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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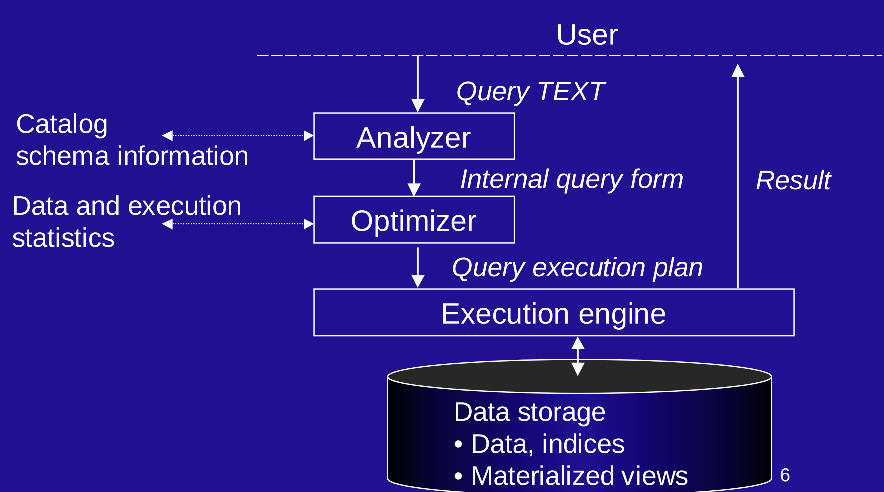
DBMS architecture



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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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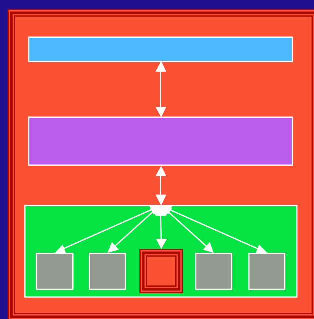
Identifying your target

- 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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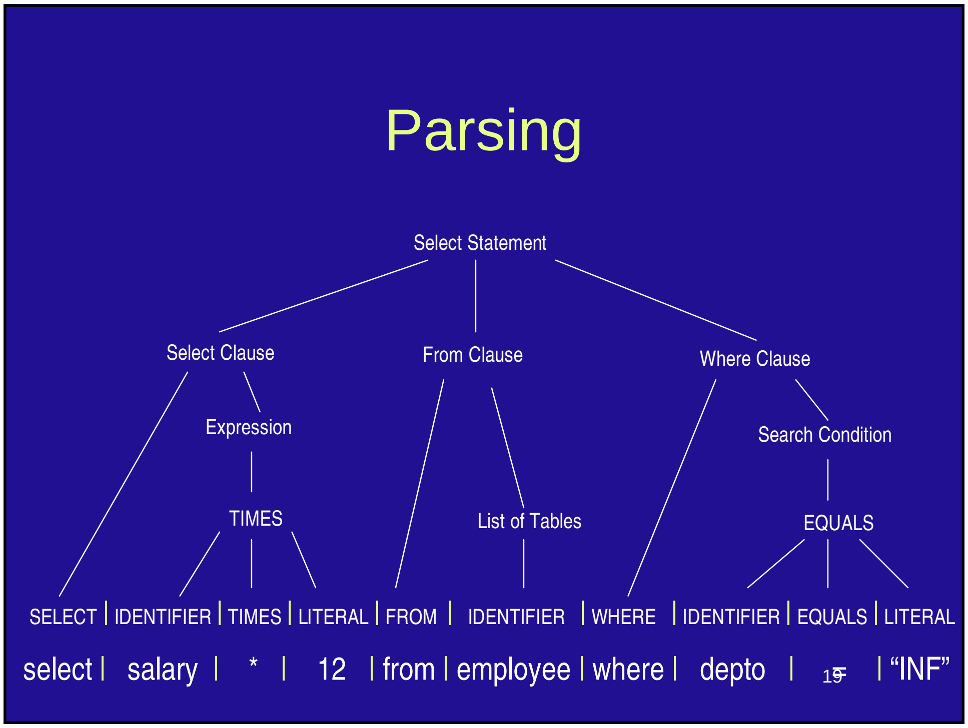
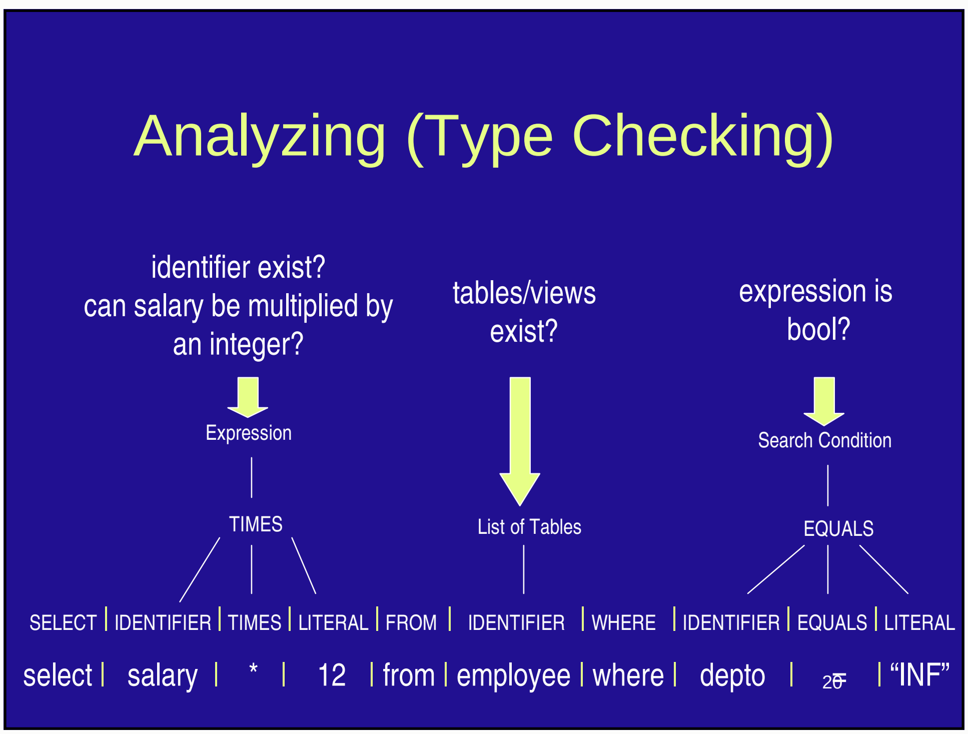
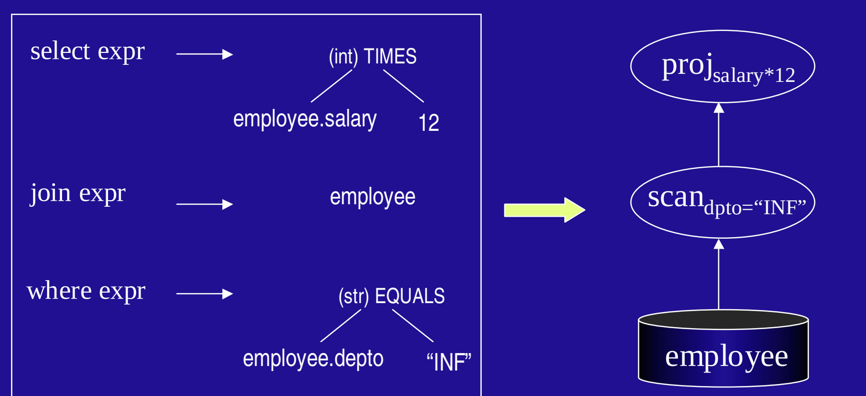

Parsing
Select Statement
Select Clause
From Clause
Where Clause
Expression
Search Condition
TIMES
List of Tables
EQUALS
SELECT | IDENTIFIER | TIMES | LITERAL | FROM | IDENTIFIER | WHERE | IDENTIFIER | EQUALS | LITERAL
select | salary | * | 12 | from | employee | where | depto | = | “INF”
19


