

*The nuts and bolts of
DBMS construction:
building your own prototype*

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Part 1: Goal and methodology

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Motivation

- www.amazon.com:
 - 48 books on compiler construction, several on optimizing compilers;
 - 1 book on DBMS system implementation!!
- Researchers wanting to test new concepts are forced to build entire systems from scratch
- Students learning how to prototype a DBMS have a hard time finding resources
- Haven't we made construction of DBMS any easier in the last 20 years?

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Goal of the tutorial

- To outline techniques for building
 - advanced research experimental systems
 - simple but useful query engines
- To map resources providing
 - Building blocks, or
 - Knowledge on how to build a building block if there is not a satisfactory one at hand

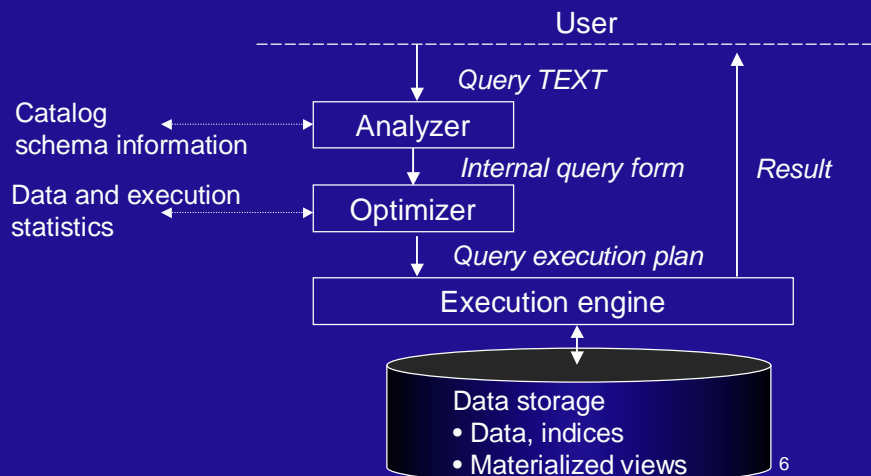
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Method followed in the sequel

- Outline a realistic architecture
 - Identify **components** and **interfaces**
- Study the interfaces and define ways to **combine the components**
- Use the above components as **building-blocks** for simple but realistic case studies

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DBMS architecture



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Recommended prototype design methodology

1. What is the component of interest (the one you want to study / implement / test) ?
2. Where would it fit into a functional system ? (What modules would it interact with ?)
3. Which of these interactions are interesting for you ?
4. How to get (satisfactory approximations of) the modules interacting with yours ?

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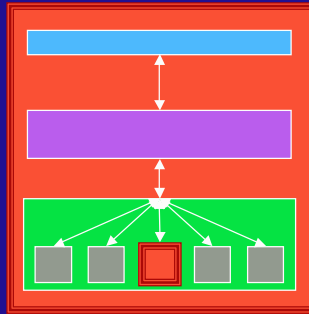
Identifying your target

- Already a good step in clarifying ideas
- A new component:
 - A new XML indexing technique
 - A new (physical) join operator
 - A new query plan enumeration algorithm
- Sometimes a whole system is sought (*framework* rather than *component*)
 - A generic framework for query optimization
 - A framework for distributed XML management
 - An XML benchmark

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Identifying your target

- Component vs. framework
 - software engineering issue, with a DB twist



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Identifying module interactions

- Start by considering an "ideal,complete" system architecture
- Your component interacts with others
 - XML index: storage manager, execution engine, query optimizer...
 - Join algorithm: execution engine, optimizer..
 - QEP enumerator: parser, storage and statistics descriptions...

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Identifying relevant module interactions

- Maybe the trickiest step
- Two ways out
 - Do it seriously:
build, or find, a real-life (complex, tested, documented) system, and build on it.
 - Intelligent pruning:
assume away a number of features, simulate or ignore them
 - Good enough for a paper
 - If you assume away too much, not even good for a paper

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Module interactions for an XML indexing technique

- **MUST CONSIDER**
 - a real, disk-based, persistent storage
 - an execution model
 - notions of an algebra
- **MAY IGNORE**
 - query parsing (query rewriting, view unfolding...)
 - transaction management (index locking ?)

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Module interactions for a new join algorithm

- **MUST CONSIDER**
 - A very precise execution model
 - Depending on the algorithm, memory management, or persistent storage of intermediary results
 - Notions of the optimizer
- **MAY IGNORE**
 - Storage management, query parsing, optimization details

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Module interactions for a QEP enumerator

- **MUST CONSIDER**
 - Query language expressive power
 - Storage description language / generality
 - Algebra
- **MAY IGNORE / abstract away**
 - Storage manager
 - Query execution engine
 - Cost model
(once characterized by assumptions)

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Getting the right components

- Finding existing components
 - In general: public domain tools with user groups tend to be solid (and sometimes complex)
 - Alternatively: academic prototypes with open source code are usually easy to understand (but not always work)
- Devising new ones
 - In general: text books + lots of programming
 - Alternatively: implementing algorithms suggested on research literature

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Part 2: A look into DBMS internals

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Query Parsing and Analyzing

1. Scan – identify basic language elements (tokens)
2. Parse – identify language structures
3. Analyze – check whether identifiers refer to existing objects, whether expressions are sound, and whether they are used correctly
4. Generate intermediate representation of the query

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Tokenizing

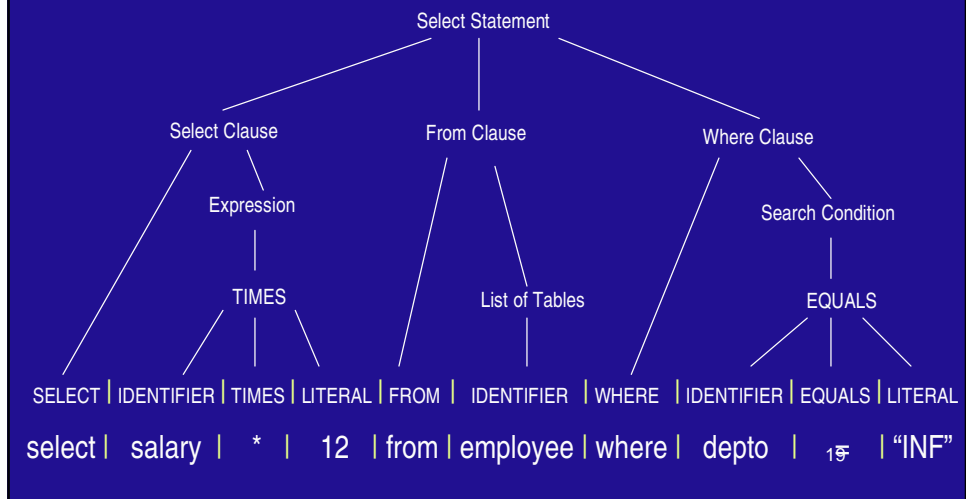
```
select salary*12  
from employee  
where depto="INF"
```



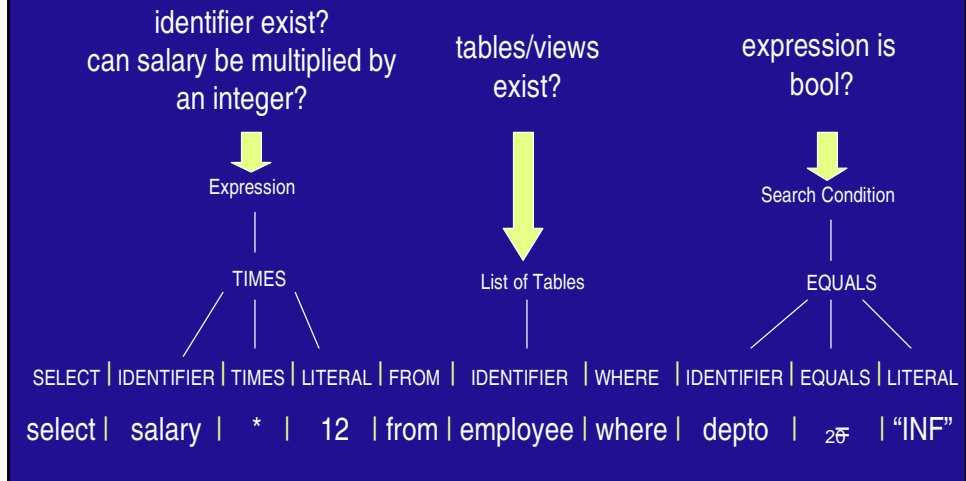
```
SELECT | IDENTIFIER | TIMES | LITERAL | FROM | IDENTIFIER | WHERE | IDENTIFIER | EQUALS | LITERAL  
select | salary | * | 12 | from | employee | where | depto | = | "INF"
```

