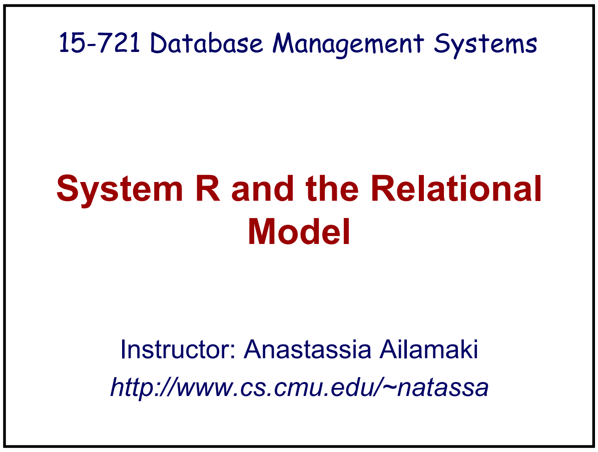
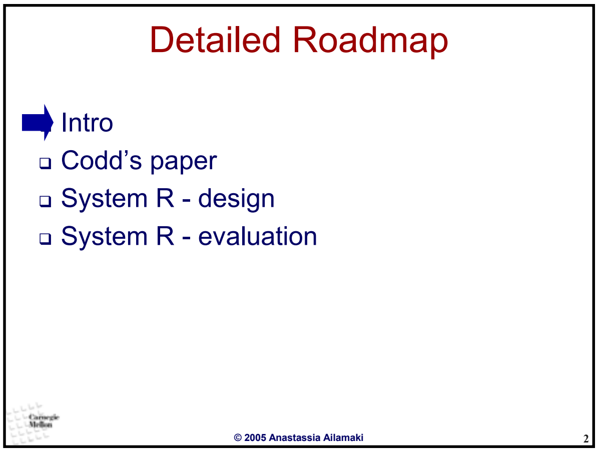


15-721 Database Management Systems

System R and the Relational Model

Instructor: Anastassia Ailamaki

http://www.cs.cmu.edu/~natassa



Detailed Roadmap

- ➡ Intro
- ❑ Codd’s paper
- ❑ System R - design
- ❑ System R - evaluation

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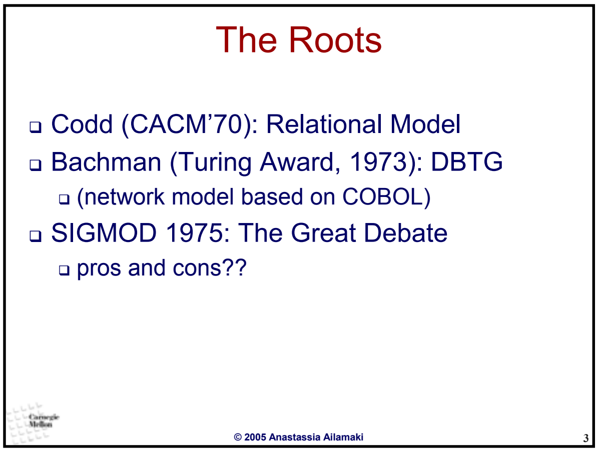

The Roots

- ❑ Codd (CACM’70): Relational Model
- ❑ Bachman (Turing Award, 1973): DBTG
  - ❑ (network model based on COBOL)
- ❑ SIGMOD 1975: The Great Debate
  - ❑ pros and cons??

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The Roots

CODASYL:

- RL too much math
- Implementation
- OLTP <-> operators

Relational:

- DBTG complicated
- No easy set queries
- No semantics

Late 70's: Relational Model wins

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Relational Prototypes

- SQL,Quel (user-friendlier than Rel. algebra)
- Performance issue addressed

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Relational Prototypes

System R

@ IBM SJ, 1974-78

- compiler
- RDS/RSS links
- Recovery scheme
- No hashing

INGRES

@ UCB 1973-77

- Interpreter
- Unix FS (no recovery!)
- 16-bit PDP-11

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Impact

System R

- ESVAL / HP Allbase, IDMS/SQL,
- Oracle, DB2, SQL/DS
- Query optimization
- Compilation

