Database Internals

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CSE 594
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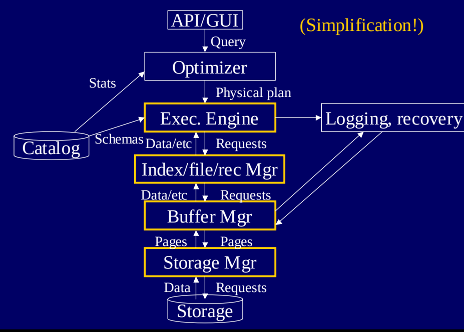
Database Management Systems



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Outline

- Sketch of physical storage
- Basic techniques
  - Indexing
  - Sorting
  - Hashing
- Relational execution
  - Basic principles
  - Primitive relational operators
  - Aggregation and other advanced operators
- Querying XML
- Popular research areas
- Wrap-up: execution issues

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General Emphasis of Today's Lecture

- Goal: cover basic *principles* that are applied throughout database system design
- *Use the appropriate strategy in the appropriate place*

  Every (reasonable) algorithm is good *somewhere*
- … And a corollary: database people always thing they know better than anyone else!

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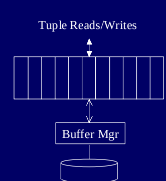
What's the "Base" in "Database"?

- Not just a random-access file *(Why not?)*
  - Raw disk access; contiguous, striped
  - Ability to force to disk, pin in buffer
  - Arranged into pages
- Read & replace pages
  - LRU (not as good as you might think – *why not?*)
  - MRU (one-time sequential scans)
  - Clock, etc.
  - DBMIN (min # pages, local policy)



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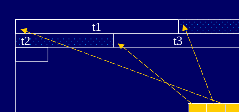
Storing Tuples

Tuples
- Many possible layouts
  - Dynamic vs. fixed lengths
  - Ptrs, lengths vs. slots
- Tuples grow down, directories grow up
- Identity and relocation

Objects are harder
- Horizontal, path, vertical partitioning
- Generally no algorithmic way of deciding



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Alternative File Organizations

Many alternatives, *each ideal for some situation, and poor for others:*

- Heap files: for *full* file scans or frequent updates
  - Data unordered
  - Write new data at end
- Sorted Files: if retrieved in sort order or want range
  - Need *external sort* or an *index* to keep sorted
- Hashed Files: if selection on equality
  - Collection of *buckets* with *primary* & *overflow* pages
  - *Hashing function* over *search key attributes*

Model for Analyzing Access Costs

We ignore CPU costs, for simplicity:

- **b(T):** The number of data pages in table T
- **r(T):** Number of records in table T
- **D:** (Average) time to read or write disk page
- Measuring number of page I/O's ignores gains of pre-fetching blocks of pages; thus, I/O cost is only approximated.
- Average-case analysis; based on several simplistic assumptions.
  - * *Good enough to show the overall trends!*

Assumptions in Our Analysis

- Single record insert and delete.
- Heap Files:
  - Equality selection on key; exactly one match.
  - Insert always at end of file.
- Sorted Files:
  - Files compacted after deletions.
  - Selections on sort field(s).
- Hashed Files:
  - No overflow buckets, 80% page occupancy.

Cost of Operations

	Heap File	Sorted File	Hashed File
Scan all recs			
Equality Search			
Range Search			
Insert			
Delete			

Cost of Operations

	Heap File	Sorted File	Hashed File
Scan all recs	b(T) D	b(T)D	1.25 b(T) D
Equality Search	b(T) D / 2	D $\log_2$ b(T)	D
Range Search	b(T) D	D $\log_2$ b(T) + (# pages with matches)	1.25 b(T) D
Insert	2D	Search + b(T) D	2D
Delete	Search + D	Search + b(T) D	2D

* *Several assumptions underlie these (rough) estimates!*

Speeding Operations over Data

- Three general data organization techniques:
  - Indexing
  - Sorting
  - Hashing

Technique I: Indexing

GMUW §4.1-4.3

- An *index* on a file speeds up selections on the *search key attributes* for the index (trade space for speed).
  - Any subset of the fields of a relation can be the search key for an index on the relation.
  - *Search key* is not the same as *key* (minimal set of fields that uniquely identify a record in a relation).
- An index contains a collection of *data entries*, and supports efficient retrieval of all data entries **k*** with a given key value **k**.

