Database System Architecture

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Outline

System R discussion

Relational DBMS architecture

Alternative architectures & tradeoffs

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System R Design

Already had essentially the same architecture as a modern RDBMS!

» SQL

» Many storage & access methods (B-trees, etc)

» Cost-based optimizer

» Compiling queries to assembly

» Lock manager

» Recovery via log + shadow pages

» View-based access control

System R Motivation

Navigational DBMS are hard to use

Can relational DBMS really be practical?

Navigational vs Relational Data

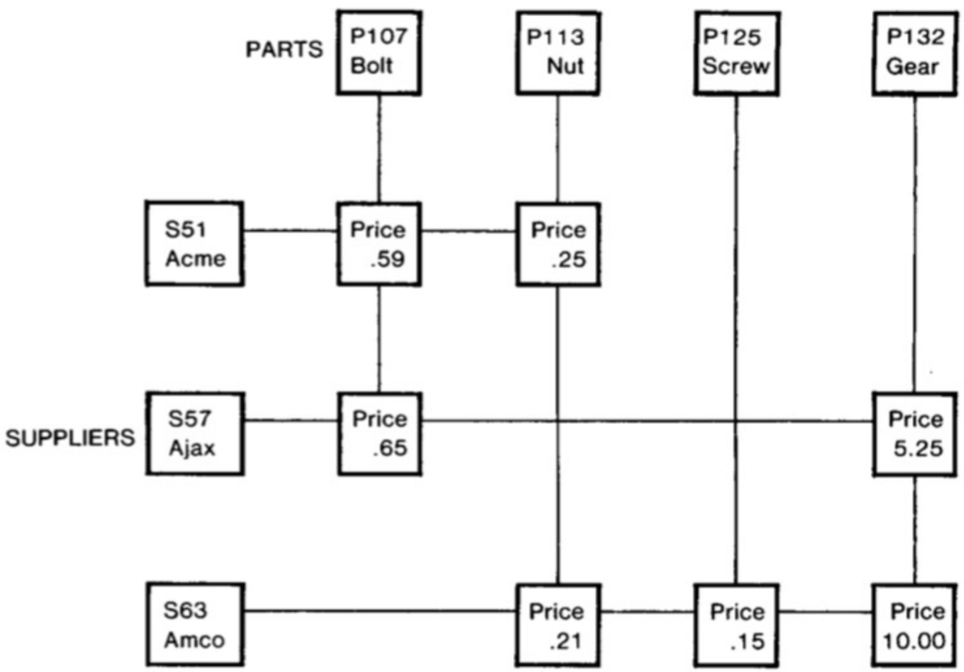


Fig. 1(a). A "Navigational" Database.

PARTS

PARTNO	NAME
P107	Bolt
P113	Nut
P125	Screw
P132	Gear

SUPPLIERS

SUPPNO	NAME
S51	Acme
S57	Ajax
S63	Amco

PRICES

PARTNO	SUPPNO	PRICE
P107	S51	.59
P107	S57	.65
P113	S51	.25
P113	S63	.21
P125	S63	.15
P132	S57	5.25
P132	S63	10.00

Fig. 1(b). A Relational Database.

Why is the relational model more flexible?

Three Phases of Development

Why was System R built in 3 phases?