INGRES

- INGRES Corp., Britton-Lee IDM, Sybase
- Clean QUEL
- Queries for views
- Protection, integrity

- But: both systems unfaithful to Rel. Model:
  - allow duplicate records
  - No notion of domain or primary key

Detailed Roadmap

- Intro
- Codd's paper
- System R - design
- System R - evaluation

Codd, CACM'70

Goals:

- (logical + physical) Data independence
  - Ordering (sorted vs. raw)
  - Indexing (existence or not)
  - Access path dependency
- Avoid inconsistencies

(putting things in context: DBTG)

DBTG = CODASYL = Network model:

- repeating groups
- records (eg., ‘employee’, ‘department’)
- sets (eg., ‘employee works in a department’)
  - [‘marketing’, {John, Mary, Mike}]
  - [‘sales’, {Peter, Tom}]
  - ...

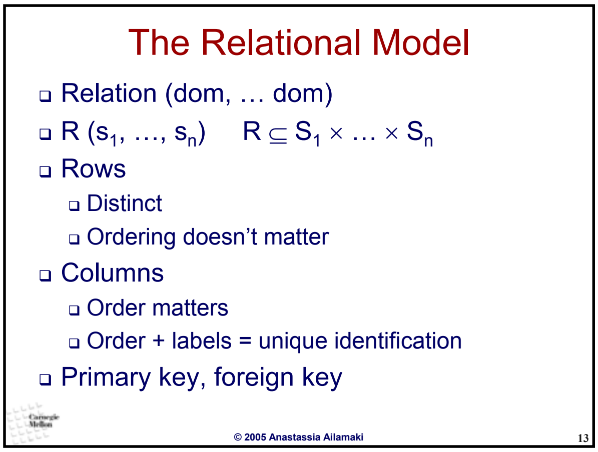
(putting things in context: DBTG)

QL: ‘fetch’, ‘fetch next’, ‘fetch within parent’

- Fast, for suitable queries;
- bad for rest
- even worse, apps break if schema changes

Salvation:

- Everything is a table - no ‘DBTG sets’, no repeating groups
- In detail:



The Relational Model

- Relation (dom, … dom)
- R (s_1, …, s_n) $R \subseteq S_1 \times \ldots \times S_n$
- Rows
  - Distinct
  - Ordering doesn’t matter
- Columns
  - Order matters
  - Order + labels = unique identification
- Primary key, foreign key

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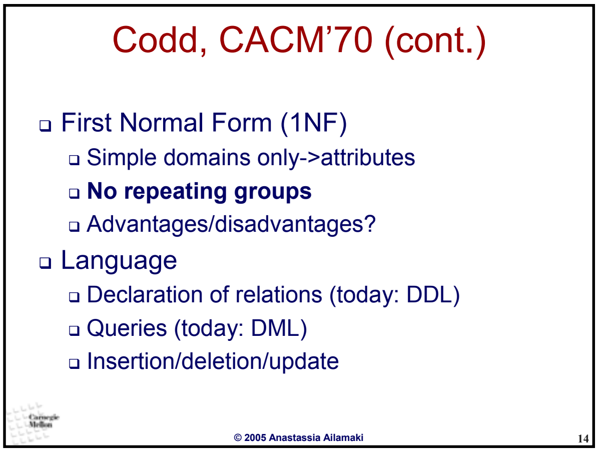

Codd, CACM’70 (cont.)