Alternatives for Data Entry k* in Index

- Three alternatives:
  - Data record with key value **k**
    - Clustered -> fast lookup
    - Index is large; only 1 can exist
  - <**k**, rid of data record with search key value **k**>, OR
  - <**k**, list of rids of data records with search key **k**>
    - Can have secondary indices
    - Smaller index may mean faster lookup
    - Often not clustered -> more expensive to use
- Choice of alternative for data entries is orthogonal to the indexing technique used to locate data entries with a given key value **k**.

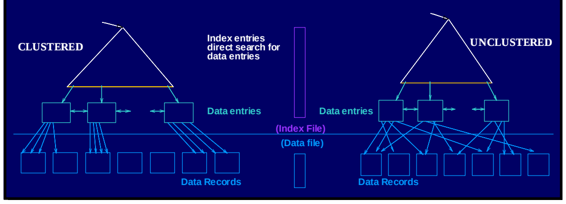
Classes of Indices

- *Primary* vs. *secondary*: primary has primary key
- *Clustered* vs. *unclustered*: order of records and index approximately same
  - Alternative 1 implies clustered, but not vice-versa.
  - A file can be clustered on at most one search key.
- *Dense* vs. *Sparse*: dense has index entry per data value; sparse may "skip" some
  - Alternative 1 always leads to dense index.
  - Every sparse index is clustered!
  - Sparse indexes are smaller; however, some useful optimizations are based on dense indexes.

Clustered vs. Unclustered Index

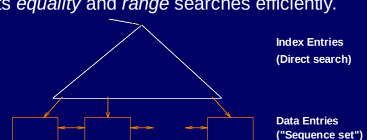
Suppose Index Alternative (2) used, records are stored in Heap file

- Perhaps initially sort data file, leave some gaps
- Inserts may require overflow pages



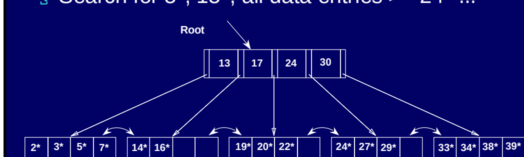
B+ Tree: The World's Favourite Index

- Insert/delete at $\log_F N$ cost
  - (F = fanout, N = # leaf pages)
  - Keep tree *height-balanced*
- Minimum 50% occupancy (except for root).
- Each node contains **d** <= *m* <= 2**d** entries. **d** is called the *order* of the tree.
- Supports *equality* and *range* searches efficiently.



Example B+ Tree

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



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

B+ Trees in Practice

- Typical order: 100. Typical fill-factor: 67%.
  - average fanout = 133
- Typical capacities:
  - Height 4: 133^4 = 312,900,700 records
  - Height 3: 133^3 = 2,352,637 records
- Can often hold top levels in buffer pool:
  - Level 1 = 1 page = 8 Kbytes
  - Level 2 = 133 pages = 1 Mbyte
  - Level 3 = 17,689 pages = 133 MBytes

Inserting Data into a B+ Tree

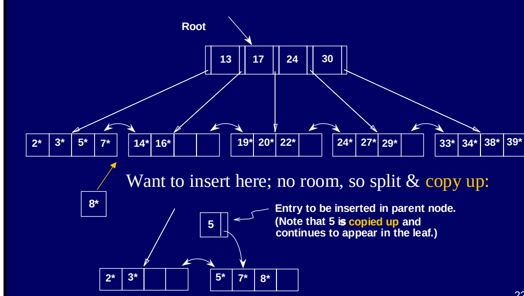
- Find correct leaf L.
- Put data entry onto L.
  - If L has enough space, done!
  - Else, must split L (into L and a new node L2)
    - Redistribute entries evenly, copy up middle key.
    - Insert index entry pointing to L2 into parent of L.
- This can happen recursively
  - To split index node, redistribute 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.