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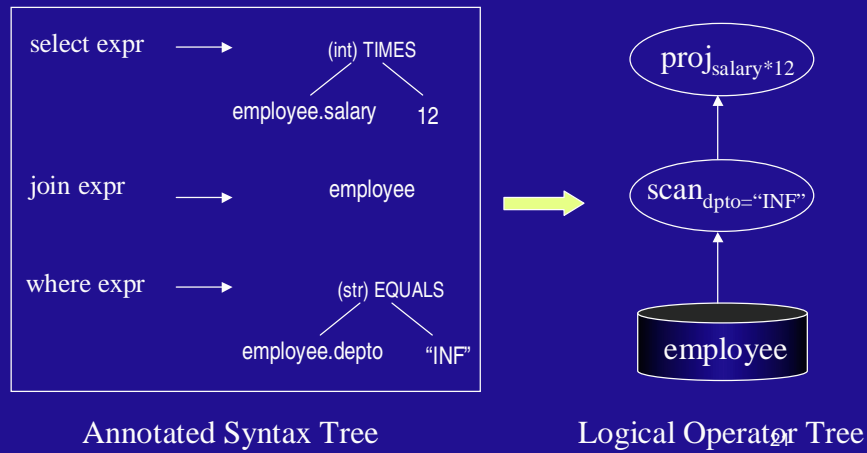
Parsing



Analyzing (Type Checking)



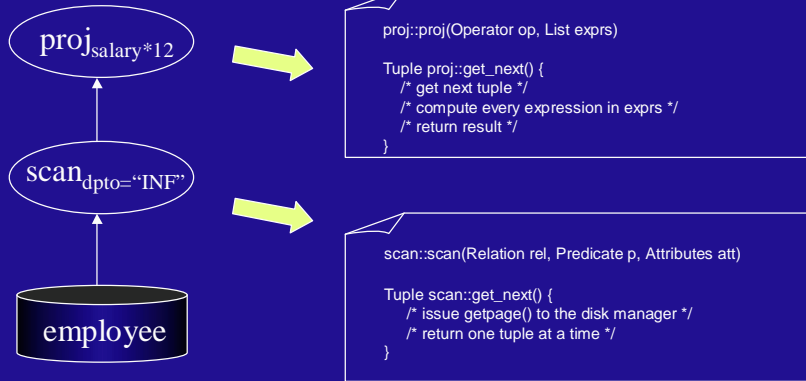
Intermediate Representation



Query Execution

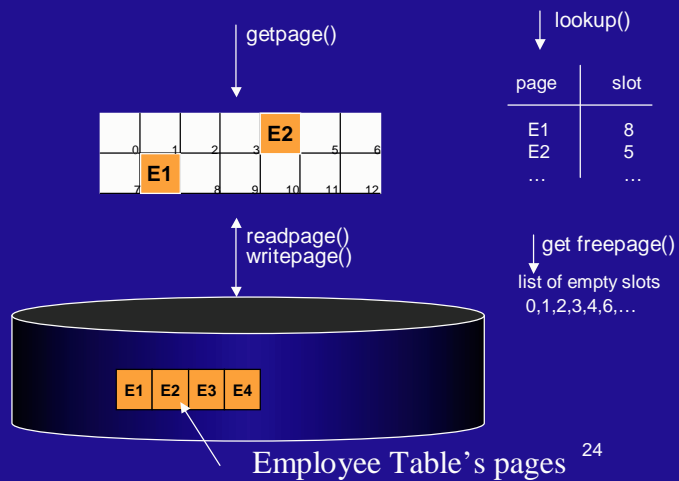
1. Plan Generation - transform the intermediate representation into an executable plan
2. Plan Execution – carry on the steps that the plan determines

Plan Generation

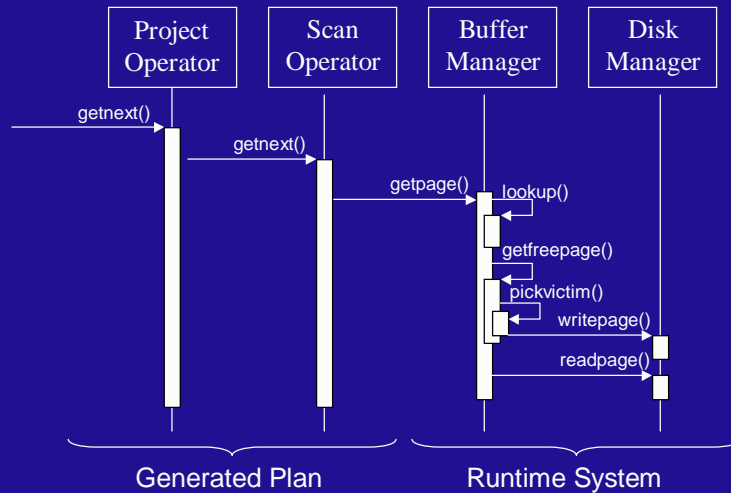


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Buffer and Storage Manager



Plan Execution



More Complex Queries

- The order of operators in an optimal plan may not resemble that of the query text
- Several possibilities of Query Optimization
 - Choosing more efficient access paths
 - Reducing the size of intermediate results
 - Choosing among several algorithms for a given operator

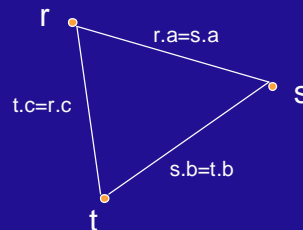
Query Optimizing

1. Internal representation now stores a graph of the relations involved
2. Optimization tries to order the operations in the graph in the best possible way
3. The best algorithms are chosen for each operation

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Query Graphs

```
select ...  
from r,s,t  
where r.a = s.a  
and s.b=t.b  
and t.c=r.c
```



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Dynamic Programming Enumeration

- Start by choosing the best way to access each relation
- Then the best way to join every pair of relation
- Then the best way to join each pair with the third relation
- At each step, keep only the best performing alternative (and those that have “interesting orders”)

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Dynamic Programming Enumeration

Best way to join with third relation	$r \bowtie s \bowtie t$	$r \bowtie t \bowtie s$	$s \bowtie t \bowtie r$
Best way to join two relations	$r \bowtie s$	$r \bowtie t$	$s \bowtie t$
Best access path to a single relation	r	s	t

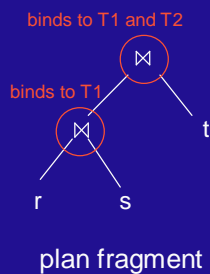
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Transformation-Based Enumeration

- A transformation is a triple $\langle \text{pattern}, \text{condition}, \text{substitution} \rangle$
- **Pattern** is a sub-tree with wildcards to be matched to the plan
- Once a pattern is bound to the plan, the **condition** is tested
- If the condition passed the **substitution** is done
- Repeat the cycle

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Transformation-Based Enumeration



	Pattern	Condition	Substitution
T1 join commutativity		true	
T2 join associativity		* joins ***	

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Cost Model

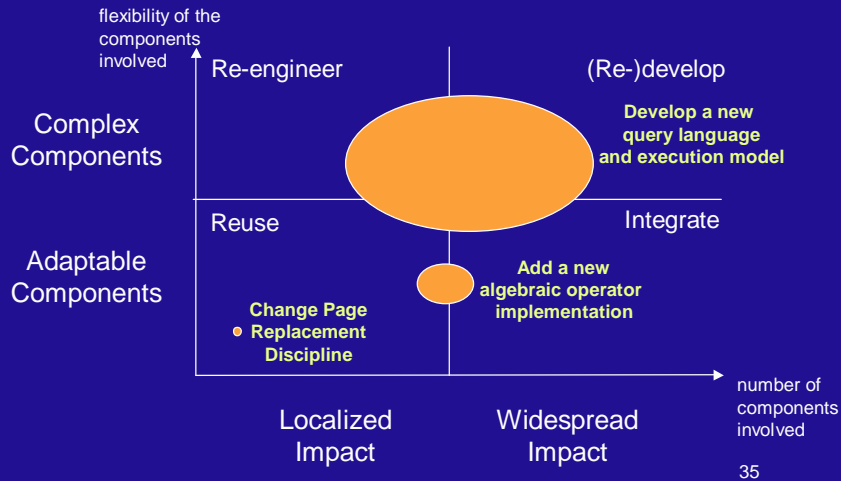
- Estimates work and cardinality of the results for each operation
- Most difficult aspect of optimization (tens of thousands of code lines in commercial products)
- Very prone to errors because of estimates made over estimates

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Part III: Case Studies
(Please, do try this at home!)

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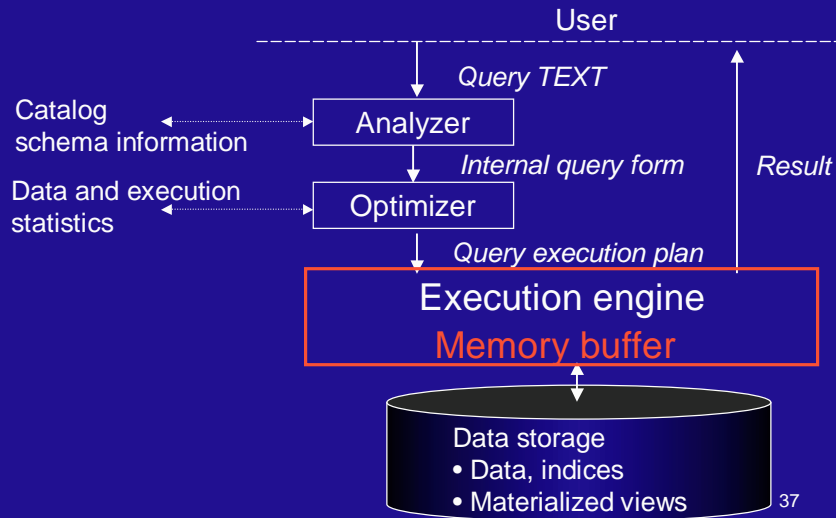
What if I wanted to...