- First Normal Form (1NF)
  - Simple domains only->attributes
  - **No repeating groups**
  - Advantages/disadvantages?
- Language
  - Declaration of relations (today: DDL)
  - Queries (today: DML)
  - Insertion/deletion/update

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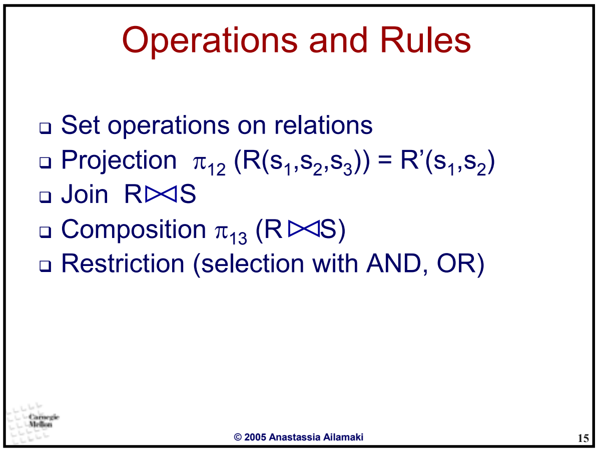

Operations and Rules

- Set operations on relations
- Projection π_{12} (R(s_1,s_2,s_3)) = R’(s_1,s_2)
- Join $R \bowtie S$
- Composition π_{13} ($R \bowtie S$)
- Restriction (selection with AND, OR)

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(‘Restriction’)

$R' = R_{(2,3)} \mid_{(1,2)} S$

i.e., give the (2,3) tuples of ‘R’ that match a tuple from ‘S’

Formally: R’ is the maximal subset of R s.t.

$\text{projection}_{(2,3)}(R') = \text{projection}_{(1,2)}(S)$

[hence CODASYL’s complaints!]

Operations and Rules - cont’d

- Redundancy (no derivable relations)
  - ‘strong’ (an existing table is a projection of some other)
  - ‘weak’(…... of some join)
  - [either way, the yet-to-be-invented Functional Dependencies would capture them]
- Consistency
  - [the penalty for redundancy: need to check]

Reminders

Goals:

- (logical + physical) Data independence
- Avoid inconsistencies

Today:

Five fundamental operators, for rel. algebra

- ?
- ?
- ?
- ?
- ?

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Today:

Five fundamental operators, for rel. algebra

- union
- difference
- selection
- projection
- cartesian product

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Today:

For Inconsistencies:

- Functional Dependencies and
- Normal Forms (remember 3NF and BNCF?)

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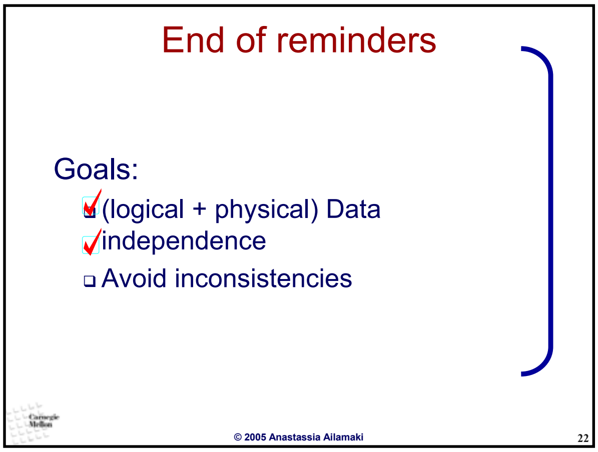

End of reminders

Goals:

- ☑ (logical + physical) Data
- ☑ independence
- □ Avoid inconsistencies

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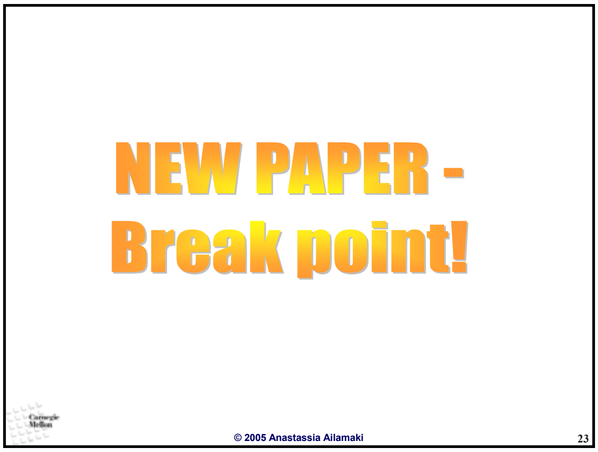

NEW PAPER - Break point!