Storage in System R Phase 0

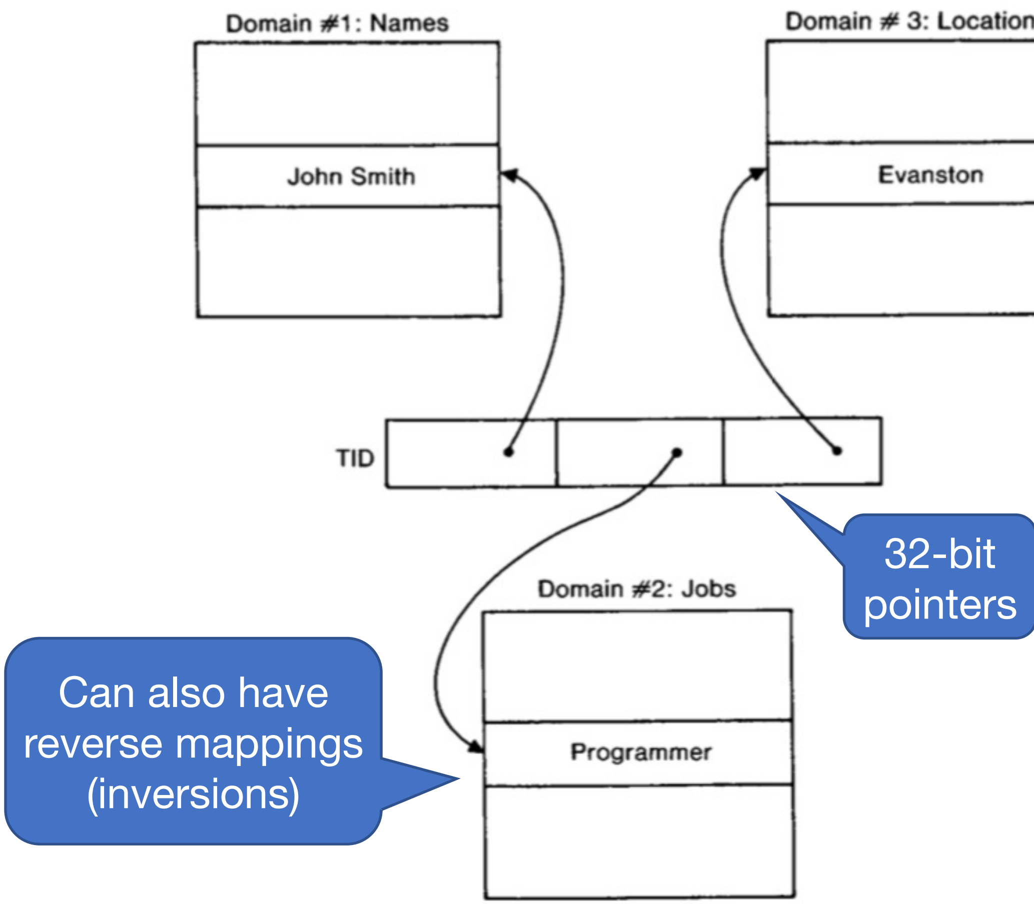


Fig. 2. XRM Storage Structure.

What was the issue with this design?

Too many I/Os:

- For each tuple, look up all its fields
- Use "inversions" to find TIDs with a given value for a field

Storage in System R Phase 1

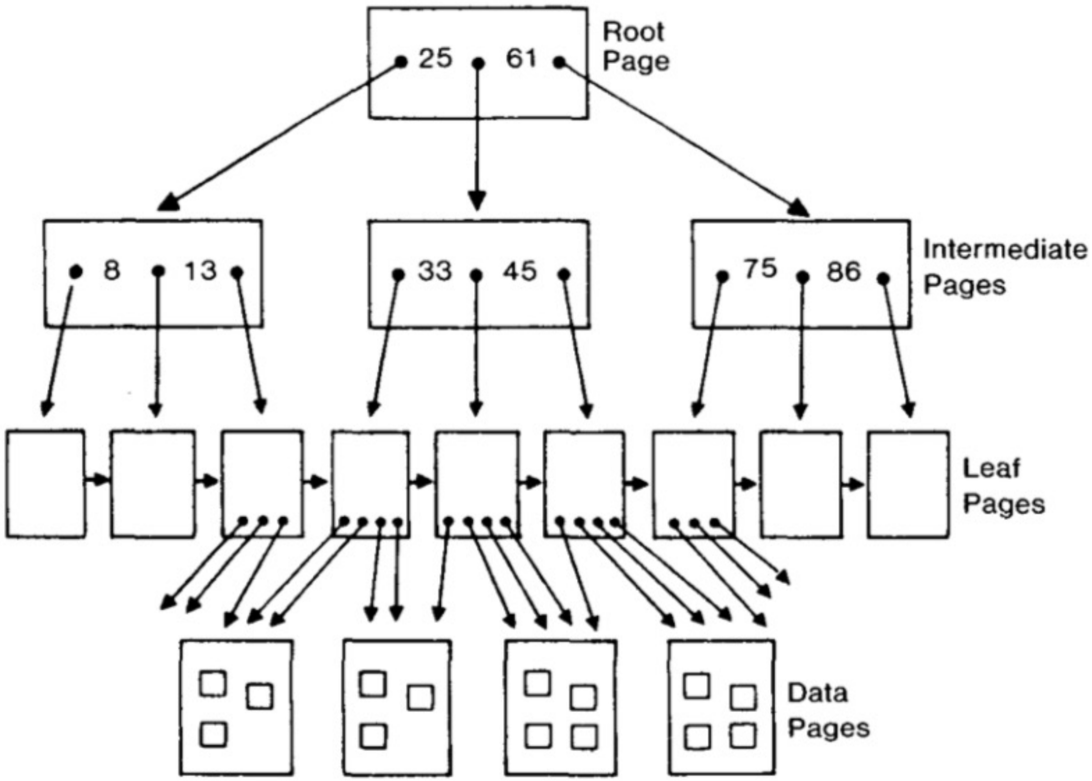


Fig. 6. A B-Tree Index.