Analyzing (Type Checking)
identifier exist?
can salary be multiplied by
an integer?
tables/views
exist?
expression is
bool?
Expression
Search Condition
TIMES
List of Tables
EQUALS
SELECT | IDENTIFIER | TIMES | LITERAL | FROM | IDENTIFIER | WHERE | IDENTIFIER | EQUALS | LITERAL
select | salary | * | 12 | from | employee | where | depto | = | “INF”
20

Intermediate Representation



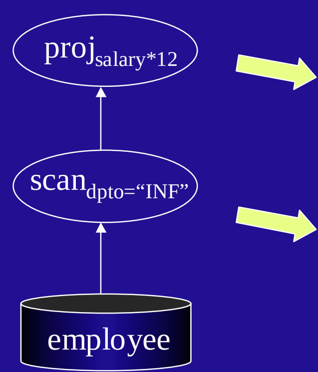
Annotated Syntax Tree

Logical Operator Tree

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




```
proj::proj(Operator op, List exprs)

Tuple proj::get_next() {
    /* get next tuple */
    /* compute every expression in exprs */
    /* return result */
}
```

```
scan::scan(Relation rel, Predicate p, Attributes att)

Tuple scan::get_next() {
    /* issue getpage() to the disk manager */
    /* return one tuple at a time */
}
```

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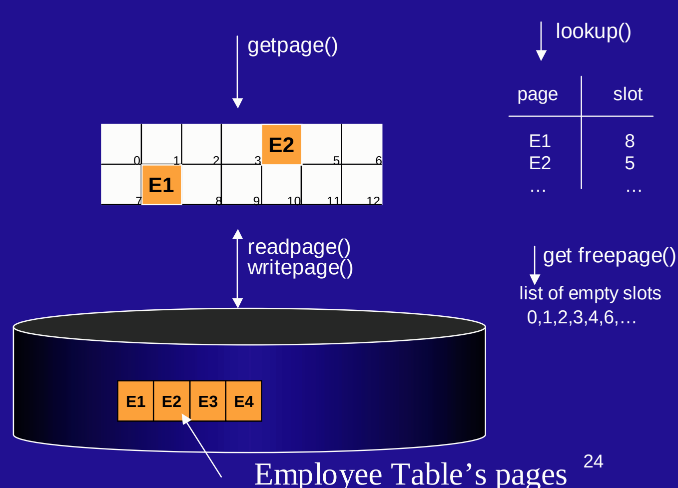
Buffer and Storage Manager



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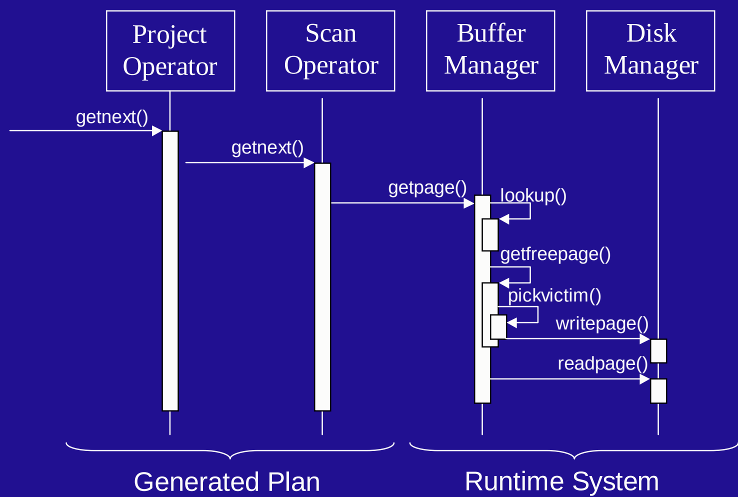
Plan Execution



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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

