “cost”?