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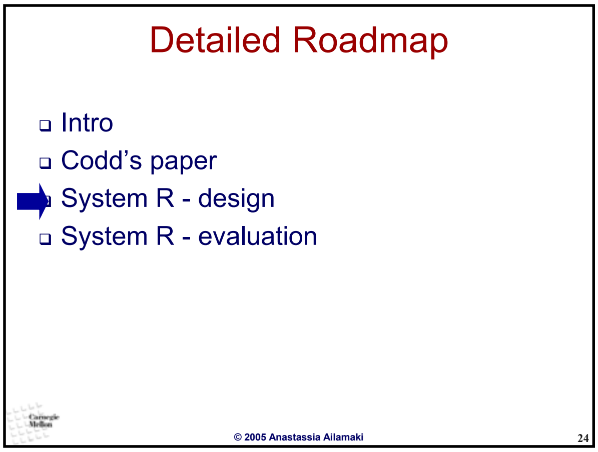

Detailed Roadmap

- □ Intro
- □ Codd’s paper
- ➡ □ System R - design
- □ System R - evaluation

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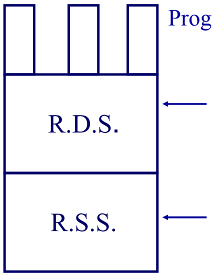
System R Architecture

Multiple virtual machines!



Programs (Sequel, QBE, etc.)

Relational Data System (auth, integrity, view, query optimization, catalog mgmt)

Relational Storage System (device mgmt, space alloc, buffers, Xact consistemcy - locking, recovery)

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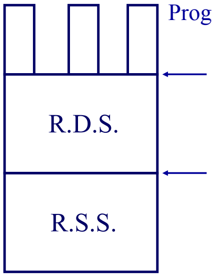
System R Architecture (cont.)



Programs (Sequel, QBE, etc.)

Relational Data Interface (called from host language, supports emulators, etc.)

Relational Storage Interface (access to tuples)

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Even more detailed Roadmap

- ❑ Intro
- ❑ Codd’s paper
- ❑ System R - design
  - ❑ RDS (QL, Data control, Q-opt)
  - ❑ RSS (Segments, rel, images, links, CC, recovery)
- ❑ System R - evaluation

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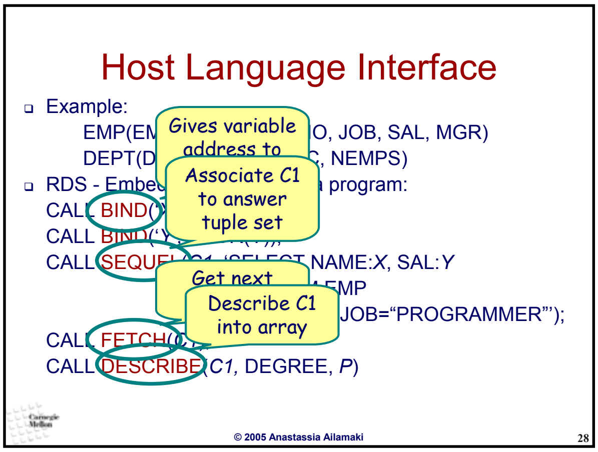


Host Language Interface

- Example:

  EMP(EM O, JOB, SAL, MGR)

  DEPT(D C, NEMPS)

- RDS - Embe a program:

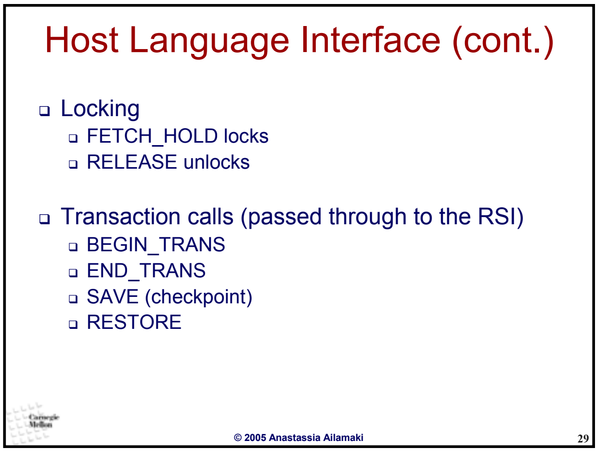
```
CALL BIND(‘X
CALL BIND(‘Y
CALL SEQUEL(C1, ‘SELECT NAME:X, SAL:Y
                          EMP
                          JOB=“PROGRAMMER”’);
CALL FETCH(C1);
CALL DESCRIBE(C1, DEGREE, P)
```

Gives variable address to

Associate C1 to answer tuple set

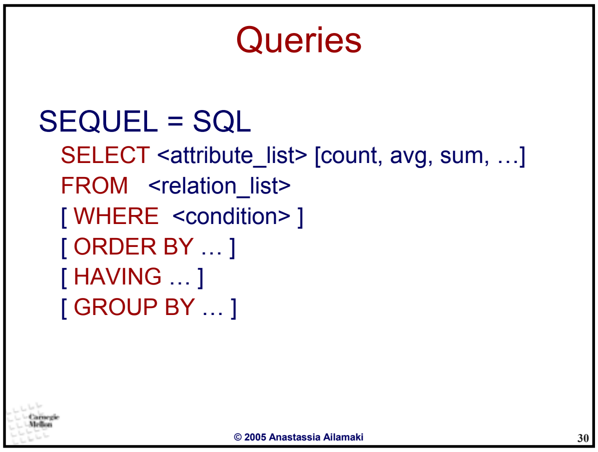
Get next

Describe C1 into array



Host Language Interface (cont.)

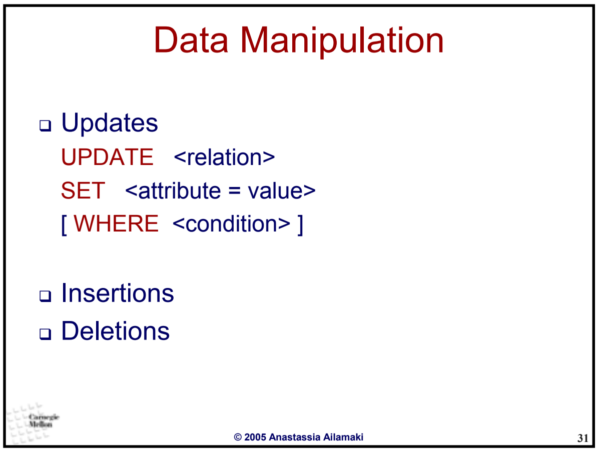
- Locking
  - FETCH_HOLD locks
  - RELEASE unlocks
- Transaction calls (passed through to the RSI)
  - BEGIN_TRANS
  - END_TRANS
  - SAVE (checkpoint)
  - RESTORE



Queries

SEQUEL = SQL

```
SELECT <attribute_list> [count, avg, sum, …]
FROM   <relation_list>
[ WHERE  <condition> ]
[ ORDER BY … ]
[ HAVING … ]
[ GROUP BY … ]
```

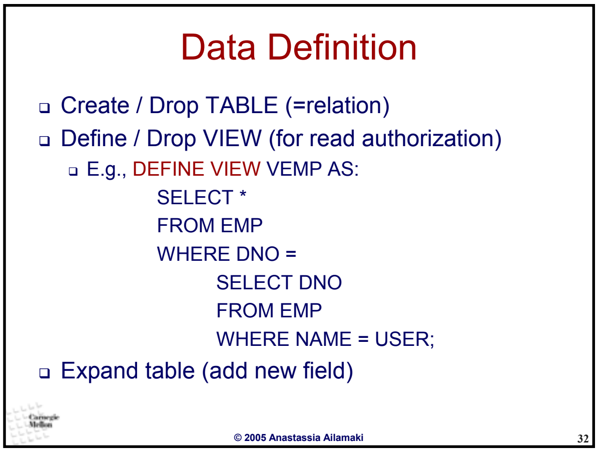


Data Manipulation

- Updates

```
UPDATE   <relation>
SET   <attribute = value>
[ WHERE  <condition> ]
```