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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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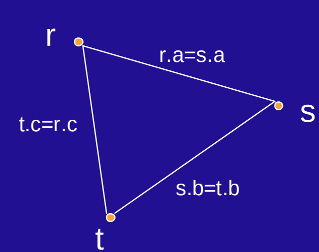
Query Graphs

```
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”)

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

Transformation-Based Enumeration

- A transformation is a triple <pattern, condition, substitution>
- 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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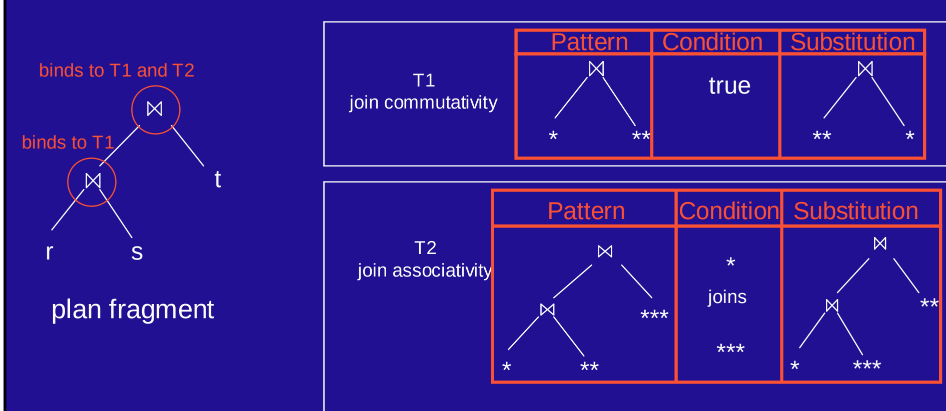
Transformation-Based Enumeration



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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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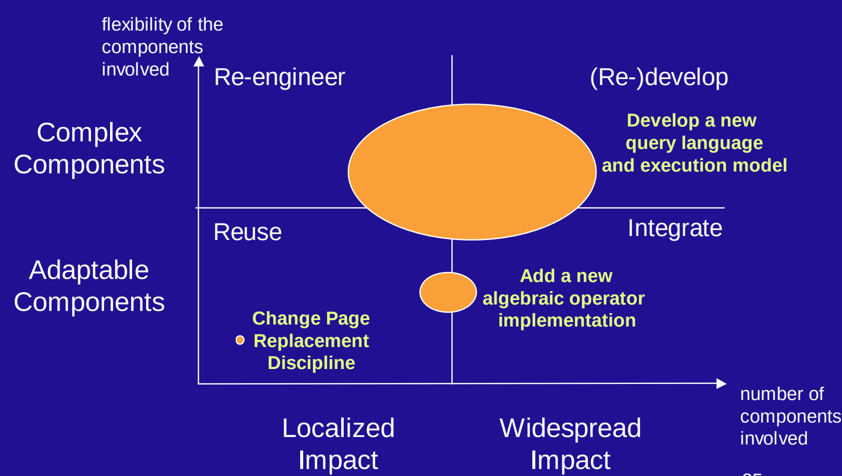
What if I wanted to…



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Case 1

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

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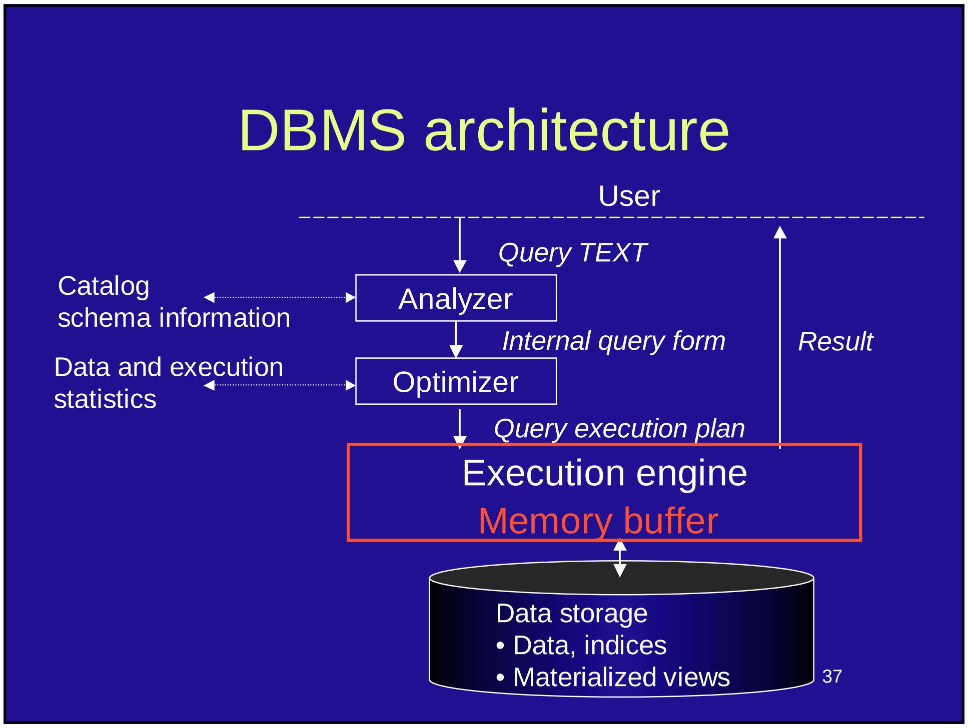
DBMS architecture
User