Inserting 8* into Example B+ Tree

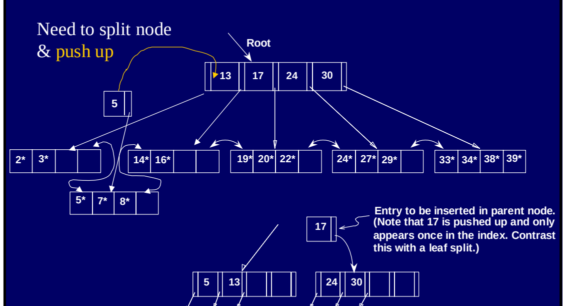
- Observe how minimum occupancy is guaranteed in both leaf and index pg splits.
- Recall that all data items are in leaves, and partition values for keys are in intermediate nodes

Note difference between *copy-up* and *push-up*.

Inserting 8* Example: Copy up



Inserting 8* Example: Push up



Deleting Data from a B+ Tree

- Start at root, find leaf L where entry belongs.
- 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, must delete entry (pointing to L or sibling) from parent of L.
- Merge could propagate to root, decreasing height.

B+ Tree Summary

B+ tree and other indices ideal for range searches, good for equality searches.

- Inserts/deletes leave tree height-balanced; $\log_F N$ cost.
- High fanout (F) means depth rarely more than 3 or 4.
- Almost always better than maintaining a sorted file.
- Typically, 67% occupancy on average.
- Note: Order (d) concept replaced by physical space criterion in practice ("at least half-full").
  - Records may be variable sized
  - Index pages typically hold more entries than leaves

Other Kinds of Indices

- Multidimensional indices
  - R-trees, kD-trees, …
- Text indices
  - Inverted indices
- etc.

Objects and Indices

Multi-level hierarchy: Object.Subobject.Subsubobject

- Want to query for objects with submember of specific value
- Vehicles with Vehicle.Mfr.Name = "Ferrari"
- Companies with Company.Division.Loc = "Modena"

Vehicle(Mfr, Model)

01	03	Testarosa
10	03	360 Modena
02	04	TT

Company(Name, Division)

03	Ferrari	05, 06

Division(Name, Loc)

05	Assembly	Modena
06	Design	Modena

Example Class Hierarchy

Vehicle(Mfr, Model)

01	03	Testarosa
10	03	360 Modena
02	04	Z3

Company(Name, Division)

03	Ferrari	05, 06
04	BMW	07

Division(Name, Loc)

05	Assembly	Modena
06	Design	Modena
07	Quality Ctrl.	Modena

Access Support Relations

- Speed up finding a sub- or super-object
- Create a table with a tuple per path through the object hierarchy

VehicleOID	CompanyOID	DivisionOID

Beyond Objects

More complex than objects: semistructured data (e.g. XML)

- Self-describing (embedded labels)
- Irregular structure
- "Weaker" typing (potentially)
- XPath expressions

OO indexing techniques applicable?

Why or why not?

Speeding Operations over Data

- Three general data organization techniques:
  - Indexing
  - Sorting
  - Hashing

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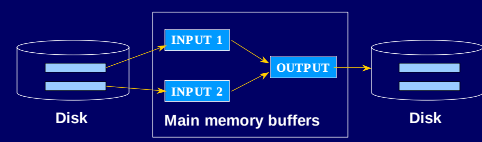
Technique II: Sorting

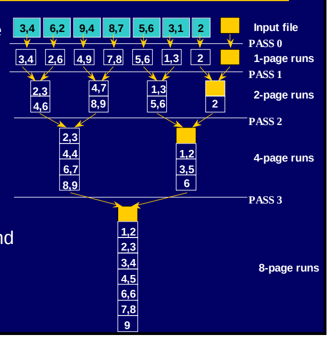
GMUW §2.3

- Pass 1: Read a page, sort it, write it.
  - only one buffer page is used
- Pass 2, 3, …, etc.:
  - three buffer pages used.