B-tree nodes contain values of the column(s) indexed on

Data pages can contain all fields of the record

Give an example query that would be faster with B-Trees!

API

Mostly the same SQL language as today

Embedded SQL in PL/I and COBOL

» .NET added LINQ in 2007

Interesting additions:

» "EXISTS"

» "LIKE"

» Prepared statements

» Outer joins

```
SELECT expression(s)
FROM table
WHERE EXISTS
(SELECT expr FROM table WHERE cond)
```

```
WHERE name LIKE 'Mat%'
```

```
stmt = prepare("SELECT name FROM
                table WHERE id=?")
execute(stmt, 5)
```

Query Optimizer

How did the System R optimizer change after Phase 0?

Query Compilation

Why did System R compile queries to assembly code?

How did it compile them?

Do databases still do that today?

Example 1:

```
SELECT   SUPPNO, PRICE
FROM     QUOTES
WHERE    PARTNO = '010002'
AND MINQ<=1000 AND MAXQ>=1000;
```

Operation	CPU time (msec on 168)	Number of I/Os
Parsing	13.3	0
Access Path Selection	40.0	9
Code Generation	10.1	0
Fetch answer set (per record)	1.5	0.7

Recovery

Goal: get the database into a consistent state after a failure

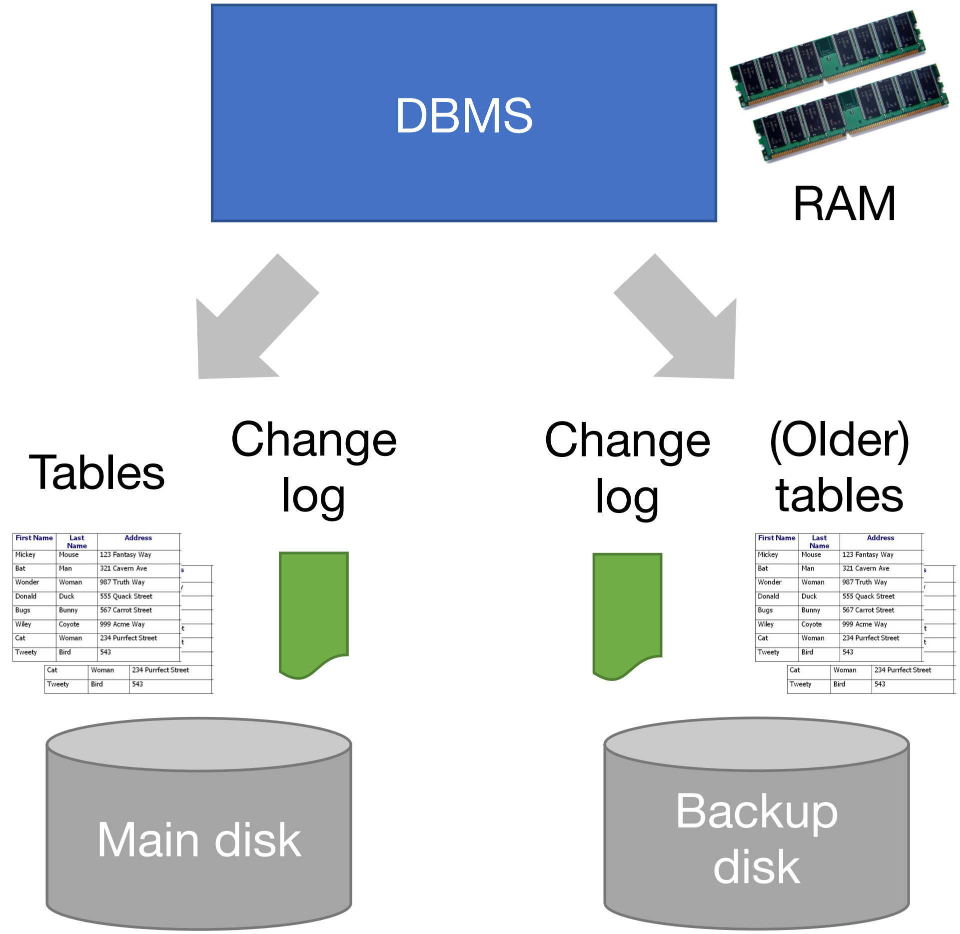
“A consistent state is defined as one in which the database does not reflect any updates made by transactions which did not complete successfully.”