Query TEXT
Catalog
schema information
Analyzer
Internal query form
Result
Data and execution
statistics
Optimizer
Query execution plan
Execution engine
Memory buffer
Data storage
• Data, indices
• Materialized views
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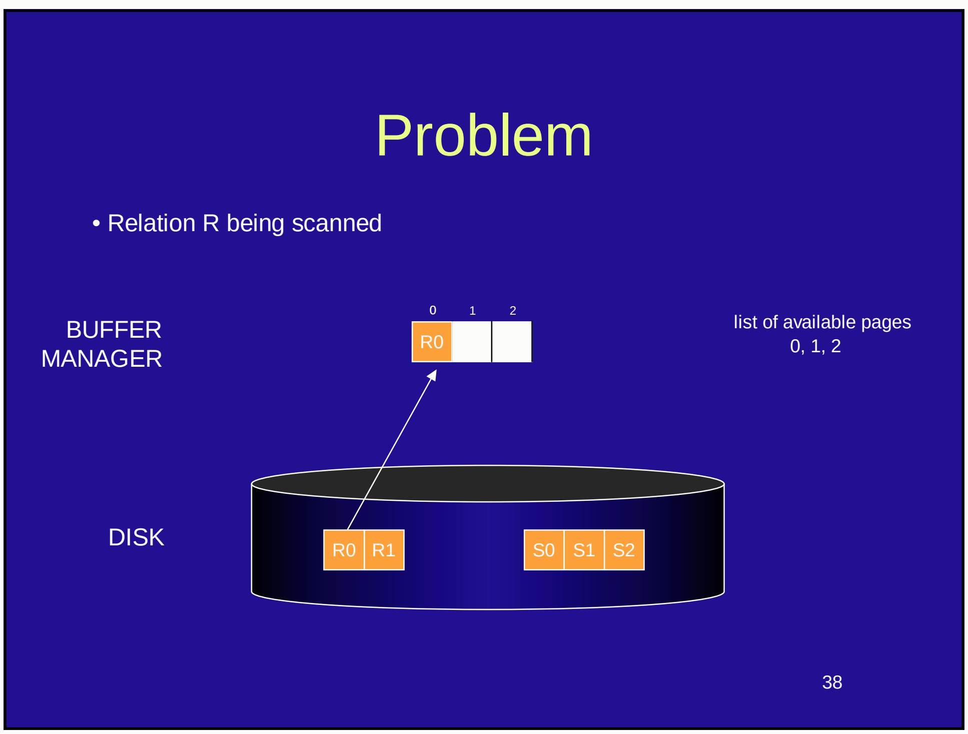
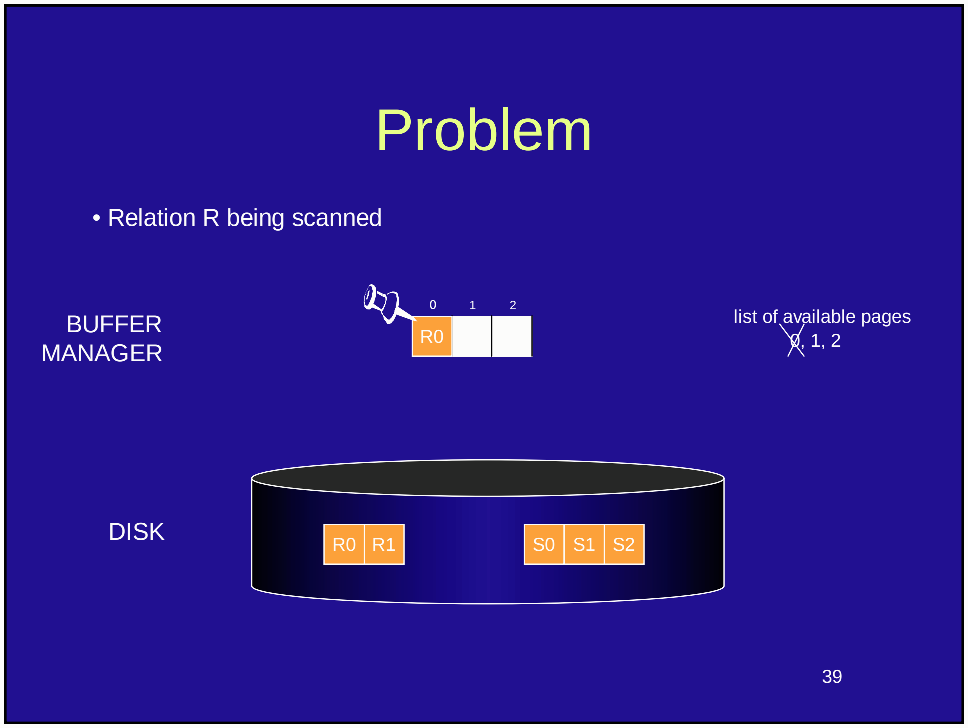
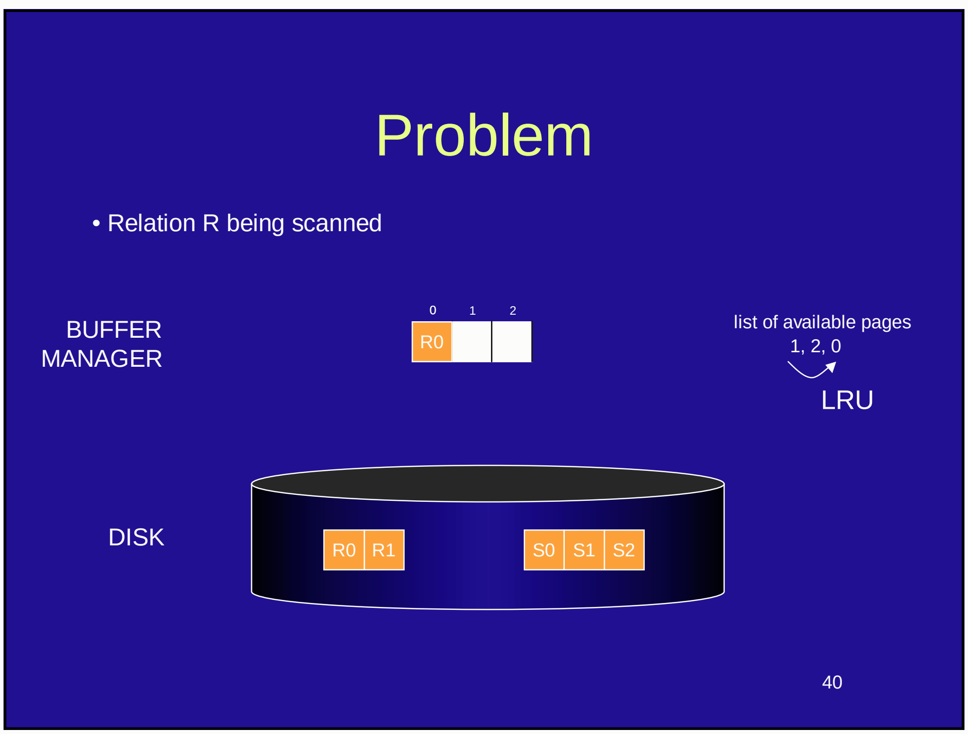
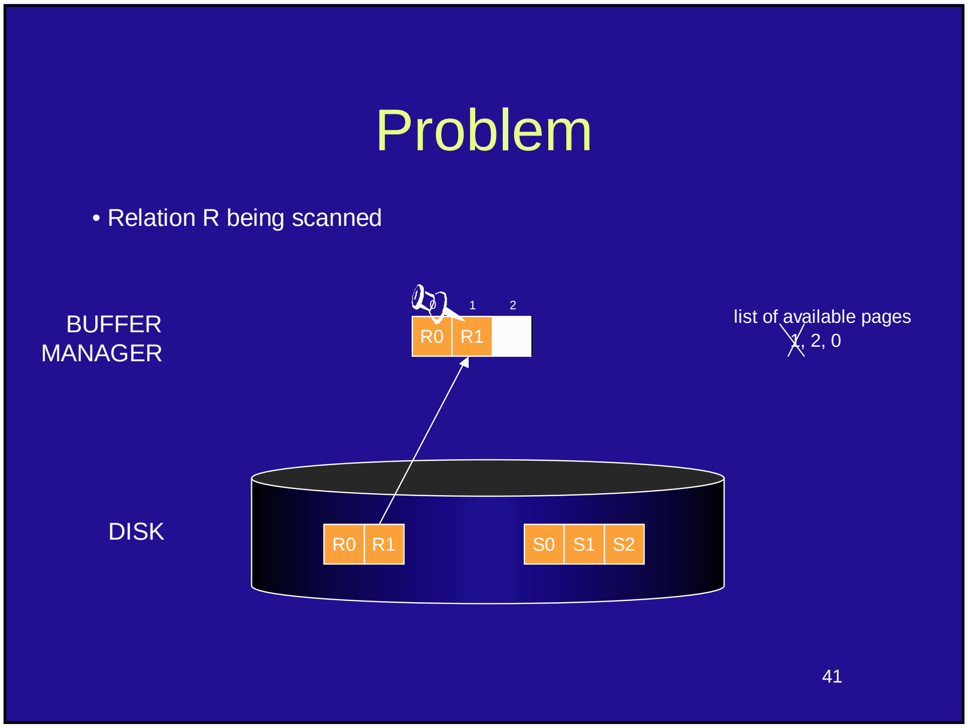
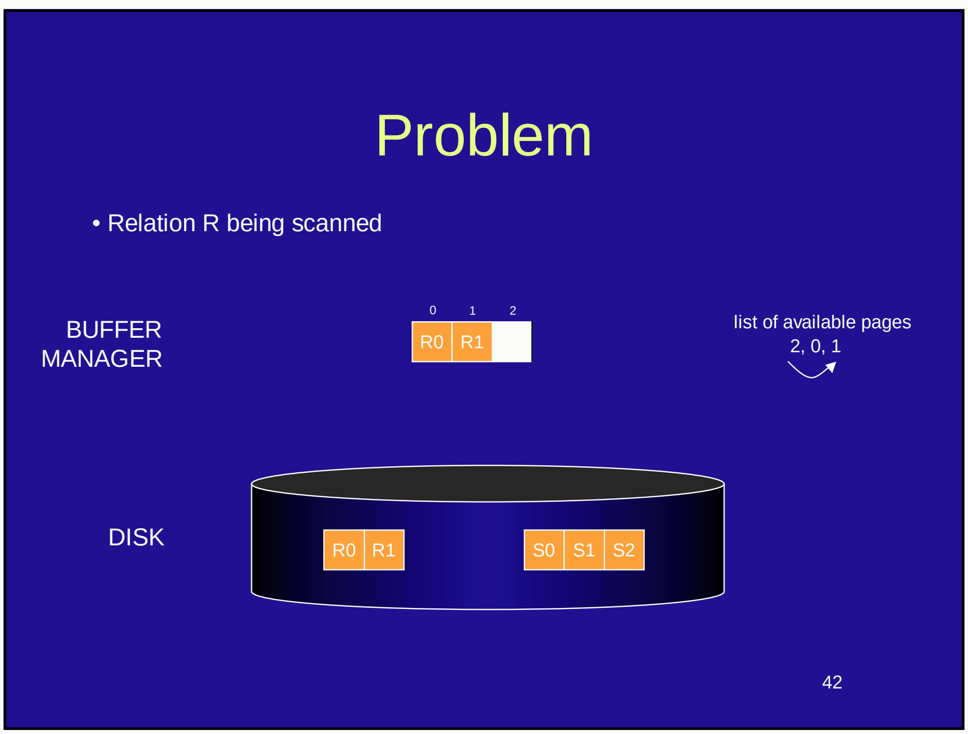
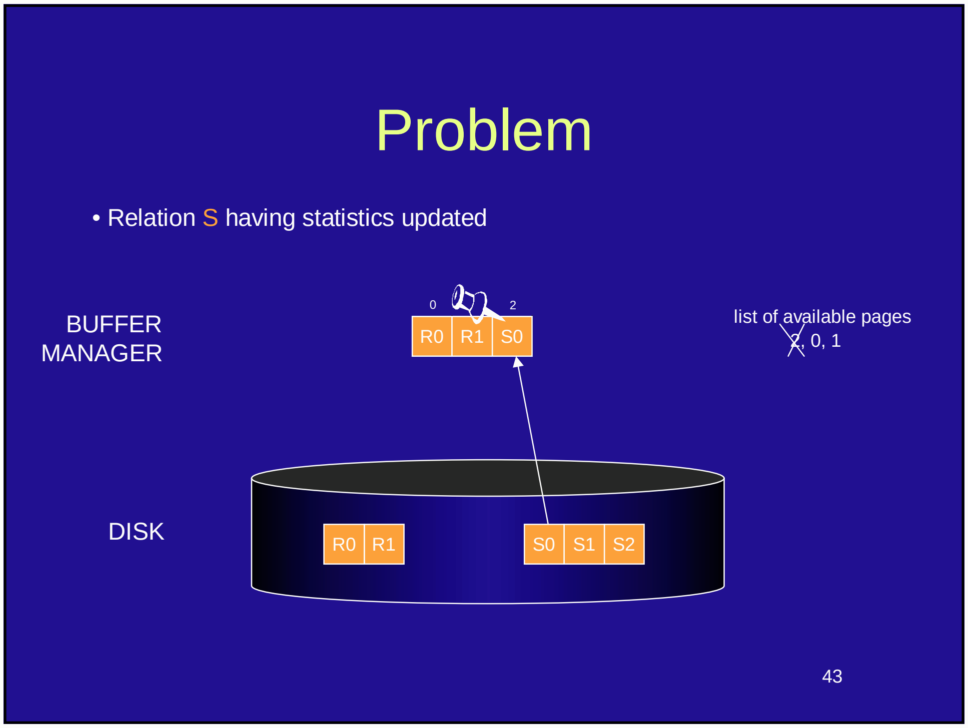

Problem
• Relation R being scanned
BUFFER
MANAGER
0
1
2
R0
list of available pages
0, 1, 2
DISK
R0
R1
S0
S1
S2
38

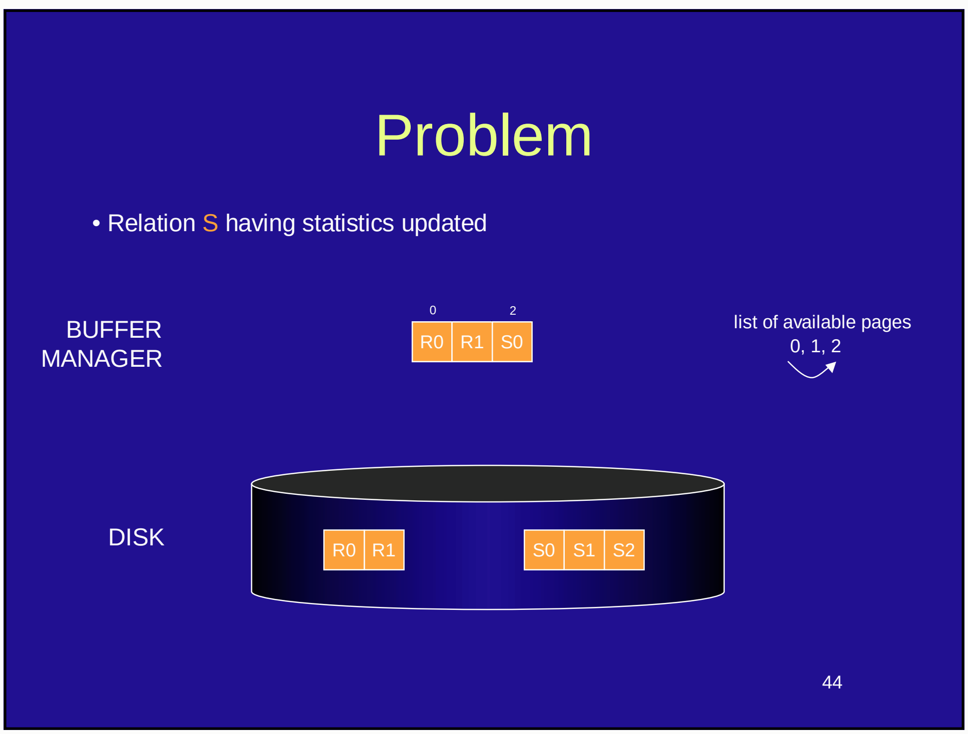

Problem
• Relation R being scanned
BUFFER MANAGER
0 1 2
R0
list of available pages
0, 1, 2
DISK
R0 R1
S0 S1 S2
39


Problem
• Relation R being scanned
BUFFER MANAGER
0 1 2
R0
list of available pages
1, 2, 0
LRU
DISK
R0 R1
S0 S1 S2
40


Problem
• Relation R being scanned
BUFFER MANAGER
0 1 2
R0 R1
list of available pages
1, 2, 0
DISK
R0 R1
S0 S1 S2
41

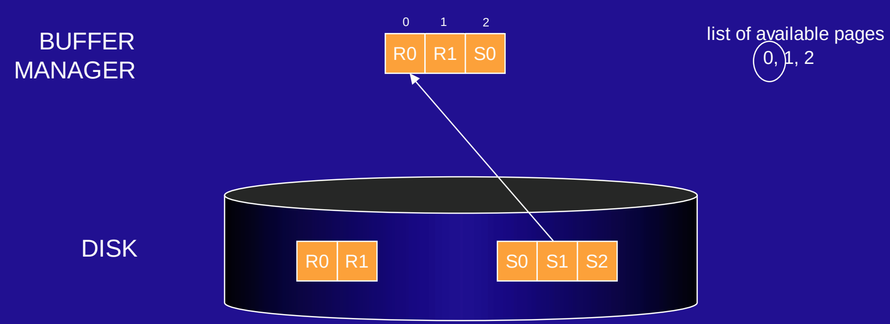