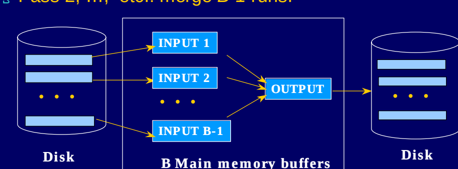
Two-Way External Merge Sort

- Each pass we read, write each page in file.
- N pages in the file => the number of passes
  $= \lceil \log_2 N \rceil + 1$
- Total cost is:
  $$2N\left(\lceil \log_2 N \rceil + 1\right)$$
- *Idea:* ***Divide and conquer:*** sort subfiles and merge



General External Merge Sort

- *How can we utilize more than 3 buffer pages?*
- To sort a file with *N* pages using *B* buffer pages:
  - Pass 0: use *B* buffer pages. Produce $\lceil N / B \rceil$ sorted runs of *B* pages each.
  - Pass 2, …, etc.: merge *B-1* runs.



Cost of External Merge Sort

- Number of passes: $1 + \lceil \log_{B-1} \lceil N / B \rceil \rceil$
- Cost = 2N * (# of passes)
- With 5 buffer pages, to sort 108 page file:
  - Pass 0: $\lceil 108 / 5 \rceil$ = 22 sorted runs of 5 pages each (last run is only 3 pages)
  - Pass 1: $\lceil 22 / 4 \rceil$ = 6 sorted runs of 20 pages each (last run is only 8 pages)
  - Pass 2: 2 sorted runs, 80 pages and 28 pages
  - Pass 3: Sorted file of 108 pages

Speeding Operations over Data

- Three general data organization techniques:
  - Indexing
  - Sorting
  - Hashing

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Technique 3: Hashing

GMUW §4.4

- A familiar idea:
  - Requires “good” hash function (may depend on data)
  - Distribute data across buckets
  - Often multiple items in same bucket (buckets might overflow)
- Types of hash tables:
  - Static
  - Extendible (requires directory to buckets; can split)
  - Linear (two levels, rotate through + split; bad with skew)
  - Can be the basis of disk-based indices!

    We won't get into detail because of time, but see text

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Making Use of the Data + Indices: Query Execution

GMUW §6

- Query plans & exec strategies
- Basic principles
- Standard relational operators
- Querying XML

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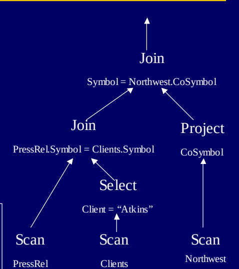
Query Plans

- Data-flow graph of relational algebra operators
- *Typically*: determined by optimizer

```
SELECT *
FROM PressRel p, Clients C
WHERE p.Symbol = c.Symbol
 AND c.Client = 'Atkins'
 AND c.Symbol IN
(SELECT CoSymbol FROM Northwest)
```



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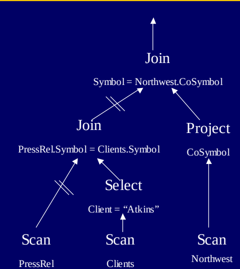
Execution Strategy Issues

- Granularity & parallelism:
  - Pipelining vs. blocking
  - Materialization



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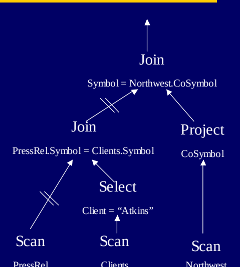
Iterator-Based Query Execution

- Execution begins at root
  - *open, next, close*
  - Propagate calls to children

    May call multiple child *nexts*
- ✓ Efficient scheduling & resource usage

Can you think of alternatives and their benefits?