Case 1

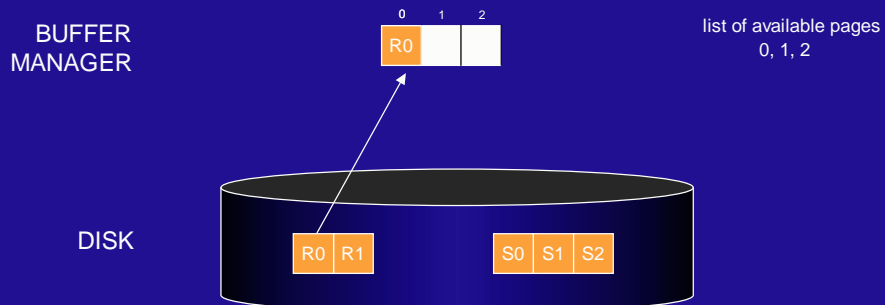
- Problem - LRU discipline may give poor cache hits
- Solution - Replace LRU discipline by MRU
- Implementation - Localized change in existing component of PostgreSQL

DBMS architecture



Problem

- Relation R being scanned



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Problem

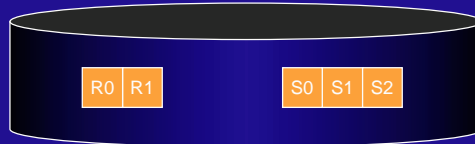
- Relation R being scanned

BUFFER
MANAGER



list of available pages
~~0~~, 1, 2

DISK

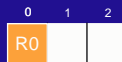


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Problem

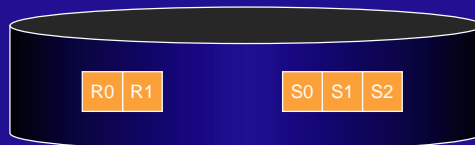
- Relation R being scanned

BUFFER
MANAGER



list of available pages
1, 2, 0
LRU

DISK



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Problem

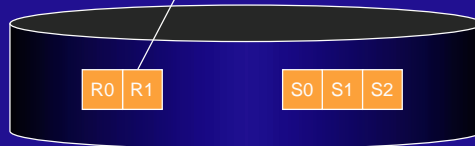
- Relation R being scanned

BUFFER
MANAGER



list of available pages
~~X~~ 2, 0

DISK



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Problem

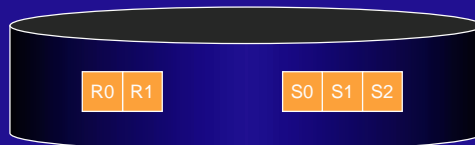
- Relation R being scanned

BUFFER
MANAGER



list of available pages
2, 0, 1

DISK



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Problem

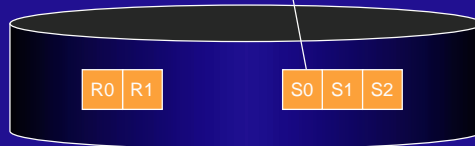
- Relation **S** having statistics updated

BUFFER
MANAGER



list of available pages
~~0, 1~~

DISK



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Problem

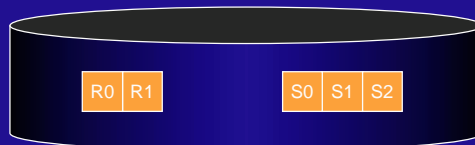
- Relation **S** having statistics updated

BUFFER
MANAGER



list of available pages
0, 1, 2

DISK

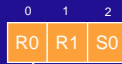


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Problem

- Relation S scan steals R's pages! What if R is accessed again?

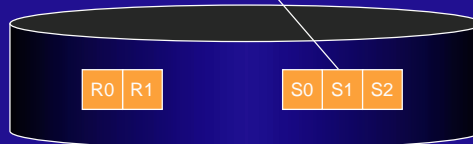
BUFFER
MANAGER



list of available pages

0, 1, 2

DISK



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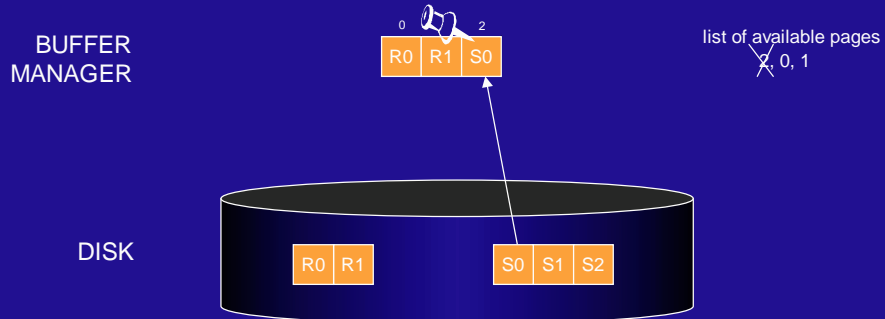
Most Recently Used Page Replacement

- If S won't likely be scanned again, why is it stealing pages from R?
- Utilities such as statistics gathering could use MRU replacement
- In some cases big repeated scans can do too, so to avoid buffer flooding

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Statistics using MRU

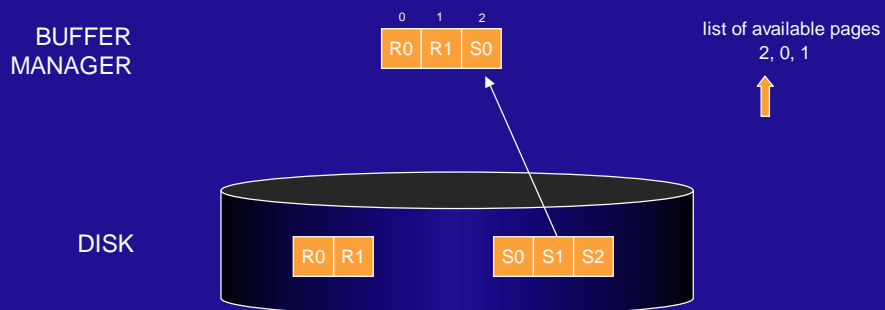
- When page S0 gets unpinned, the buffer #2 will be put in front of the available list



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Statistics using MRU

- When page S0 gets unpinned, the buffer #2 will be put in front of the available list



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Implementation Ingredients

- PostgreSQL
 - Open source database
 - Big user (and development) community
 - Complete implementation:
 - Fairly complete SQL 92
 - Concurrency
 - Recovery
 - Transactions

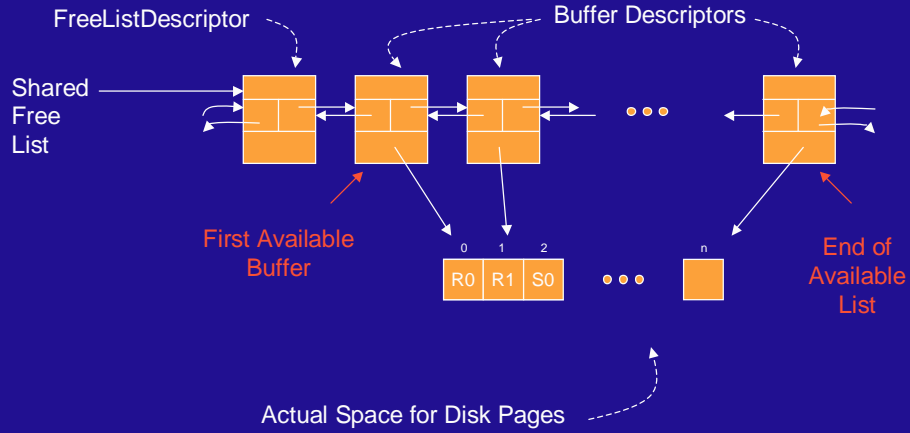
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PostgreSQL Resources

- Download Sources
 - www.postgresql.org
- Development Documentation
 - developer.postgresql.org
- Discussion List for Developers
 - pgsql-hackers

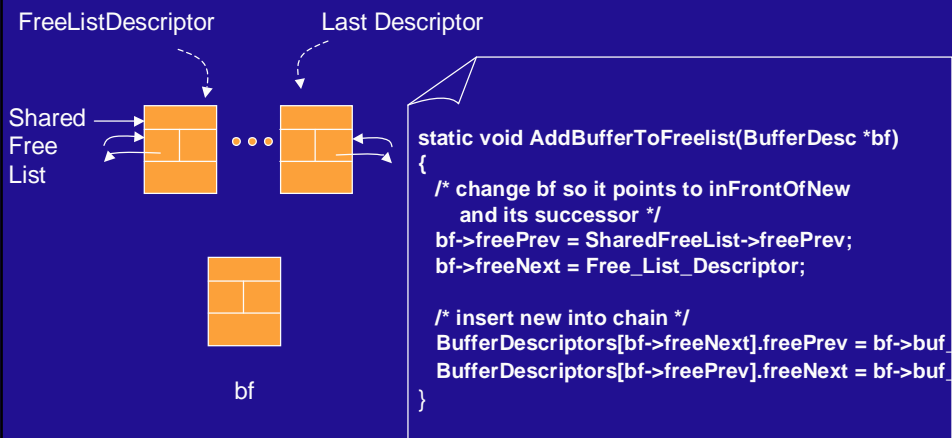
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PostgreSQL Buffer Manager