Recovery

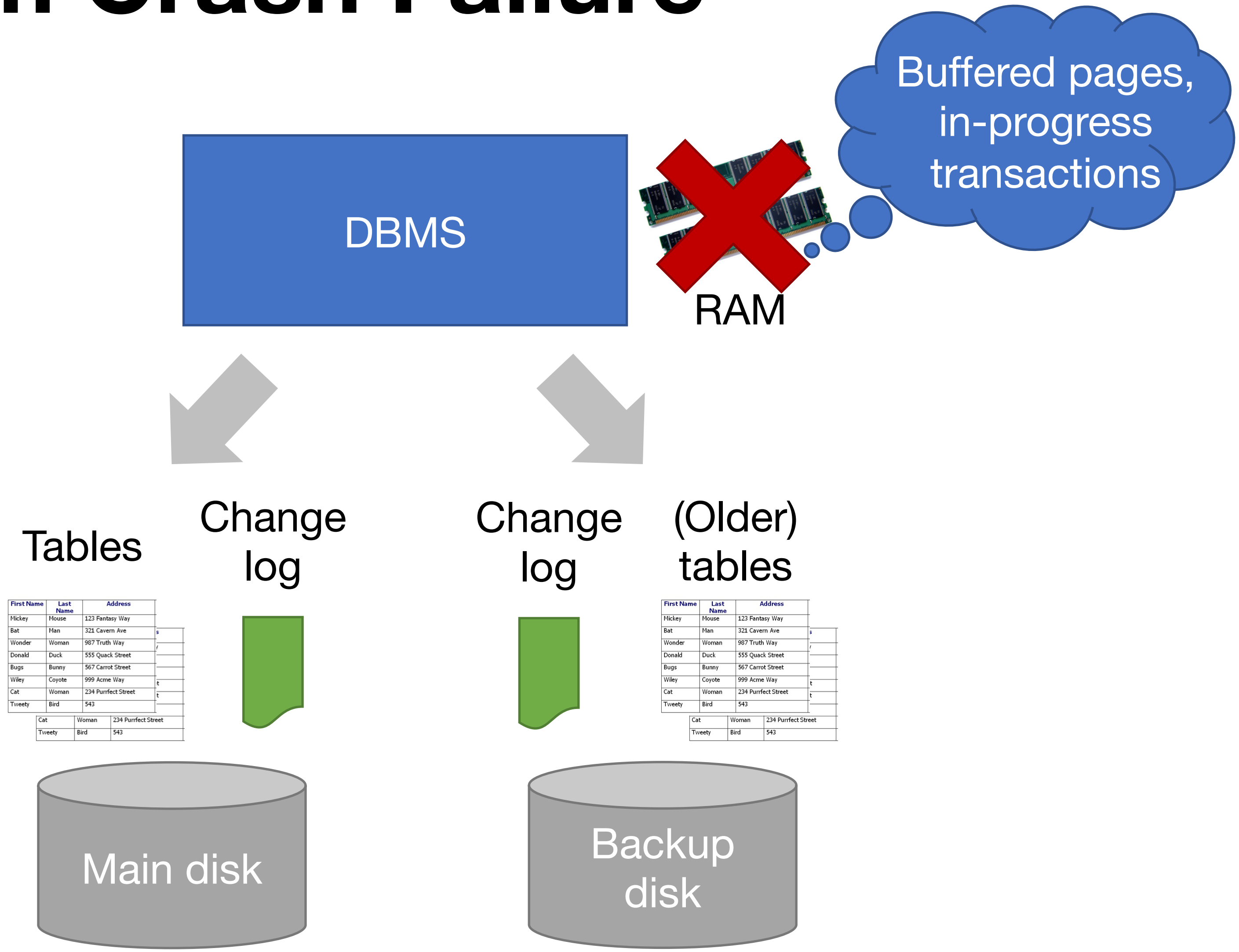
Three main types of failures:

- » Disk (storage media) failure
- » System crash
- » Transaction failure

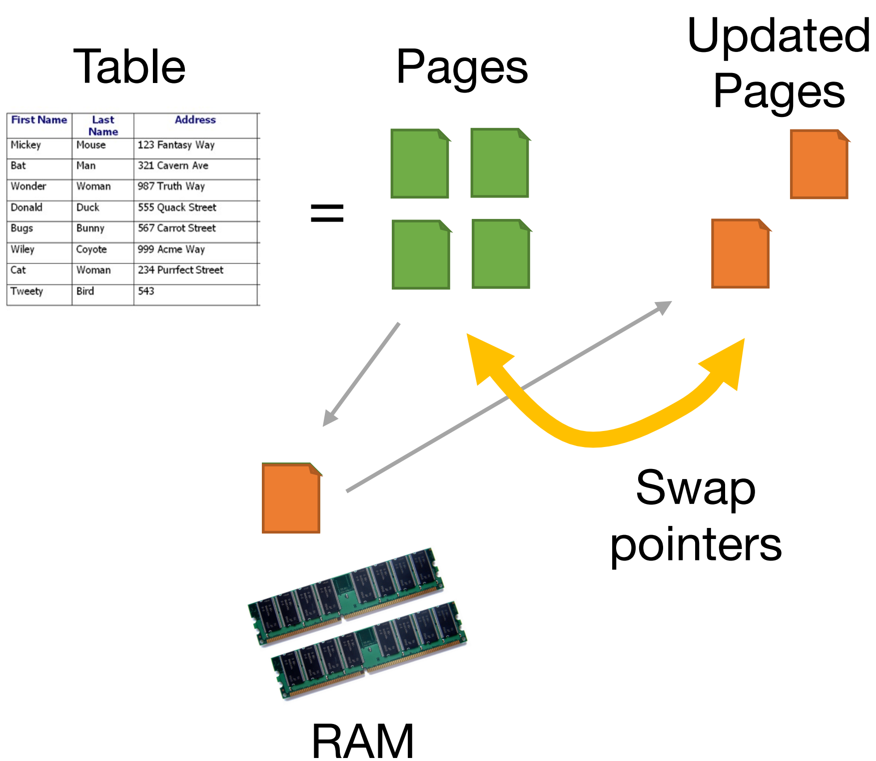
Handling Storage Failure



System Crash Failure



Handling Crash Failures: Shadow Pages



Why do we need both shadow pages and a change log?

A Later Note on Recovery

In retrospect, we regret not supporting the LOG and NO SHADOW option. As explained in Section 3.8, the log makes shadows redundant, and the shadow mechanism is quite expensive for large files.

Jim Gray, "The Recovery Manager of the System R Database Manager", 1981

Transaction Failure

```
BEGIN TRANSACTION;

SELECT balance FROM accounts
  WHERE user_id = 1;

  UPDATE accounts WHERE user_id = 1
     SET balance = balance – 100;
  COMMIT TRANSACTION;

  ROLLBACK TRANSACTION;
```

Handling Transaction Failures

Just undo any changes they made, which we logged in the change log

Nobody else “saw” these changes due to System R’s **locking mechanism**

Locking

The problem:

- Different transactions are concurrently trying to read and update various data records
- Each transaction wants to see a static view of the database (maybe lock whole DB)
- For efficiency, we can't let them do that!

Fundamental Tradeoff

Finer-grained locking

Lock smaller units of data (records or fields), lock for specific operations (e.g. R/W)

+ Allows more transactions to run concurrently
– More runtime overhead

Coarser-grained locking

Lock bigger units of data (e.g. whole table) for broader purposes (e.g. all operations)

+ More efficient to implement
– Less concurrency

Even if fine-grained locking were free, in some cases where it would give unacceptable perf!