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Basic Principles

- Many DB operations require reading tuples, tuple vs. previous tuples, or tuples vs. tuples in another table
- Techniques generally used:
  - *Iteration*: for/while loop comparing with all tuples on disk
  - *Index*: if comparison of attribute that's indexed, look up matches in index & return those
  - *Sort*: iteration against presorted data (*interesting orders*)
  - *Hash*: build hash table of the tuple list, *probe* the hash table
- *Must be able to support larger-than-memory data*

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Basic Operators

- One-pass operators:
  - Scan
  - Select
  - Project
- Multi-pass operators:
  - Join
    - Various implementations
    - Handling of larger-than-memory sources
  - Semi-join
  - Aggregation, union, etc.

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1-Pass Operators: Scanning a Table

- Sequential scan: read through blocks of table
- Index scan: retrieve tuples in index order
  - May require 1 seek per tuple!
- Cost in page reads -- b(T) blocks, r(T) tuples
  - b(T) pages for sequential scan
  - Up to r(T) for index scan if unclustered index
  - Requires memory for one block

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1-Pass Operators: *Select* (σ)

- Typically done while scanning a file
- If unsorted & no index, check against predicate:

```
Read tuple
While tuple doesn't meet predicate
  Read tuple
Return tuple
```

- Sorted data: can stop after particular value encountered
- Indexed data: apply predicate to index, if possible
- If predicate is:
  - conjunction: may use indexes and/or scanning loop above (may need to sort/hash to compute intersection)
  - disjunction: may use union of index results, or scanning loop

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1-Pass Operators: *Project* (Π)

- Simple scanning method often used if no index:

```
Read tuple
While more tuples
  Output specified attributes
  Read tuple
```

- Duplicate removal may be necessary
  - Partition output into separate files by bucket, do duplicate removal on those
  - If have many duplicates, sorting may be better
- If attributes belong to an index, don't need to retrieve tuples!

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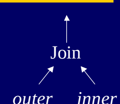
Multi-pass Operators: *Join* ($\triangleright\triangleleft$) -- Nested-Loops Join



- Requires two nested loops:

```
For each tuple in outer relation
  For each tuple in inner, compare
  If match on join attribute, output
```

- Results have order of outer relation
- Can do over indices
- ✓ Very simple to implement, supports any joins predicates
- ✓ Supports any join predicates
- × Cost: # comparisons = t(R) t(S)
  - # disk accesses = b(R) + t(R) b(S)

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Block Nested-Loops Join

- Join a page (block) at a time from each table:

```
For each page in outer relation
  For each page in inner, join both pages
    If match on join attribute, output
```

- ✓ More efficient than previous approach:
- × Cost: # comparisons still = t(R) t(S)
  - # disk accesses = b(R) + b(R) * b(S)

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Index Nested-Loops Join

```
For each tuple in outer relation
  For each match in inner's index
    Retrieve inner tuple + output joined tuple
```

- Cost: b(R) + t(R) * cost of matching in S
- For each R tuple, costs of probing index are about:
  - 1.2 for hash index, 2-4 for B+-tree and:
    - Clustered index: 1 I/O on average
    - Unclustered index: Up to 1 I/O per S tuple

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Two-Pass Algorithms

Sort-based

Need to do a multiway sort first (or have an index)

Approximately linear in practice, 2 b(T) for table T

Hash-based

Store one relation in a hash table

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(Sort-)Merge Join

- Requires data sorted by join attributes

  `Merge and join sorted files, reading sequentially a block at a time`
  - Maintain two file pointers
    - While tuple at R < tuple at S, advance R (and vice versa)
    - While tuples match, output all possible pairings
  - Preserves sorted order of "outer" relation
- ✓ Very efficient for presorted data
- ✓ Can be "hybridized" with NL Join for range joins
- × May require a sort before (adds cost + delay)
- Cost: b(R) + b(S) plus sort costs, if necessary

  In practice, approximately linear, 3 (b(R) + b(S))

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Hash-Based Joins

- Allows partial pipelining of operations with equality comparisons
- Sort-based operations block, but allow range and inequality comparisons
- Hash joins usually done with static number of hash buckets
  - Generally have fairly long chains at each bucket
  - What happens when memory is too small?