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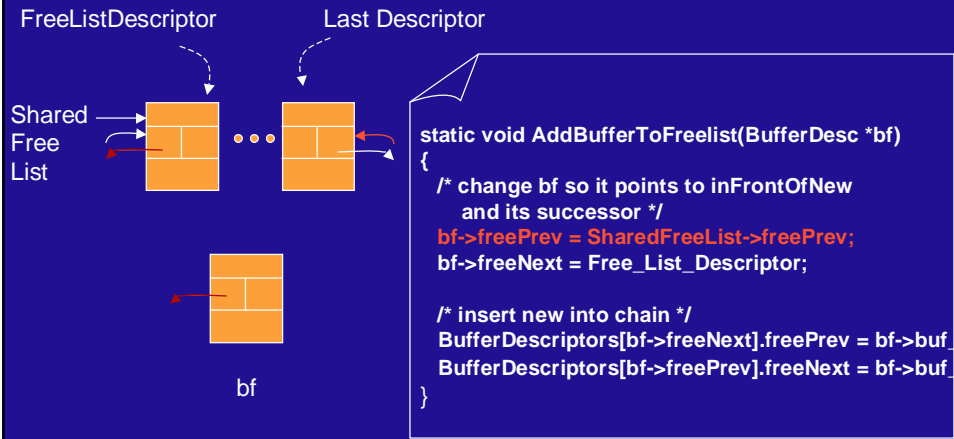
Adding a Buffer



/src/backend/storage/buffer/freelist.c

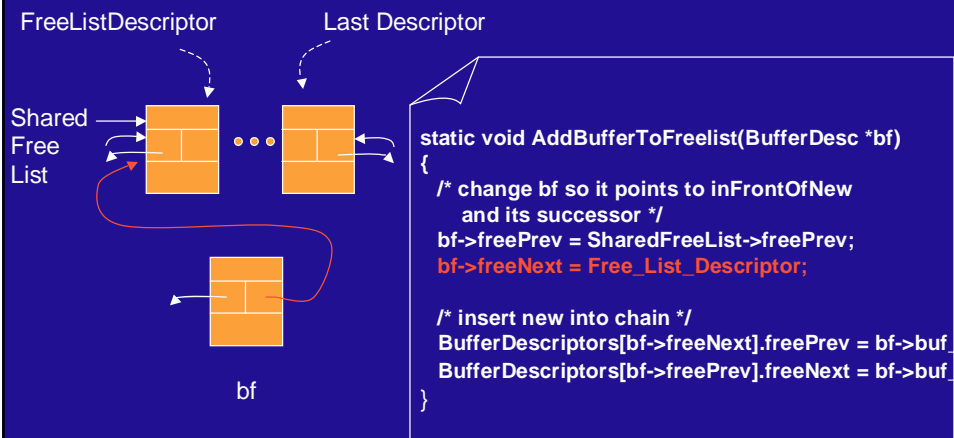
52

Adding a Buffer



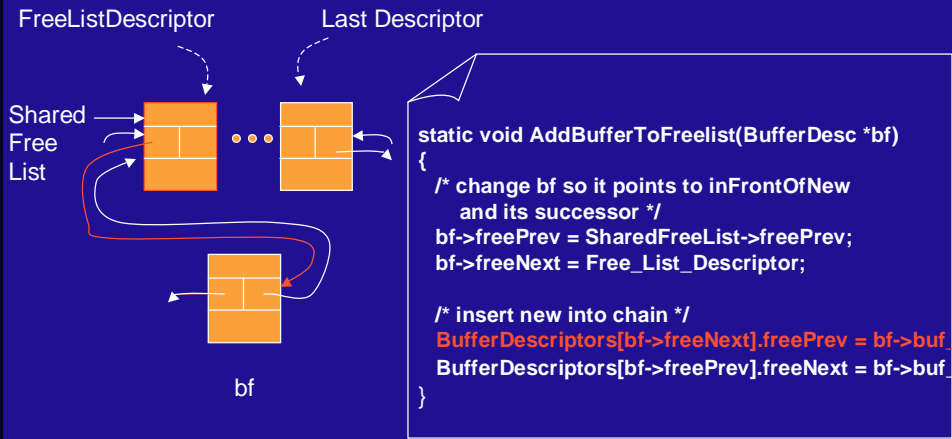
53

Adding a Buffer



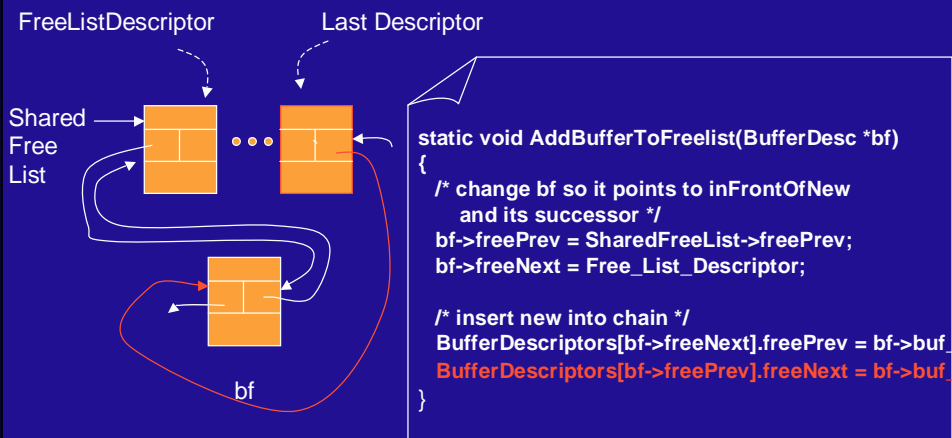
54

Adding a Buffer



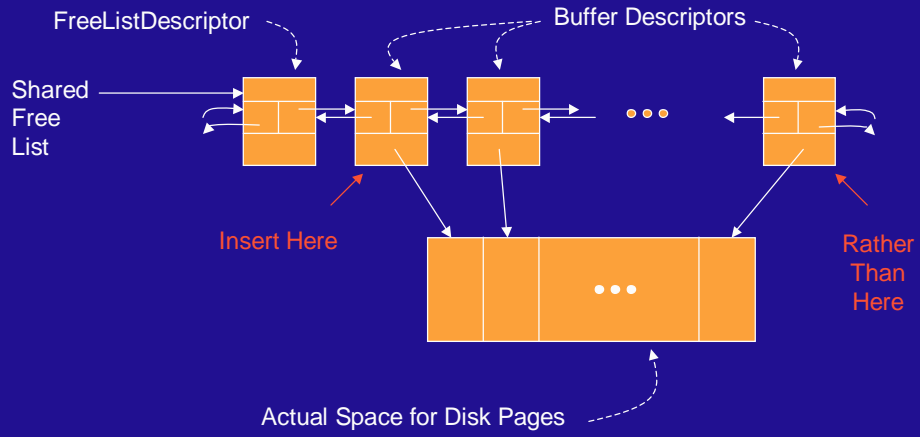
55

Adding a Buffer



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Implementing MRU



DEMO

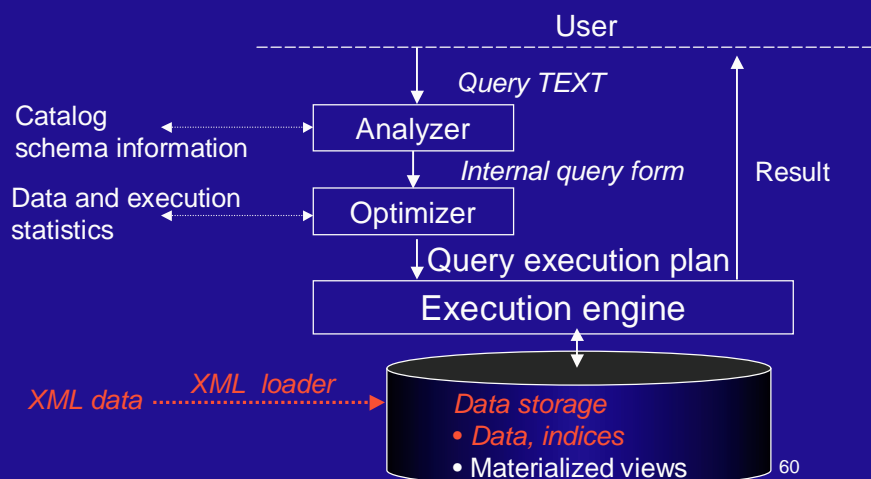
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Case 2