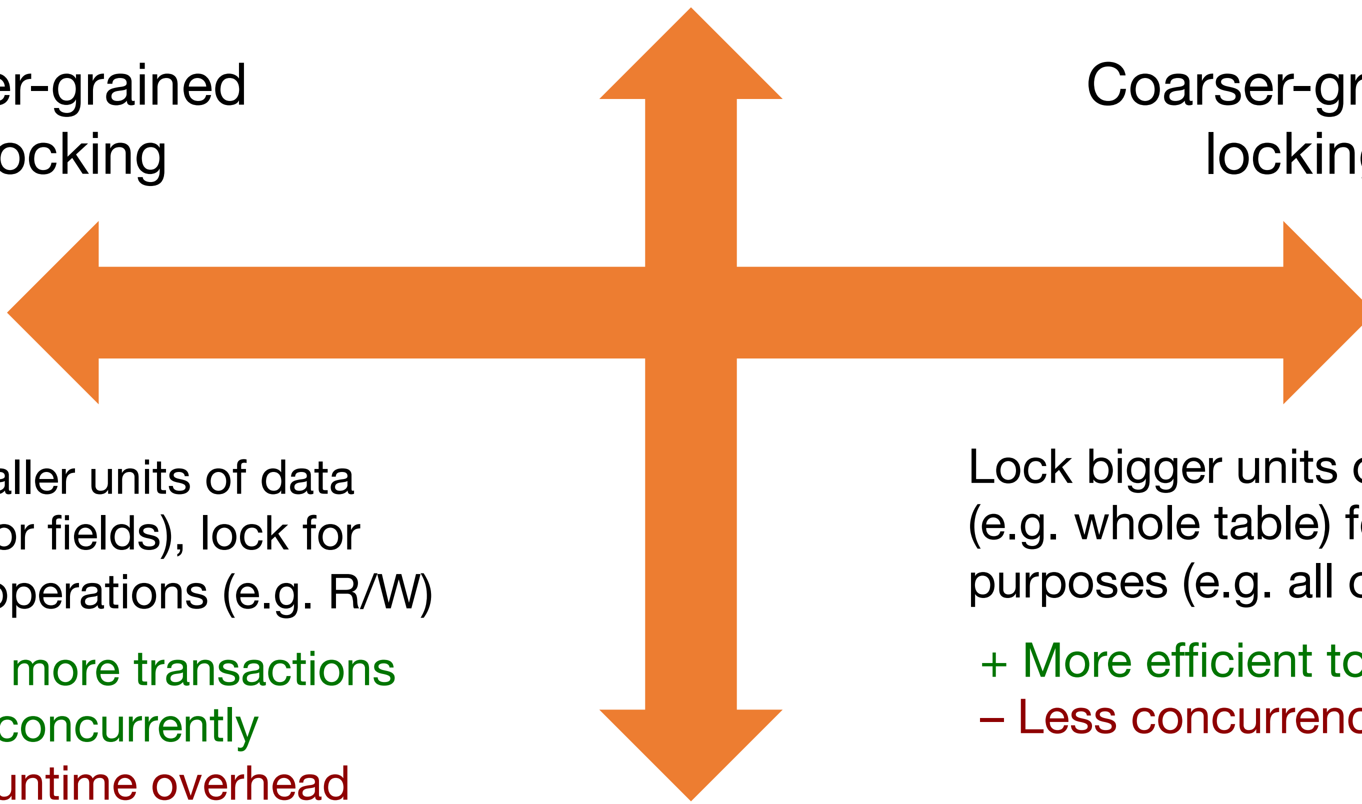
Fundamental Tradeoff

Strong isolation level

Closer to exclusive view of DB (can't see others' changes)

Finer-grained locking

Coarser-grained locking



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Weak isolation level

See others' changes, but more concurrency

Locking and Isolation in System R

Locking:

» Started with "predicate locks" based on expressions: too expensive

» Moved to hierarchical locks: record/page/table, with read/write types and intentions

Isolation levels:

» Level 1: Transaction may read uncommitted data; successive reads to a record may return different values

» Level 2: Transaction may only read committed data, but successive reads can differ

» Level 3: Successive reads return same value

Most apps chose Level 3 since others weren't much faster

Are There Alternatives to Locking for Concurrency?

Authorization

Goal: give some users access to just parts of the database

- A manager can only see and update salaries of her employees
- Analysts can see user IDs but not names
- US users can't see data in Europe

Authorization

System R used view-based access control

» Define SQL views (queries) for what the user can see and grant access on those

```
CREATE VIEW canadian_customers AS
SELECT customer_name, email_address
FROM customers
WHERE country = “Canada”;
```

Elegant implementation: add the user’s SQL query on top of the view’s SQL query

User Evaluation

How did the developers evaluate System R?

What was the user feedback?