Problem
• Relation R being scanned
BUFFER MANAGER
0 1 2
R0 R1
list of available pages
2, 0, 1
DISK
R0 R1
S0 S1 S2
42


Problem
• Relation S having statistics updated
BUFFER MANAGER
0
2
R0
R1
S0
list of available pages
2, 0, 1
DISK
R0
R1
S0
S1
S2
43


Problem
• Relation S having statistics updated
BUFFER MANAGER
0
2
R0
R1
S0
list of available pages
0, 1, 2
DISK
R0
R1
S0
S1
S2
44

Problem

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

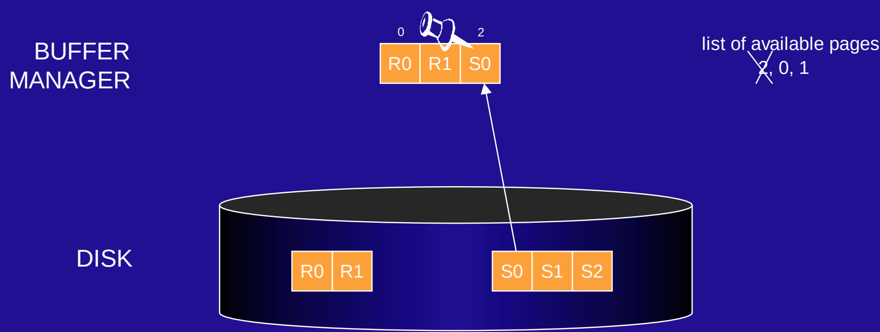


Most Recently Used Page Replacement

- 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

Statistics using MRU

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



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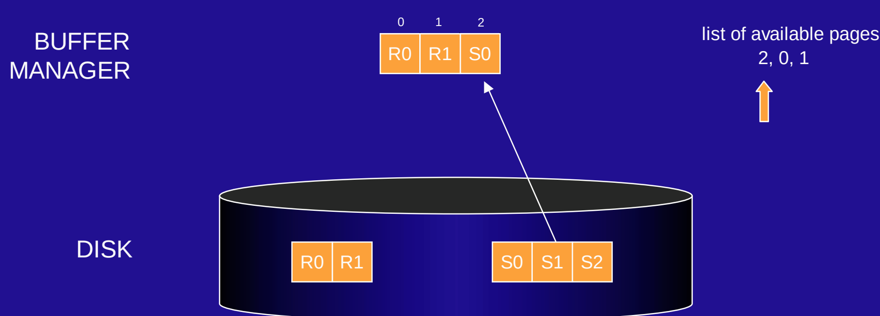
Statistics using MRU

• 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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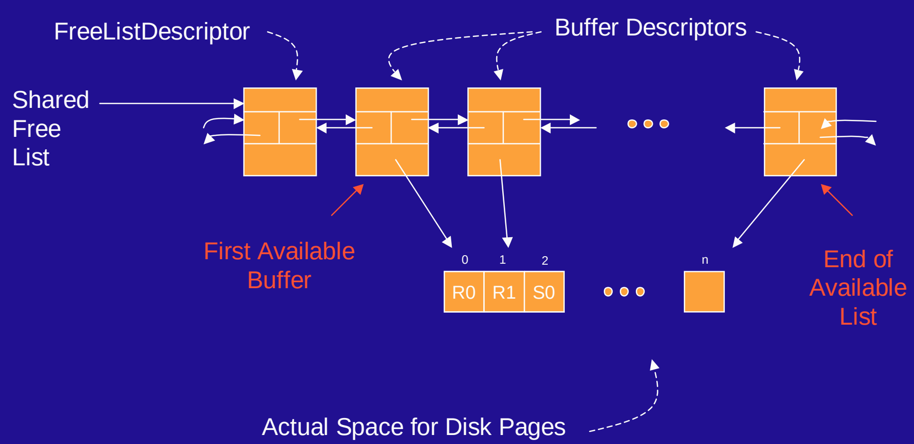
PostgreSQL Buffer Manager



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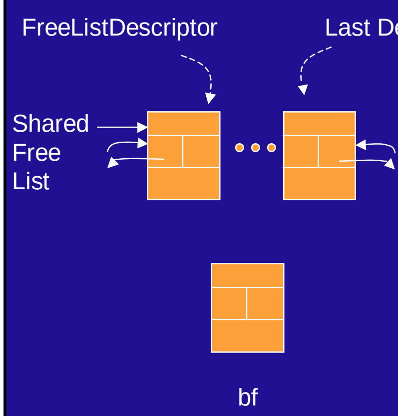
Adding a Buffer