- Problem – build a simple **persistent XML storage system**
- Solution: use an embedded database library and customize storage structures

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Simple XML storage system



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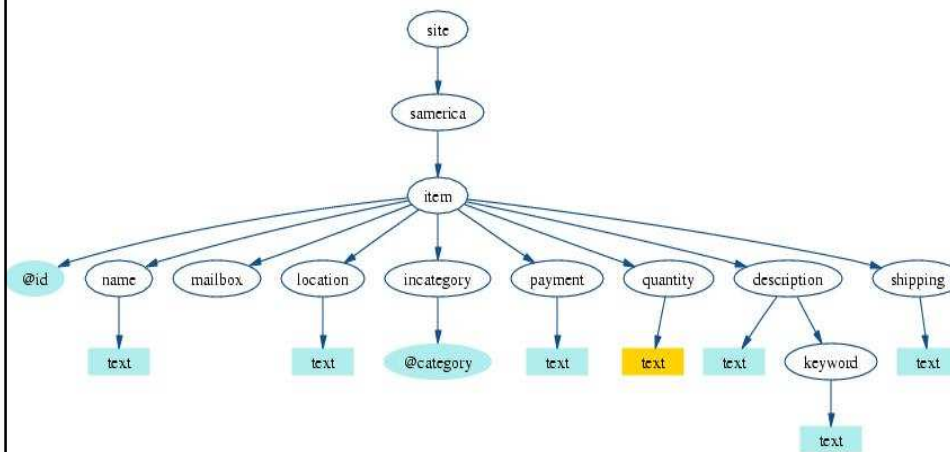
XML documents are data trees

Snippet of XML data (auction site) generated for the XMark benchmark:
<site>

```
<samerica>  
  <item id="item6">  
    <location>UnitedStates</location> <quantity>1</quantity>  
    <name>chair</name>  
    <payment>Creditcard, Cash</payment>  
    <description>nice<keyword>wooden</keyword>  
      window</description>  
    <shipping>See description for charges</shipping>  
    <incategory category="category0" />  
    <incategory category="category1" />  
    <mailbox />  
  </item>  
</samerica>  
</site>
```

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XML documents are data trees



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Simple data and storage model for XML

1. Add unique identifiers to all XML nodes

```

1 <site>
2 <samerica> 4
3 <item id="item6">
4   5 <location>UnitedStates</location> 6<quantity>1</quantity>
5   7 <name>chair</name>
6   8 <payment>Creditcard, Cash</payment>
7   9 <description>nice 10<keyword>wooden</keyword>
8     chair</description>
9   11 <shipping>See description for charges</shipping>
10  12<incategory category="category0" /> 13
11  14<incategory category="category1" /> 15
12  16<mailbox />
13 </item>
14 </samerica>
15 </site>

```

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Simple data and storage model for XML

2. Separate tree structure (edges) from tree values (leaves)

Edge(pID, tag,	cID, attr)	Value(id, val)
- site	1	3 "item6"
1 samerica	2	5 "United States"
2 item	3	6 "1"
3 id	4 X
2 name	5	9 "nice" "chair"
.....	10 "wooden"
2 description	9	
9 keyword	10	
.....	

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Simple data and storage model for XML

3. Many variants exist

Simple variant: partition by tag

Edge(pID, tag,	cID, attr)	Value(id, val)
- site	1	3 "item6"
1 samerica	2	5 "United States"
2 item	3	6 "1"
3 id	4 X
2 name	5	9 "nice" "chair"
.....	10 "wooden"
2 description	9	
9 keyword	10	
.....	

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Simple data and storage model for XML

A small step forward: indexing elements by their content

Edge(pID, tag,	cID, attr)	Value(id, val)
- site	1	3 "item6"
1 samerica	2	5 "United States"
2 item	3	6 "1"
3 id	4 X
2 name	5	
.....	

Index `<item>` elements by their @id value

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Implementation of a simple storage system for XML

- We need
 - An XML parser
 1. Give unique IDs to XML nodes
 2. Separate structure from content
 - A storage for
 - One edge sequence per tag
 - ID-value pairs
 - Indices (e.g., B+trees)

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Implementation of a simple storage system for XML

- We need
 - An XML parser org.apache.xerces
 1. Give unique IDs to XML nodes [you do it](#)
 2. Separate structure from content [you do it](#)
 - A storage BerkeleyDB www.sleepycat.com
 - One edge sequence per tag [use BerkeleyDB](#)
 - ID-value pairs [use BerkeleyDB](#)
 - Indices (e.g., B+trees) [use BerkeleyDB](#)
[B+trees](#)

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Parsing and loading XML documents

```
import org.apache.xerces.parsers.*;
public class myParser extends DefaultHandler implements
    Parser {
    .....
    XMLReader saxP = new SAXParser();
    saxP.setContentHandler(this);
    saxP.parse(XMLDocName);
    .....
    public void startElement(String nsURI, String tag,
        String qName, Attributes attrs){
        // give it a number (unique ID), push on the stack
        // record the attributes
        // record the edge connecting to its father
    }
}
```

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Parsing and loading XML documents

```
import org.apache.xerces.parsers.*;
public class myParser extends DefaultHandler
    implements Parser {
    .....
    public void characters(char[] buffer, int start, int end){
        // record the characters as composing a value
        // record the edge connecting to the stack top
    }
    public void endElement(String nsURI, String IName,
        String qName) {
        // pop the stack
    }
}
```

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Loading XML data and structure into a persistent storage

- BerkeleyDB: embedded storage library
- Offers Java/C++ API for storing **items** in **databases** by **keys**
 - An item is a sequence of bytes
 - A key is a sequence of bytes
 - A database is a collection of (key, item) pairs
- Four database types:
 - B+ tree
 - Queue (fixed length)
 - Hashtable
 - RecordNumber (var. length)

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Loading XML data and structure into a persistent storage

- Four Berkeley DB database types:
 - B+ tree
 - Queue (fixed length)
 - Hashtable
 - RecordNumber (var. length)
- What do we need ?
 - Queue databases for edge sequences
 - One for edges starting in /site/samerica/item elements
 - RecordNumber databases for values
 - One RecordNumber database for /site/samerica/item/@id values
 - B+ tree indices on item IDs by item/@id value
 - One B+ tree database with (item/@id, item ID) pairs⁷²

Loading element identifiers into BerkeleyDB

```
import com.sleepycat.db.*;
.....
Db myDb = new Db();
myDb.open(null, "dataFile0", "item", Db.DB_QUEUE,
// transaction, data file name, database name, database type
      Db.DB_WRITE|Db.DB_CREATE, 644, 4);
//          operation flags, access rights, item length
.....
IntDbt myID = new IntDbt(elementID);
// IntDbt extends Dbt (wrapper BDB class for items and keys)
IntDbt myKey = new IntDbt(crt);
myDb.put(myKey, myID);
```

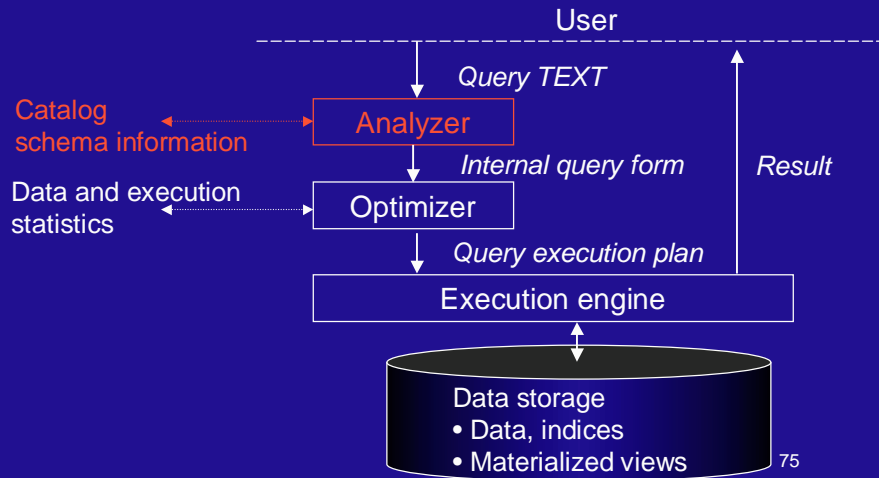
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Case 3

- Problem – AQuery language works with array data types and array expressions that need to be checked
- Solution – Create type checker for the language
- Implementation - Use parser generation tools and integrate type checker

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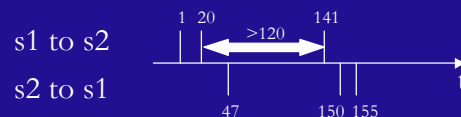
DBMS architecture



Motivational Query

- Create a log of flow information. A flow from src to dest ends after a 2-minutes silence
- Grouping by source and destination alone does not do the job

Packets	src	dst	len	time
	s1	s2	250	1
	s1	s2	270	20
	s1	s2	235	141
	s2	s1	330	47
	s2	s1	280	150
	s2	s1	305	155