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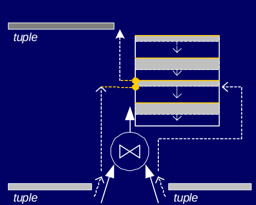
Hash Join




```
Read entire inner
  relation into hash
  table (join attributes
  as key)
For each tuple from
  outer, look up in hash
  table & join
```

- ✓ Very efficient, very good for databases
- × Not fully pipelined
- × Supports equijoins only
- × Delay-sensitive

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Running out of Memory

- Prevention: First partition the data by value into memory-sized groups

  `Partition both relations in the same way, write to files`

  `Recursively join the partitions`
- Resolution: Similar, but do when hash tables full

  `Split hash table into files along bucket boundaries`

  `Partition remaining data in same way`

  `Recursively join partitions with diff. hash fn!`
- Hybrid hash join: flush "lazily" a few buckets at a time
- Cost: <= 3 * (b(R) + b(S))

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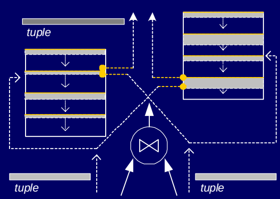
Pipelined Hash Join Useful for Joining Web Sources



- Two hash tables
- As a tuple comes in, add to the appropriate side & join with opposite table
- ✓ Fully pipelined, adaptive to source data rates
- ✓ Can handle overflow as with hash join
- × Needs more memory

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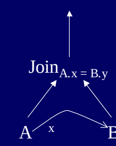
The Semi-Join/Dependent Join

- Take attributes from left and feed to the right source as input/filter
- Important in data integration
- Simple method:
  - for each tuple from left
    - send to right source
    - get data back, join
- More complex:
  - Hash "cache" of attributes & mappings
  - Don't send attribute already seen
  - Bloom joins (use bit-vectors to reduce traffic)



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Aggregation (γ)

- Need to store entire table, coalesce groups with matching GROUP BY attributes
- Compute aggregate function over group:
  - If groups are sorted or indexed, can iterate:
    - Read tuples while attributes match, compute aggregate
    - At end of each group, output result
  - Hash approach:
    - Group together in hash table (leave space for agg values!)
    - Compute aggregates incrementally or at end
    - At end, return answers
- Cost: b(t) pages. How much memory?

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Other Operators

- Duplicate removal very similar to grouping
  - All attributes must match
  - No aggregate
- Union, difference, intersection:
  - Read table R, build hash/search tree
  - Read table S, add/discard tuples as required
  - Cost: b(R) + b(S)

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Relational Operations

In a whirlwind, you've seen most of relational operators:

- Select, Project, Join
- Group/aggregate
- Union, Difference, Intersection
- Others are used sometimes:
  - Various methods of "for all," "not exists," etc
  - Recursive queries/fixpoint operator
  - etc.

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Recall XML

Element

```
<db>
 <store>
  <manager>Griffith</manager>
  <manager>Sims</manager>
  <location>
    <address>12 Pike Pl.</address>
    <city>Seattle</city>
  </location>
 </store>
 <store>
  <manager>Jones</manager>
  <address>30 Main St.</address>
  <city>Berkeley</city>
 </store>
</db>
```

Data value

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Querying XML with XQuery

"Query over all stores, managers, and cities":

```
FOR $s = (document)/db/store,
    $m = $s/manager/data(),
    $c = $s//city/data()

WHERE {join + select conditions}
RETURN {XML output}
```

Query operations evaluated over all possible tuples of ($s, $m, $c) that can be matched on input