```
static void AddBufferToFreelist(BufferDesc *bf)
{
  /* change bf so it points to inFrontOfNew
     and its successor */
  bf->freePrev = SharedFreeList->freePrev;
  bf->freeNext = Free_List_Descriptor;

  /* insert new into chain */
  BufferDescriptors[bf->freeNext].freePrev = bf->buf_
  BufferDescriptors[bf->freePrev].freeNext = bf->buf_
}
```

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

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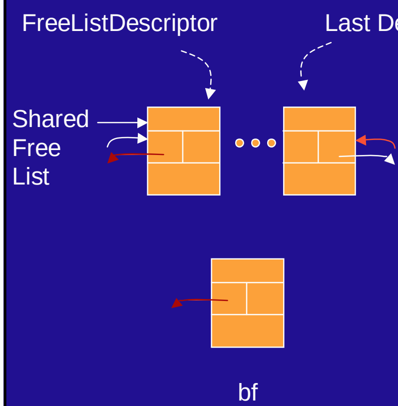
Adding a Buffer

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}
```

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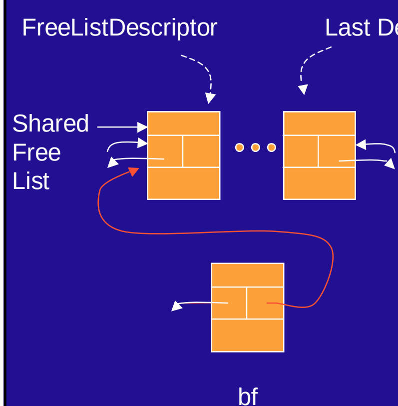
Adding a Buffer




```
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}
```

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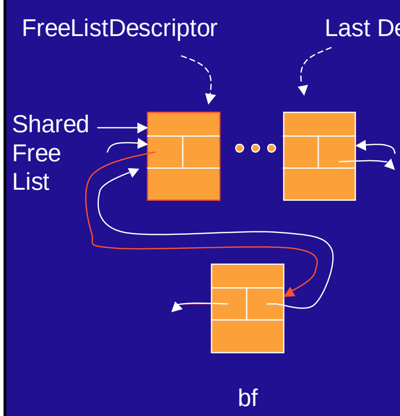
Adding a Buffer

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{
  /* change bf so it points to inFrontOfNew
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  bf->freePrev = SharedFreeList->freePrev;
  bf->freeNext = Free_List_Descriptor;

  /* insert new into chain */
  BufferDescriptors[bf->freeNext].freePrev = bf->buf_
  BufferDescriptors[bf->freePrev].freeNext = bf->buf_
}
```

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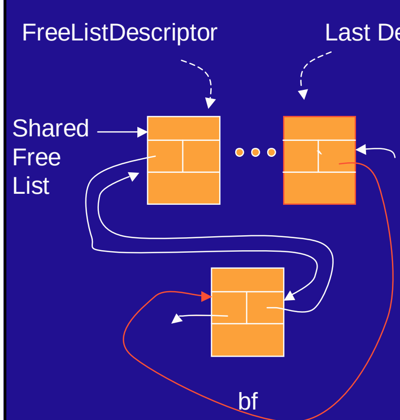
Adding a Buffer




```
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{
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     and its successor */
  bf->freePrev = SharedFreeList->freePrev;
  bf->freeNext = Free_List_Descriptor;