AQuery in Pictures

Packets	src	dst	len	time
	s1	s2	250	1
	s1	s2	270	20
	s2	s1	330	47
	s1	s2	235	141
	s2	s1	280	150
	s2	s1	305	155

```
SELECT src, dst, count(*), avg(len)
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP BY src, dst, sums (deltas(time) > 120)
```

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AQuery in Pictures

Packets	src	dst	len	time
	s1	s2	250	1
	s1	s2	270	20
	s2	s1	330	47
	s1	s2	235	141
	s2	s1	280	150
	s2	s1	305	155

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SELECT src, dst, count(*), avg(len)
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       ASSUMING ORDER src, dst, time
GROUP BY src, dst, sums (deltas(time) > 120)
```

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AQuery in Pictures

Packets	src	dst	len	time	c1
	s1	s2	250	1	F
	s1	s2	270	20	F
	s1	s2	235	141	T
	s2	s1	330	47	F
	s2	s1	280	150	F
	s2	s1	305	155	F

```
SELECT src, dst, count(*), avg(len)
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP BY src, dst, sums (deltas(time) > 120)
```

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AQuery in Pictures

Packets	src	dst	len	time	c1	c2
	s1	s2	250	1	F	0
	s1	s2	270	20	F	0
	s1	s2	235	141	T	1
	s2	s1	330	47	F	1
	s2	s1	280	150	F	1
	s2	s1	305	155	F	1

```
SELECT src, dst, count(*), avg(len)
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP BY src, dst, sums (deltas(time) > 120)
```

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AQuery in Pictures

Packets	src	dst	len	time	c1	c2
{	s1	s2	250	1	F	0
	s1	s2	270	20	F	0
{	s1	s2	235	141	T	1
{	s2	s1	330	47	F	1
	s2	s1	280	150	F	1
{	s2	s1	305	155	F	1

```

SELECT src, dst, count(*), avg(len)
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP BY src, dst, sums (deltas(time) > 120)
    
```

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AQuery in Pictures

Packets	src	dst	len	time
{	s1	s2	250	1
	s1	s2	270	20
{	s1	s2	235	141
{	s2	s1	330	47
	s2	s1	280	150
{	s2	s1	305	155

src	dst	len	time
s1	s2	[250,270]	[1,20]
s1	s2	[235]	[141]
s2	s1	[330,280,305]	[47,150,155]

```

SELECT src, dst, count(*), avg(len)
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP BY src, dst, sums (deltas(time) > 120)
    
```

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AQuery in Pictures

Packets	src	dst	len	time
{	s1	s2	250	1
	s1	s2	270	20
{	s1	s2	235	141
	s2	s1	330	47
{	s2	s1	280	150
	s2	s1	305	155

src	dst	len	time
s1	s2	[250,270]	[1,20]
s1	s2	[235]	[141]
s2	s1	[330,280,305]	[47,150,155]

src	dst	avg(len)	count(*)
s1	s2	260	2
s1	s2	235	1
s2	s1	305	3

```

SELECT src, dst, count(*), avg(len)
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP  BY src, dst, sums (deltas(time) > 120)
    
```

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Other Order Built-in Functions

- Firstn(n,col), Lastn(n,col)
 - Return a vector/array with the n first or n last elements

```

SELECT src, dest, avg(firstn(10,len))
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP  BY src, dst, sums (deltas(time) > 120)
    
```

- Non-size preserving functions may form invalid expressions

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Type-checking Problem

```
SELECT src, dst, count(*), avg(len)
FROM   Packets
       ASSUMING ORDER src, dst, time
GROUP BY src, dst, sums (deltas(time) > 120)
```

- How to make sure that expressions such as the one in the group clause are valid ?
 - Checking the type of 'time' is just the tip of the iceberg...checking size of vectors is also necessary.
 - Can sums() be applied to a result of deltas()?
 - Can sums() be applied to a result of firstn()?
 - Can those two expressions participate in a group by?

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Considering cardinality and dimension

- Type is actually a 3-tuple $\langle \text{cardinality}, \text{dimension}, \text{type} \rangle$
 - Type of column 'time' is $\langle \text{original-card}, 1, \text{integer} \rangle$ meaning that time did not suffer cardinality reduction, and that it is a vector (dimension 1) of integers
 - Type of deltas($\langle \text{original-card}, 1, \text{integer} \rangle$) is $\langle \text{original-card}, 1, \text{integer} \rangle$ meaning that the function is size-preserving and that it returns a vector of integers
 - Type of firstn(10, $\langle \text{original-card}, 1, \text{integer} \rangle$) is $\langle 10, 1, \text{integer} \rangle$
- Group by requires an expression that is $\langle \text{original-card}, ?, ? \rangle$ meaning that to every row of the table a value of group must be assigned

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Implementation Ingredients

- Scanner Generator
 - Flex
 - Given a collection of regular expressions, it generates code to tokenize any text accordingly
 - Very sophisticated, yet very simple to use
- Parser Generator
 - LLGEN (www.cs.vu.nl/~ceriel/LLgen.html)
 - Given a LL(1) grammar generates a recursive descent parser
 - Could have used yacc or bison (LALR parser generators) instead

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More Ingredients

- K (www.kx.com)
 - APL descendent very used in Wall Street
 - Very robust language for **manipulating vectors**
 - Very terse syntax
 - Somewhat long learning curve
 - Then why bother???
 - **Productivity, productivity, productivity**

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AQuery Scanner Definitions

```
...
AND                { return AQ_AND; }
AS                 { return AQ_AS; }
ASC                { return AQ_ASC; }
ASSUMING           { return AQ_ASSUMING; }
ASSUMING{spc}ORDER { return AQ_ASSUMING; }
BETWEEN           { return AQ_BETWEEN; }
DESC              { return AQ_DESC; }
DISTINCT          { return AQ_DISTINCT; }
EACH              { return AQ_EACH; }
FALSE             { return AQ_FALSE; }
FLATTEN           { return AQ_FLATTEN; }
FROM              { return AQ_FROM; }
GROUP{spc}BY      { return AQ_GROUPBY; }
...
```

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AQuery Parser Definitions