- Insertions
- Deletions

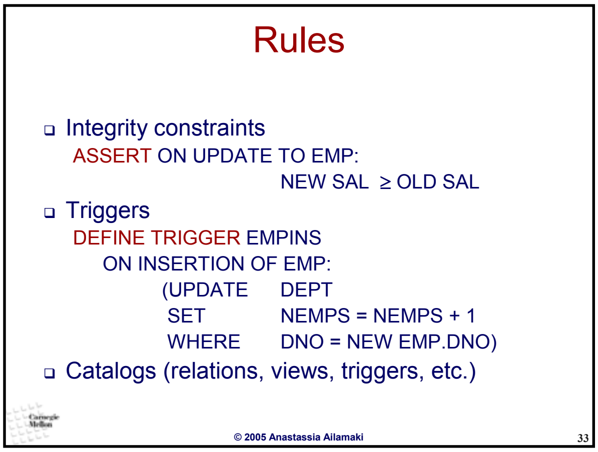


Data Definition

- Create / Drop TABLE (=relation)
- Define / Drop VIEW (for read authorization)
  - E.g., DEFINE VIEW VEMP AS:

```
SELECT *
FROM EMP
WHERE DNO =
        SELECT DNO
        FROM EMP
        WHERE NAME = USER;
```

- Expand table (add new field)



Rules

- Integrity constraints

```
ASSERT ON UPDATE TO EMP:
                        NEW SAL  ≥ OLD SAL
```

- Triggers

```
DEFINE TRIGGER EMPINS
    ON INSERTION OF EMP:
        (UPDATE     DEPT
         SET        NEMPS = NEMPS + 1
         WHERE      DNO = NEW EMP.DNO)
```

- Catalogs (relations, views, triggers, etc.)

Optimizer

- ❑ Measure mainly I/O cost
- ❑ Emphasize importance of clustering
- ❑ Based on existence of indices
- ❑ Cost model – choose cheapest plan
- ❑ Details later...

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Even more detailed Roadmap

- ❑ Intro
- ❑ Codd's paper
- ❑ System R - design
  - ❑ RDS (QL, Data control, Q-opt)
  - ➡ ❑ RSS (Segments, rel, images, links, CC, recovery)
- ❑ System R - evaluation

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RSS Segments

- ❑ Segment: logical address space
- ❑ Used to store large relations, catalogs, logs…
- ❑ No relation spans segments
- ❑ User-defined segment length
- ❑ Mapped to a set of fixed-size disk pages
  - ❑ Page map, replacement
- ❑ Segment types
  - ❑ E.g., for shared data, temporary relations, etc.

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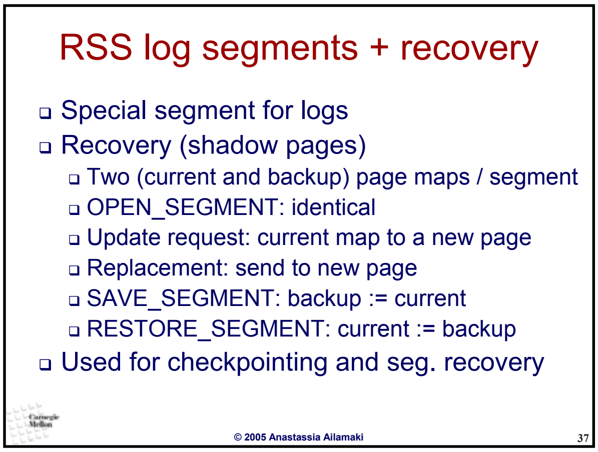
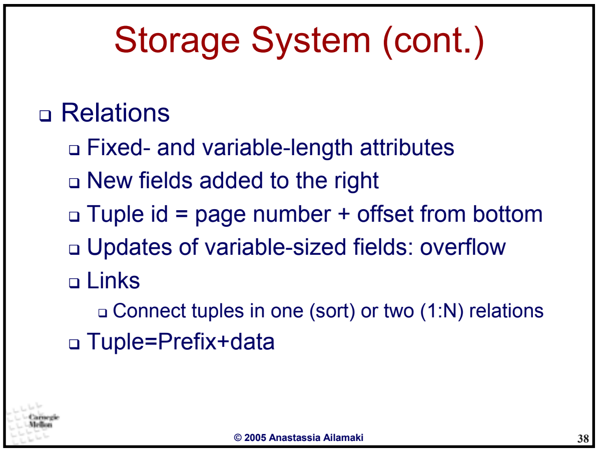