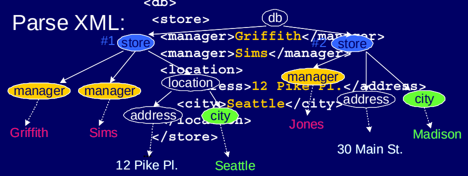
Processing XML

- Bind variables to subtrees; treat each set of bindings as a tuple
- Select, project, join, etc. on tuples of bindings
- Plus we need some new operators:
  - XML construction:
    - Create element (add tags around data)
    - Add attribute(s) to element (similar to join)
    - Nest element under other element (similar to join)
  - Path expression evaluation – create the binding tuples

Standard Method: XML Query Processing in Action

Parse XML:

```
<db>
 <store>
  <manager>Griffith</manager>
  <manager>Sims</manager>
  <location>
   <address>12 Pike Pl.</address>
   <city>Seattle</city>
  </location>
 </store>
```



Match paths:

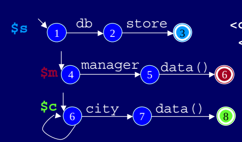
```
$s = (root)/db/store
$m = $s/manager/data()
$c = $s//city/data()
```

$s	$m	$c
#1	Griffith	Seattle
#1	Sims	Seattle
#2	Jones	Madison

X-Scan: "Scan" for Streaming XML

- We often re-read XML from net on every query
  - Data integration, data exchange, reading from Web
- Previous systems:
  - Store XML on disk, then index & query
  - Cannot amortize storage costs
- X-scan works on *streaming* XML data
  - Read & parse
  - **Evaluate path expressions to select nodes**
  - **Also has support for mapping XML to graphs**

X-Scan: Incremental Parsing & Path Matching



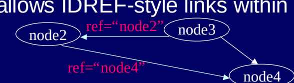

```
<db>
 <store> #1
  <manager>Griffith</manager>
  <manager>Sims</manager>
  <location>
    <address>12 Pike Pl.</address>
    <city>Seattle</city>
  </location>
 </store>
 <store> #2
  <manager>Jones</manager>
  <address>30 Main St.</address>
  <city>Berkeley</city>
 </store>
</db>
```

Tuples for query:

$s	$m	$c
#1	Griffith	Seattle
#1	Sims	Seattle
#2	Jones	Berkeley

X-Scan works on *Graphs*

- XML allows IDREF-style links within a document



  - Keep track of every ID
  - Build an "index" of the XML document's structure; add *real* edges for every subelement and IDREF
  - When IDREF encountered, see if ID is known
    - If so, dereference and follow it
    - Otherwise, parse and index until we get to it, then process the newly indexed data

Building XML Output

- Need the following operations:
  - Create XML Element
  - Create XML Attribute
  - Output Value/Variable into XML content
  - Nest XML subquery results into XML element
    (Looks very much like a join between parent query and subquery!)

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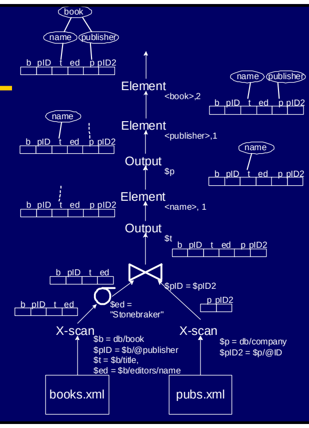
An XML Query

- X-scan creates tuples
- Select, join as usual
- Construct results
  - Output variable
  - Create element around content
- A few key extensions to standard models!



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Where's Query Execution Headed?

- *Adaptive* scheduling of operations – adjusting work to prioritize certain tuples
- *Robust* – as in distributed systems, exploit replicas, handle failures
- Show and update *partial*/tentative results
- More *interactive* and responsive to user
- More *complex data* models –XML, semistructured data

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Leading into Next Week's Topic: Execution Issues for the Optimizer

- Goal: minimize I/O costs!
- Try different orders of applying operations
  Selectivity estimates
- Choose different algorithms
  - "Interesting orders" – exploit sorts
  - Equijoin or range join?
  - Exploit indices
- How much memory do I have and need?

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