  /* insert new into chain */
  BufferDescriptors[bf->freeNext].freePrev = bf->buf_
  BufferDescriptors[bf->freePrev].freeNext = bf->buf_
}
```

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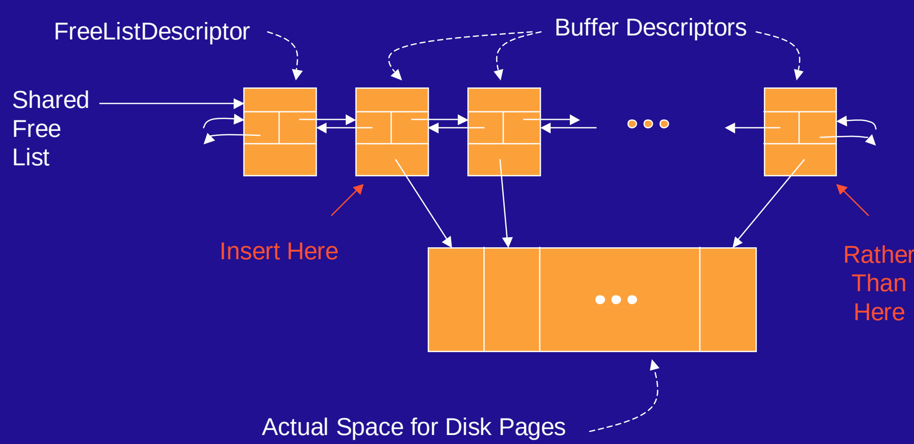
Implementing MRU



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DEMO

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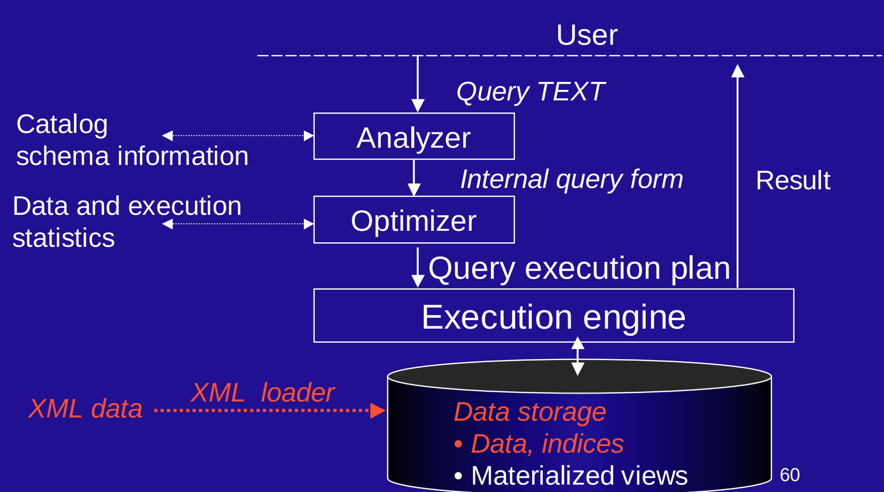
Case 2

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

Simple XML storage system



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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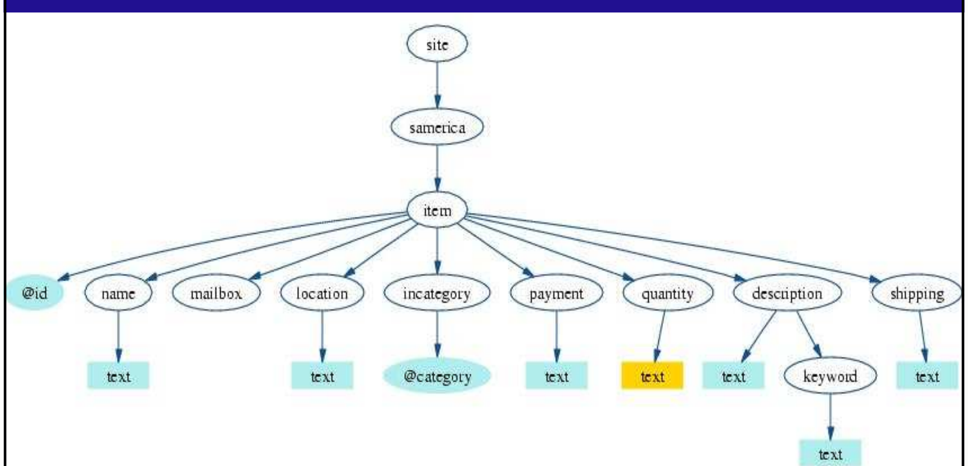
XML documents are data trees



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


Simple data and storage model for XML

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

Edge(pID, tag, cID, attr)

pID	tag	cID	attr
-	site	1	
1	samerica	2	
2	item	3	
3	id	4	X
2	name	5	
…………………………			
2	description	9	
9	keyword	10	
…………………………..			

Value(id, val)

id	val
3	"item6"
5	"United States"
6	"1"
………..	
9	"nice" "chair"
10	"wooden"

Simple data and storage model for XML

3. Many variants exist

Simple variant: partition by tag

Edge(pID, tag, cID, attr)

pID	tag	cID	attr
-	site	1	
1	samerica	2	
2	item	3	
3	id	4	X
2	name	5	
…………………………			
2	description	9	
9	keyword	10	
…………………………			

Value(id, val)

id	val
3	"item6"
5	"United States"
6	"1"
………..	
9	"nice" "chair"
10	"wooden"

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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)

pID	tag	cID	attr
-	site	1	
1	samerica	2	
2	item	3	
3	id	4	X
2	name	5	
…………………………			

Value(id, val)

id	val
3	"item6"
5	"United States"
6	"1"
………..	

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 lName,
   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
  - Hashtable
  - Queue (fixed length)
  - RecordNumber (var. length)

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Loading XML data and structure into a persistent storage

- Four Berkeley DB database types:
  - B+ tree
  - Hashtable
  - Queue (fixed length)
  - 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) pairs

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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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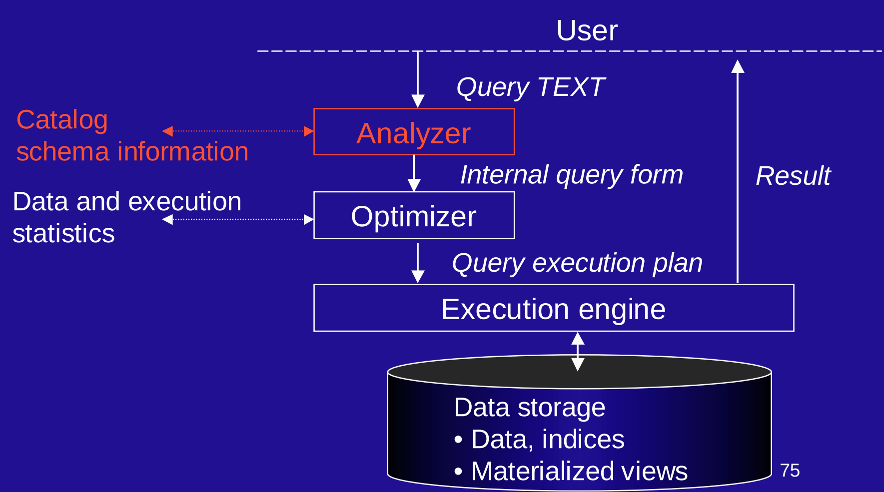
DBMS architecture

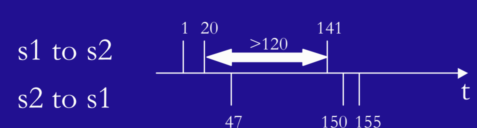


75

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



76

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

Packets	src	dst	len	time
	s1	s2	250	1
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	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	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?

85

Considering cardinality and dimension

- Type is actually a 3-tuple <cardinality, dimension, type>
  - Type of column 'time' is <original-card, 1, integer> meaning that time did not suffer cardinality reduction, ant that it is a vector (dimension 1) of integers
  - Type of deltas(<original-card, 1, integer>) is <original-card, 1, integer> meaning that the function is size-preserving and that it returns a vector of integers
  - Type of firstn(10, <original-card, 1, integer>) is <10, 1, integer>
- Group by requires an expression that is <original-card, ?, ?> 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 using???
  - 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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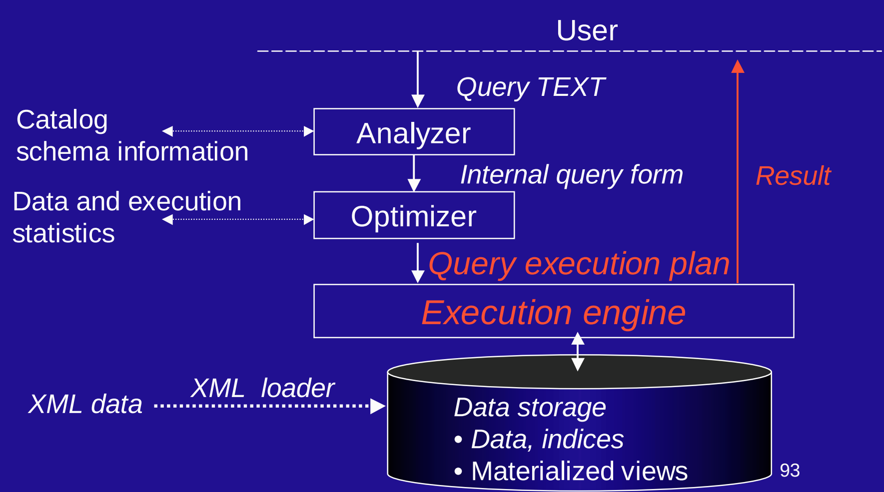
Simple XML querying system



93

Simple XML querying system

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