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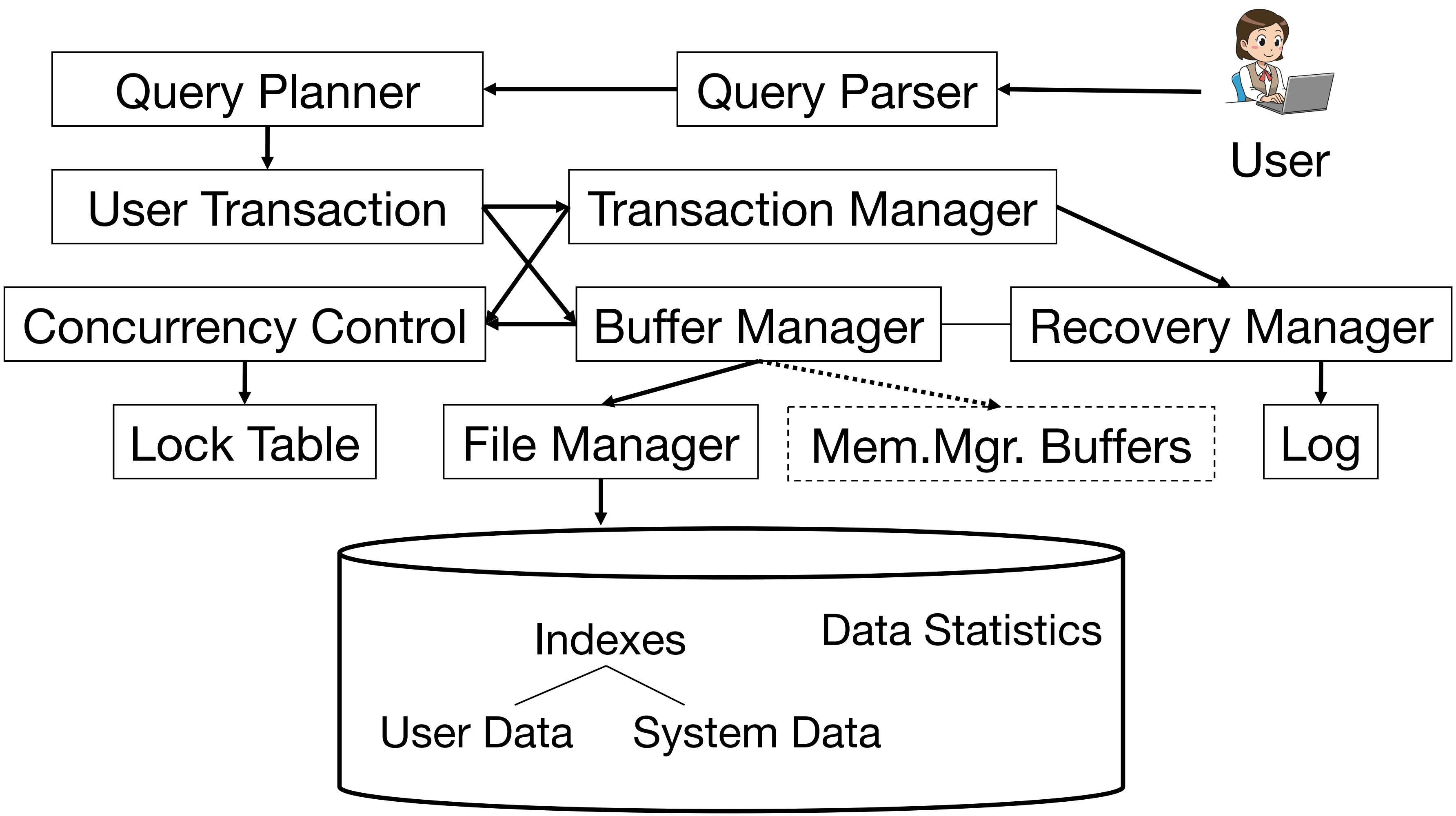
Typical RDBMS Architecture



Boundaries

Some of the components have clear boundaries and interfaces for modularity

» SQL language

» Query plan representation (relational algebra)

» Pages and buffers

Other components can interact closely

» Recovery + buffers + files + indexes

» Transactions + indexes & other data structures

» Data statistics + query optimizer

Differentiating by Workload

2 big classes of commercial RDBMS today

Transactional DBMS: focus on concurrent, small, low-latency transactions (e.g. MySQL, Postgres, Oracle, DB2) → real-time apps

Analytical DBMS: focus on large, parallel but mostly read-only analytics (e.g. Teradata, Redshift, Vertica) → “data warehouses”

How To Design Components for Transactional vs Analytical DBMS?

Component	Transactional DBMS	Analytical DBMS
Data storage		
Locking		
Recovery		

How To Design Components for Transactional vs Analytical DBMS?

Component	Transactional DBMS	Analytical DBMS
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Locking		
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Recovery		

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Component	Transactional DBMS	Analytical DBMS
Data storage	B-trees, row oriented storage	Column-oriented storage
Locking	Fine-grained, very optimized	Coarse-grained (few writes)
Recovery	Log data writes, minimize latency	Log queries

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How Can We Change the DBMS Architecture?

Decouple Query Processing from Storage Management

Example: data lake systems (Hadoop, GFS, Athena)

MapReduce, Apache Giraph, Apache Spark, Apache Storm, presto, TensorFlow	Processing engines
Parquet, {JSON} JavaScript Object Notation, Delta Lake, Hive	Open storage and metadata formats
GFS, hadoop HDFS, Amazon S3	Large-scale file systems or blob stores

Decouple Query Processing from Storage Management

Pros:

- » Can scale compute independently of storage (e.g. in public cloud)
- » Let different orgs develop different engines
- » Your data is “open” by default to new tech

Cons:

- » Harder to guarantee isolation, reliability, etc
- » Harder to co-optimize compute and storage
- » Can’t optimize across multiple engines
- » Harder to manage if too many engines!