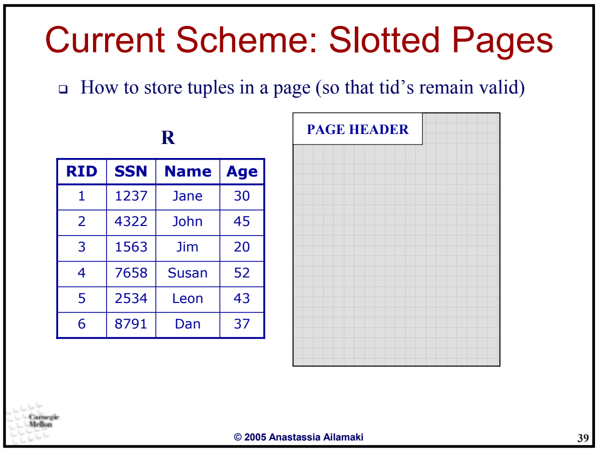
RSS log segments + recovery

- Special segment for logs
- Recovery (shadow pages)
  - Two (current and backup) page maps / segment
  - OPEN_SEGMENT: identical
  - Update request: current map to a new page
  - Replacement: send to new page
  - SAVE_SEGMENT: backup := current
  - RESTORE_SEGMENT: current := backup
- Used for checkpointing and seg. recovery



Storage System (cont.)

- Relations
  - Fixed- and variable-length attributes
  - New fields added to the right
  - Tuple id = page number + offset from bottom
  - Updates of variable-sized fields: overflow
  - Links
    - Connect tuples in one (sort) or two (1:N) relations
  - Tuple=Prefix+data



Current Scheme: Slotted Pages

- How to store tuples in a page (so that tid’s remain valid)

R

RID	SSN	Name	Age
1	1237	Jane	30
2	4322	John	45
3	1563	Jim	20
4	7658	Susan	52
5	2534	Leon	43
6	8791	Dan	37

Current Scheme: Slotted Pages

- Formal name: NSM (N-ary Storage Model)

R

RID	SSN	Name	Age
1	1237	Jane	30
2	4322	John	45
3	1563	Jim	20
4	7658	Susan	52
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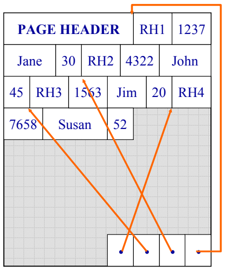

PAGE HEADER	RH1	1237
Jane	30	RH2	4322	John
45	RH3	1563	Jim	20	RH4
7658	Susan	52

- Records are stored sequentially
- Offsets to start of each record at end of page

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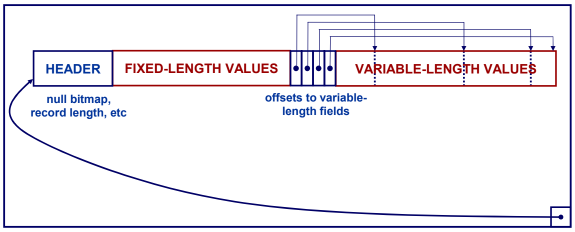
A Record in a Slotted Page



All attributes of a record are stored together

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Storage System (cont.)