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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() </numero>
  </artigo>
- Path traversals:
  - Site/regions/samerica/item
  - Site/regions/samerica/item/@id
  - Site/regions/samerica/item//keyword

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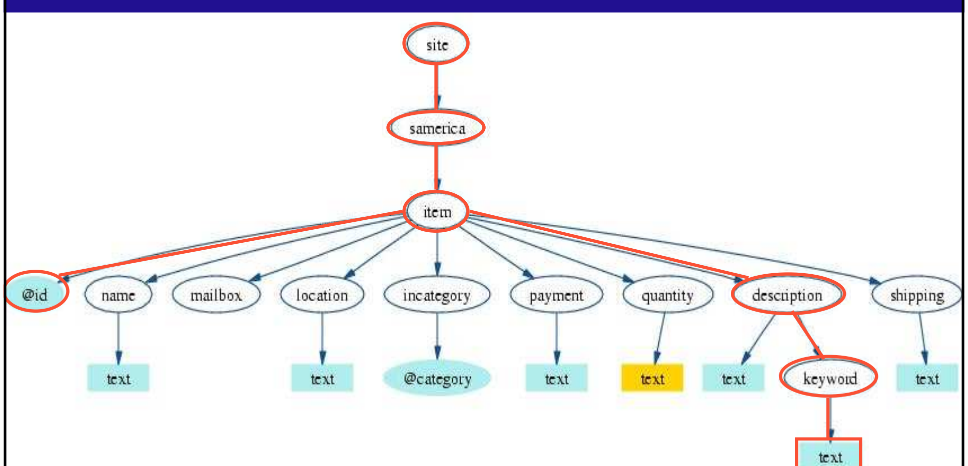
XML querying requires tree traversal



96

Tree traversal requires joins

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

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Implementing tree traversals

- site/samerica/item:
- $Edge_{site} \bowtie Edge_{samerica} \bowtie Edge_{item}$
  – 3-way join…
- site/samerica/item/keyword/description
- $Edge_{site} \bowtie Edge_{samerica} \bowtie Edge_{item} \bowtie \bowtie Edge_{description} \bowtie Edge_{keyword}$
  – 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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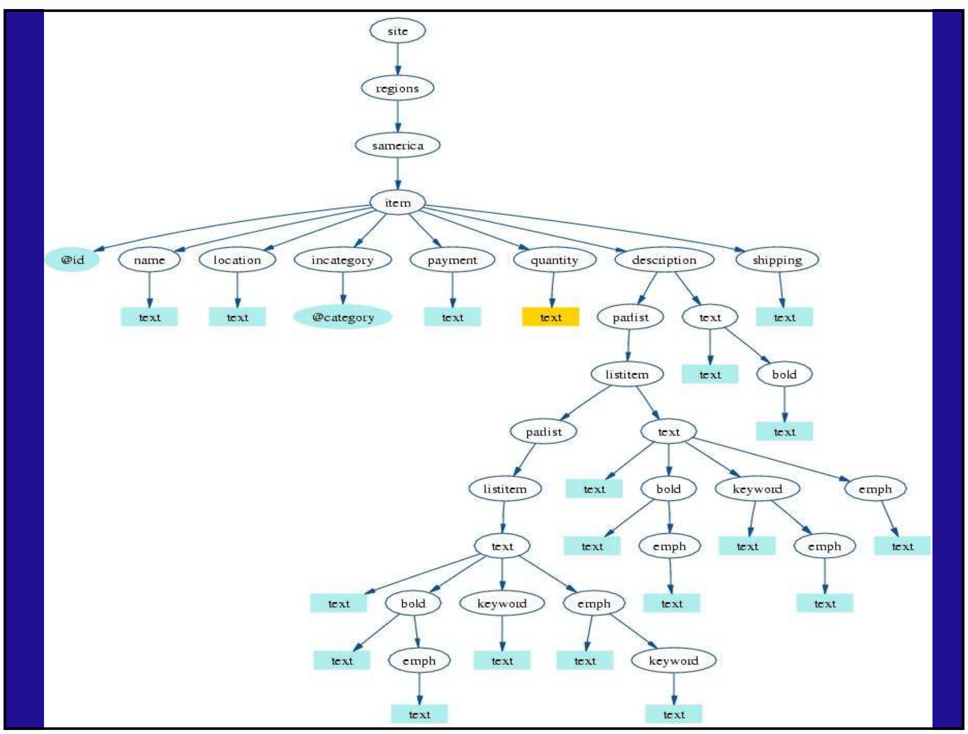

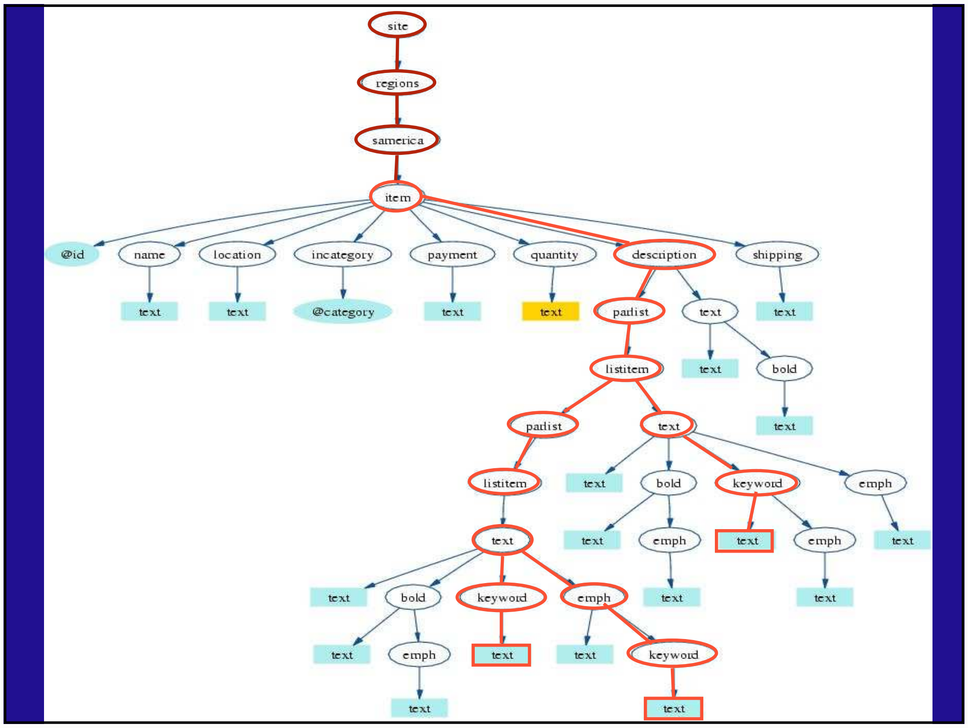

Implementing real tree traversals

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

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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 (1/2)

- One join establishes ancestor-descendent connections of arbitrary length
  – No need to store edges any longer, just IDs
- site/regions/samerica/item:
  $ID_{site} \bowtie ID_{site/regions/samerica/item}$

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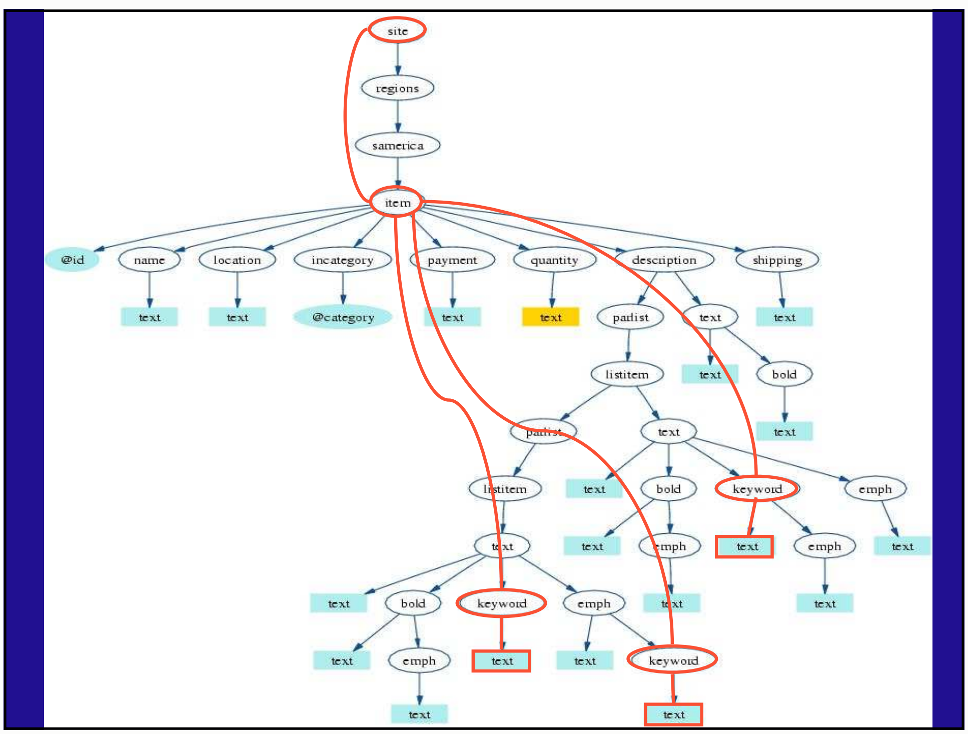

The interest of structural joins (2/2)

- 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 lName,
    String qName) {
          // same as before; update depth
    }
```

110

Loading XML data and structure, revisited with structural identifiers

- Four Berkeley DB database types:
  - B+ tree
  - Hashtable
  - Queue (fixed length)
  - 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) pairs

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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…

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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; coolean 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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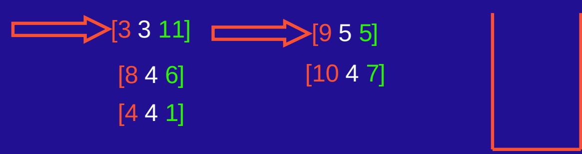
Implementing StructuralJoin

- 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 ancestores are "too old"

115

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
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117

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118

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119

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120

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
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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() </numero>
  </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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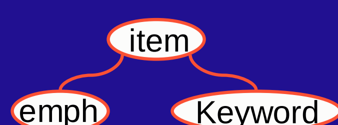
Simple extensions: twig joins

- 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)

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)

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)

134

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/xmldatasets)
- 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/dbbookl
  – 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

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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

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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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