Change the Data Model

Key-value stores: data is just key-value pairs, don’t worry about record internals

Message queues: data is only accessed in a specific FIFO order; limited operations

ML frameworks: data is tensors, models, etc

Change the Compute Model

Stream processing: Apps run continuously and system can manage upgrades, scale-up, recovery, etc

Eventual consistency: handle it at app level

Distributed Computing

December 12, 2016
Volume 14, issue 5

PDF

Life Beyond Distributed Transactions

An apostate's opinion

Pat Helland

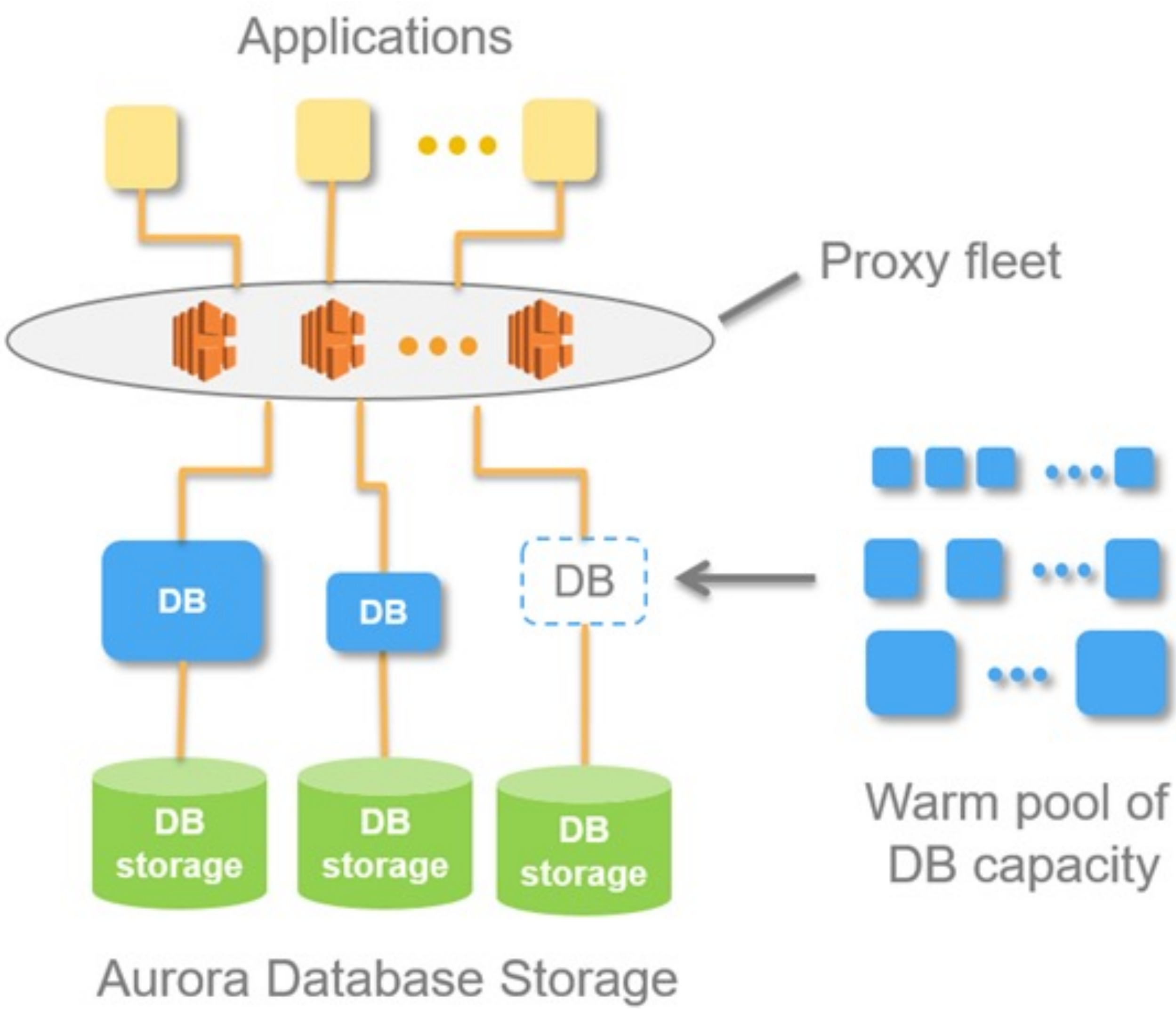
This is an updated and abbreviated version of a paper by the same name first published in CIDR (Conference on Innovative Database Research) 2007.

Transactions are amazingly powerful mechanisms, and I've spent the majority of my almost 40-year career working on them. In 1982, I first worked to provide

Different Hardware Setting

Distributed databases: need to distribute your lock manager, storage manager, etc, or find system designs that eliminate them

Public cloud: “serverless” databases that can scale compute independently of storage (e.g. AWS Aurora, Google BigQuery)



AWS Aurora Serverless

Summary

All data systems face similar issues: API, performance, reliability, concurrency, etc

Relational DBMS offer one architecture that tackles many of these concerns together

One trend is to **break apart** this monolithic architecture into specialized components