```
query_specification : { setctx(initqblk()); }
                    AQ_SELECT
                    { setsctx(SCTXSELECT); }
                    [ AQ_DISTINCT ]?
                    select_list
                    table_expression
                    [ AQ_EOC ]?
                    ;
select_list         : star_or_derived_column
                    select_list_tail
                    ;
...
derived_column     : value_expression
                    { appnexpr( POP, getctx(), getisctx()); }
                    ;
```

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D e m o

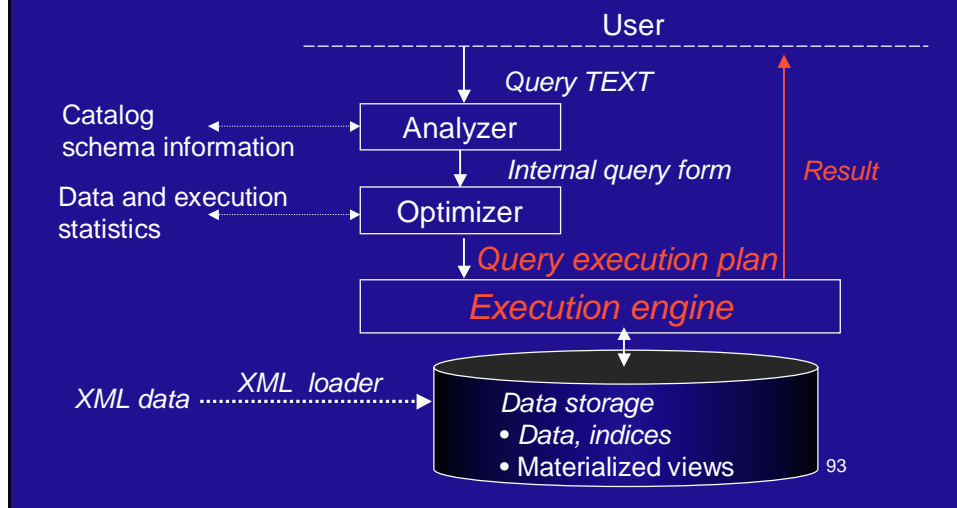
91

Case 4

- Problem – build a simple XML querying system
- Solution : use structural identifiers and twig joins
- Implementation – Develop join algorithm following classical interfaces

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Simple XML querying system



Simple XML querying system

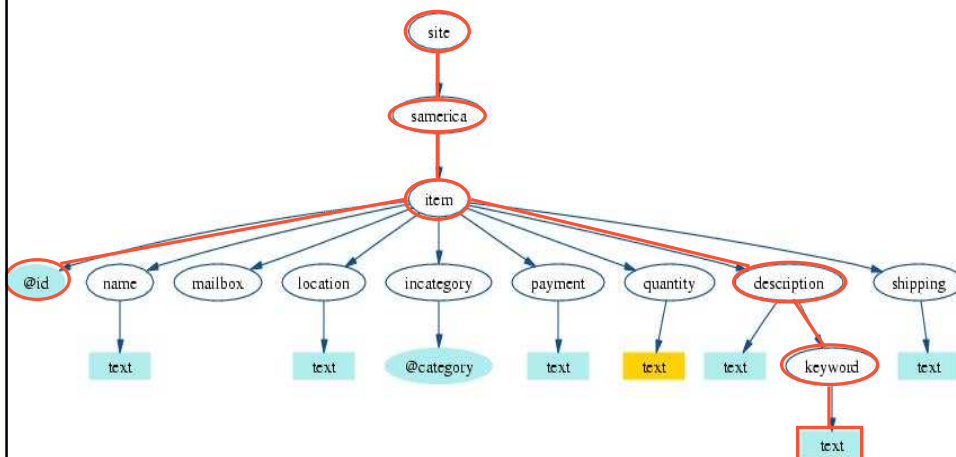
- Simple XML storage
 - The idea (already seen + revisited)
 - The implementation
- Performing XML tree traversals
 - The idea
 - The implementation

XML querying requires tree traversal

- For \$i in site/regions/samerica/item
 \$k in \$i//keyword
 return <artigo>
 <numero>\$i/@id/value()</numero>
 <keyword> \$k/text() </keyword>
 </artigo>
- Path traversals:
 - Site/regions/samerica/item
 - Site/regions/samerica/item/@id
 - Site/regions/samerica/item//keyword

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XML querying requires tree traversal



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Tree traversal requires joins

- We want:
all elements named "item",
whose parents have the tag "samerica",
whose parents have the tag "site"
- Select e3.cID
from Edge_{site} e1, Edge_{samerica} e2, Edge_{item} e3
where e1.cID=e2.pID and e2.cID=e3.cID

Edge_{item}

Edge_{samerica}

Edge_{site}

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Implementing tree traversals

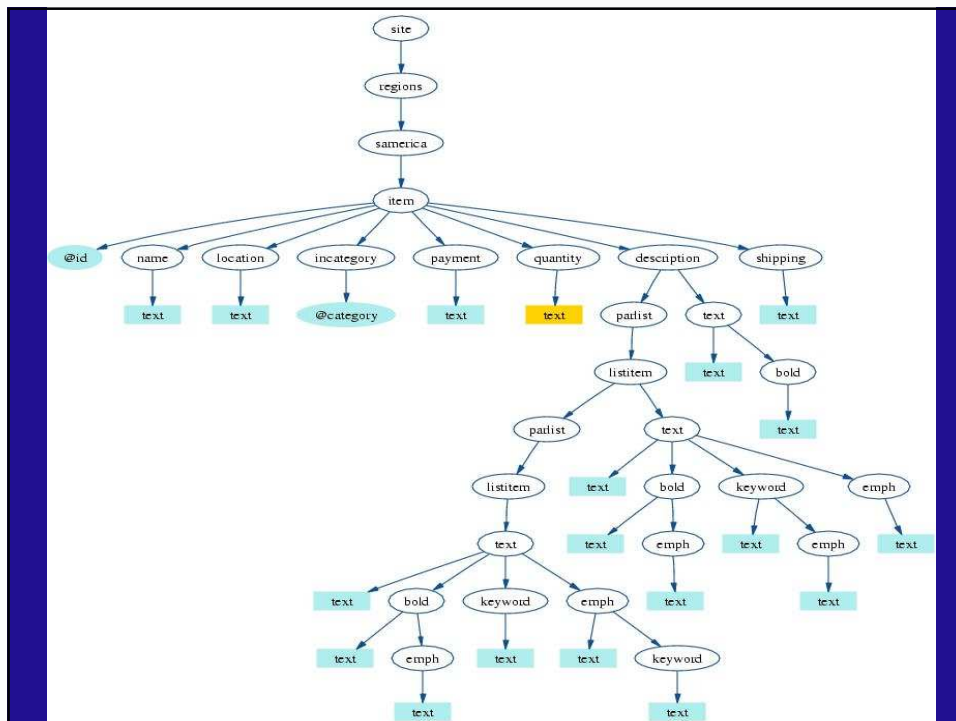
- site/samerica/item:
- Edge_{site} ⋈ Edge_{samerica} ⋈ Edge_{item}
– 3-way join...
- site/samerica/item/keyword/description
- Edge_{site} ⋈ Edge_{samerica} ⋈ Edge_{item} ⋈ Edge_{description} ⋈ Edge_{keyword}
– 5-way join...

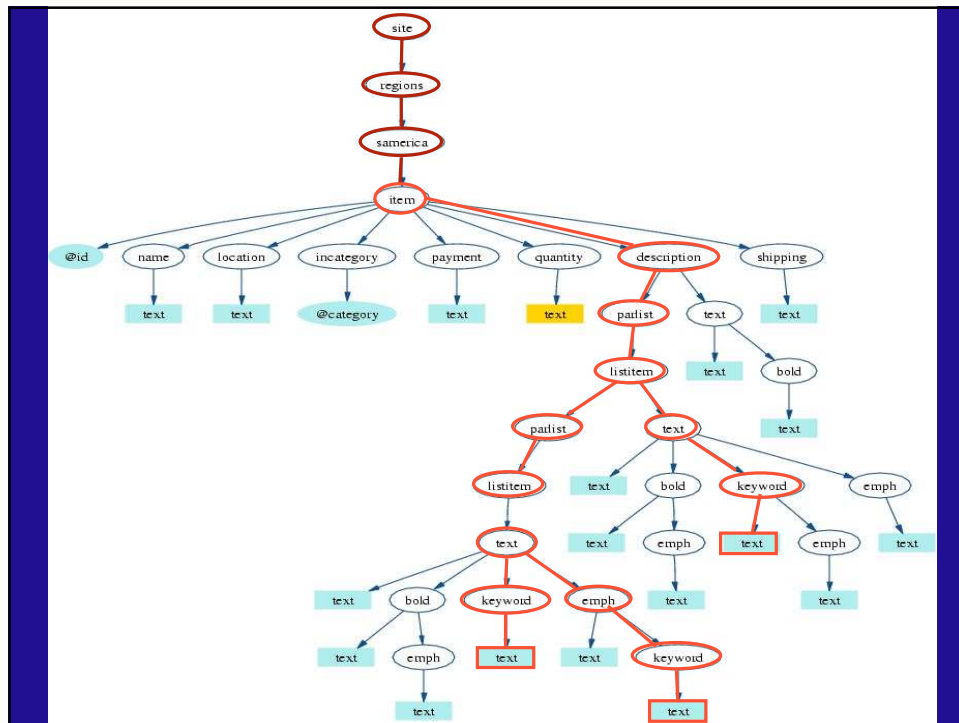
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What XML documents really look like

- A bigger fragment of an XMark-generated document (a very small one) on the next slide
- Real XMark generated documents also have
 - Asia, Australia, Europe, NAmerica, Africa
 - /site/people/person...
 - /site/catgraph/...
 - /site/open_auctions, /site/closed_auctions...

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Implementing real tree traversals

- Item//keyword requires in practice a union of
 - 7-way join
 - 8-way join
 - 10-way join
- A good moment for changing the strategy.

Solution: better unique identifiers for XML nodes

Structural identifiers (beginTagNo, endTagNo, depth)

```
[1 1 13]<site>
[2 2 12]<samerica>
[3 3 11]<item id="item6">
[4 4 1]<location>UnitedStates</location>[5 5 2]<quantity>1</quantity>
[6 4 3]<name>chair</name>
[7 4 4]<payment>Creditcard, Cash</payment>
[8 4 6]<description>nice [9 5 5] <keyword>wooden</keyword>
chair</description>
[10 4 7]<shipping>See description for charges</shipping>
[11 4 8]<incategory category="category0" />
[12 4 9]<incategory category="category1" />
[13 4 10]<mailbox />
</item>
</samerica>
</site>
```

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Structural identifiers and structural relationships

- Element x is an ancestor of element y iff:
 - $x.begin < y.begin$ and $x.end > y.end$
- Example:
 - Item [3 3 11] is an ancestor of location [4 4 1]
 - Location [4 4 1] is not an ancestor of keyword [9 5 5]
- Element x is the parent of element y iff:
 - $x.begin < y.begin$ and $x.end > y.end$
and $x.depth + 1 = y.depth$
- Example:
 - Item [3 3 11] is the parent of location [4 4 1]

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The interest of structural joins (2/2)

- One join establishes ancestor-descendent connections of **arbitrary length**
 - No need to store edges any longer, just IDs
- site/regions/samerica/item:
 $ID_{site} \bowtie ID_{site/regions/samerica/item}$
- site/regions/samerica/item//keyword:
 $ID_{site/regions.samerica/item} \bowtie (ID_{pathKeyword1} \cup ID_{pathkeyword2} \cup ID_{pathKeyword3})$

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Back to implementation

- Changing the data storage to use structural identifiers
 - Loader
 - Storage
- A simple execution engine for XML queries
 - PathAccess operator
 - Structural join
 - Value scan operator

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Parsing and loading, revisited with structural identifiers

```
import org.apache.xerces.parsers.*;
public class myParser extends DefaultHandler implements
    Parser {
    int depth;
    int endTagNo;
    .....
    XMLReader saxP = new SAXParser();
    saxP.setContentHandler(this);
    saxP.parse(XMLDocName);
    .....
    public void startElement(String nsURI, String tag,
        String qName, Attributes attrs){
        // give it a number [start, depth, end], push start
        // record the attributes; update depth
```

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Parsing and loading, revisited with structural identifiers

```
import org.apache.xerces.parsers.*;
public class myParser extends DefaultHandler
    implements Parser {
    .....
    public void characters(char[] buffer, int start, int end){
        // same as before
    }
    public void endElement(String nsURI, String IName,
        String qName) {
        // same as before; update depth
    }
}
```

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Loading XML data and structure, revisited with structural identifiers

- Four Berkeley DB database types:
 - B+ tree
 - Queue (fixed length)
 - Hashtable
 - RecordNumber (var. length)
- What do we need ?
 - Queue databases for ID sequences
 - One for IDs of /site/samerica/item elements
 - RecordNumber databases for values
 - One RecordNumber database for /site/samerica/item/@id values
 - B+ tree indices on item IDs by item/@id value
 - One B+ tree database with (item/@id, item ID) pairs¹¹¹

Implementing a simple execution engine

- Most frequently used model: iterators
 - Interface Iterator {
 - public void init();
 - public boolean hasNext();
 - public Tuple getNext();
 - }
- Model also used in java.util.Iterator, java.sql.ResultSet...

A three-operators execution engine

- **PathAccess(String path):**
 - Returns [ID] tuples, where ID is an element identifier
 - Tuples are sorted in increasing order of the start number
- **StructuralJoin(Iterator i1, Iterator i2, int col1, int col2)**
 - Joins the tuples from Iterator1 and Iterator 2 whenever i1[col1] is an ancestor of i2[col2]
- **ValueAccess(String path)**
 - Returns [ID, value] tuples, where ID is an element identifier, and value is a text value within such an element

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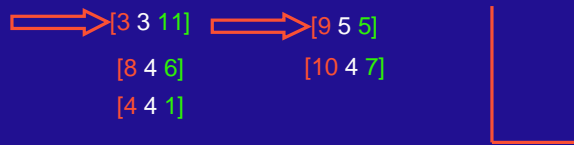
Implementing PathAccess

```
Public class PathAccess implements Operator{
    public PathAccess(String path) {
        Tuple currentTuple = null; boolean over = false; }
    Public void init() {
        /** open the database of elem. identifiers on path */ }
    Public boolean hasNext() {
        if (over) return false;
        try { currentTuple = db.get(..., Db.DB_NEXT, ...) }
        catch (Exception e) { over = true; return false; }
        return true; }
    Public Tuple getNext() { return currentTuple; }
    Public void close() { /** close the database */ }
```

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Implementing StructuralJoin

- Problem: hash-based joins won't work (no join key)
- Solution: stack-based algo on sorted inputs

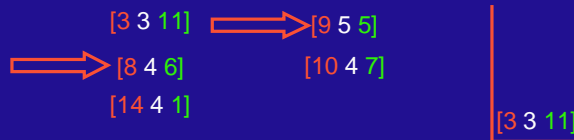


- Push successively all nodes from ancestor list
- Probe the stack with nodes from the descendent list
- Pop the stack when ancestors are "too old"

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Implementing StructuralJoin

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118

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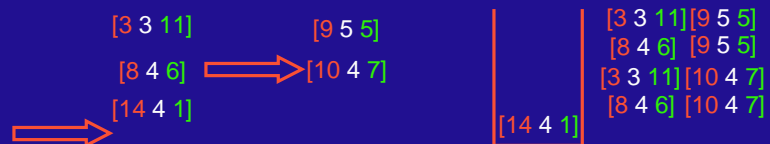


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119

Implementing StructuralJoin

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Implementing StructuralJoin

- Problem: hash-based joins won't work (no join key)
- Solution: stack-based algo on sorted inputs



- Push successively all nodes from ancestor list
- Probe the stack with nodes from the descendent list
- Pop the stack when ancestors are "too old"

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Short demo

- Loading an XML document
- QEP for joining /site/regions/samerica/item Ids with all their descendent keywords
- QEP for the query
*for \$i in site/regions/samerica/item, \$k in \$i//keyword
return <artigo>
 <numero>\$i/@id/value()</numero>
 <keyword> \$k/text() </keyword>
</artigo>*

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Simple extensions: XML indexing

- Indexing <items> by their @id:
 - Storing index entries at parsing time
 - From myParser.startElement(...)
 - Implementing a new index access physical operator
Public class indexAccess implements Iterator{... }
- Any XML indexing technique can be **implemented** and **tested** in a similar way

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Simple extensions: twig joins

- Twig joins: establish pattern relationships among several lists of node Ids *in a single join step*



- *Holistic twig joins*: improve the performance of twig joins by using B+ tree indices on ID lists

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Complex extension: query optimizer

- First choose the language
 - XPath may be too little, or too much
 - Full XQuery may be a little complex
- Example:

```
for $b in document("auction.xml")/
  site/people/person[id="person0"]
return $b/name/text()
```
- **Nice exercise** 😊

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Conclusions from building our simple system

- A simple framework can be extended in many ways
- Unless your XML research is limited to <1Mb documents, a persistent storage (even a simple one) is required in order to be plausible
 - Intelligent pruning goes a long way

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Part IV: (A non-exhaustive) Resource Directory

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Agenda

- Complete Public Source Systems
- Parser Generator Tools
- Storage Sub-systems
- Rapid Development Tools
- Generating or Obtaining Data
- Readings

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Relational Systems

- PostgreSQL (www.postgresql.org)
- MySQL (www.mysql.org)
- Predator
(www.cs.cornell.edu/database/predator)

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XML Systems

- Galax (db.bell-labs.com/galax/)
- XQEngine (www.fatdog.com)
- QizXOpen (www.xfra.net/qizxopen)
 - Storage is in files
- Rainbow (www.davis.wpi.edu)

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Stream Systems

- TelegraphCQ
(telegraph.cs.berkeley.edu)

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Storage Sub-systems

- BerkeleyDB (www.sleepycat.com)
- Shore (www.cs.wisc.edu/shore/)
- For XML problems, commercial or free-source *relational* systems may be provide *some* solutions

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Parsing Tools

- Flex
- Bison/Yacc
- LLgen
- JavaCC
- JJTree

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Rapid Development

- SWIG and Perl/Python
- “Exotic” languages
 - ML
 - K
- GraphViz for tree displaying and debugging
(www.research.att.com/tools/graphviz)

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Data generators

- Data generator of the TPC benchmarks (www.tpc.org)
- The XMark XML generator (monetdb.cwi.nl/xml/index.html)
- The ToxGene XML generator (www.cs.toronto.edu/tox/toxgene/)

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Data sources

- XML data sets at U. of Washington (www.cs.washington.edu/research/xml/datasets)
- Wharton Research Data Services (wrds.wharton.upenn.edu) finance data
- Click Stream Data (ask your web manager!)

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Readings

- If I could read one article in ... that would be ...
- Books
- Tutorials

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Query execution and optimization

- A. Silberschatz and H.Korth, "Principles of database systems", chapters on query execution and query optimization
<http://cs-www.cs.yale.edu/homes/avi/dbbook/>
 - Do read the complete examples
 - Slides are freely available
- Transformation-based optimization framework
 - Selinger, Astrahan, Lorie and Price. Access Path Selection in Relational Database Systems. SIGMOD 1979
 - G.Graefe, W.McKenna: The Volcano Optimizer Generator: Extensibility and Efficient Search, ICDE 1998

138

Adaptive (self-improving) query processing

- Entry point: survey

M. Hellerstein, M. J. Franklin, S. Chandrasekaran, A. Deshpande, K. Hildrum, S. Madden, V. Raman, and M. Shah. *Adaptive query processing: Technology in evolution*. IEEE Data Engineering Bulletin, 23(2):7--18, 2000

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Distributed query processing

- Complete overview:
 - P.Valduriez, T.Ozsu: "Principles of Distributed Database Systems", Prentice Halls, 1999
- Shorter, denser overview:
 - D. Kossmann: The State of the art in distributed query processing. [ACM Computing Surveys 32\(4\)](#): 422-469 (2000)
- Cost models for data integration frameworks
 - M.Roth, F. Ozcan, L.Haas: Cost Models DO Matter: Providing Cost Information for Diverse Data Sources in a Federated System. [VLDB 1999](#): 599-610

140

XML-on-relational

- J. Shanmugasundaram, E.Shekita, M.Carey, B.Lindsay, H.Pirahesh, B.Reinwald: Efficiently publishing relational data as XML documents. [VLDB Journal 10](#)(2-3): 133-154 (2001)
- J.Shanmugasundaram, J.Kiernan, E.Shekita, C.Fan, J.Funderburk: Querying XML Views of Relational Data. [VLDB 2001](#): 261-270
- D. DeHaan, D. Toman, M. Consens, T.Ozsu: A Comprehensive XQuery to SQL **Translation** using Dynamic Interval Encoding, SIGMOD 2003

141

Conclusion

- Yes, we have made the task of building database systems easier!
- Several research groups or public-source efforts produced components that can be reused
- A prototype may be able to take advantage of existing code and focus on its specific problem
- Careful design and understanding of current DBMS architecture are important
- The more experiments (and code) you produce, the easier it is to understand how other people's software works...

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