- Images
  - … are B-tree indices
  - “Sort” relations by one or more key attributes
  - Clustered / non-clustered
  - Unique
  - Maintained by the RSS
- Links
  - Great for joins!

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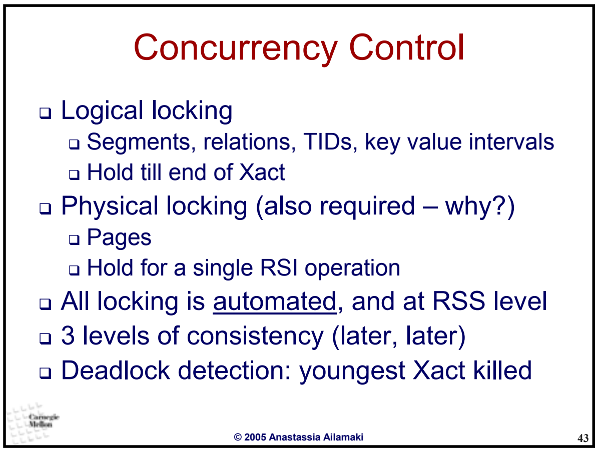
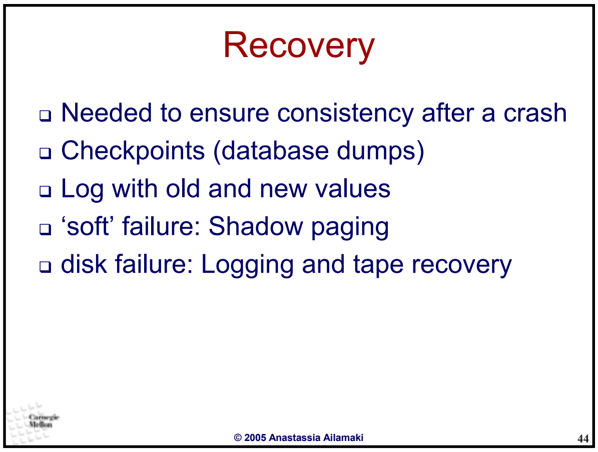


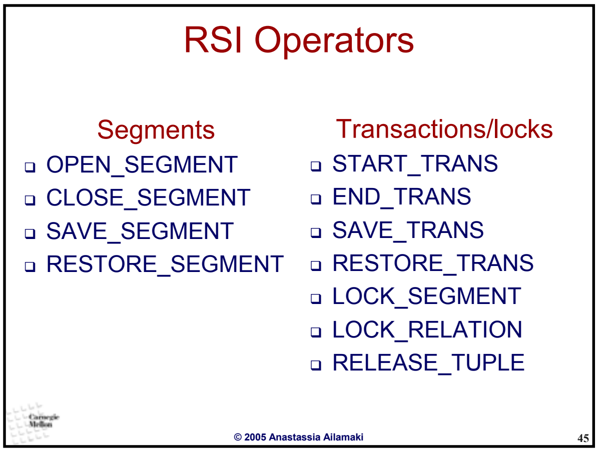
Concurrency Control

- Logical locking
  - Segments, relations, TIDs, key value intervals
  - Hold till end of Xact
- Physical locking (also required – why?)
  - Pages
  - Hold for a single RSI operation
- All locking is automated, and at RSS level
- 3 levels of consistency (later, later)
- Deadlock detection: youngest Xact killed



Recovery

- Needed to ensure consistency after a crash
- Checkpoints (database dumps)
- Log with old and new values
- ‘soft’ failure: Shadow paging
- disk failure: Logging and tape recovery



RSI Operators

Segments

- OPEN_SEGMENT
- CLOSE_SEGMENT
- SAVE_SEGMENT
- RESTORE_SEGMENT

Transactions/locks

- START_TRANS
- END_TRANS
- SAVE_TRANS
- RESTORE_TRANS
- LOCK_SEGMENT
- LOCK_RELATION
- RELEASE_TUPLE

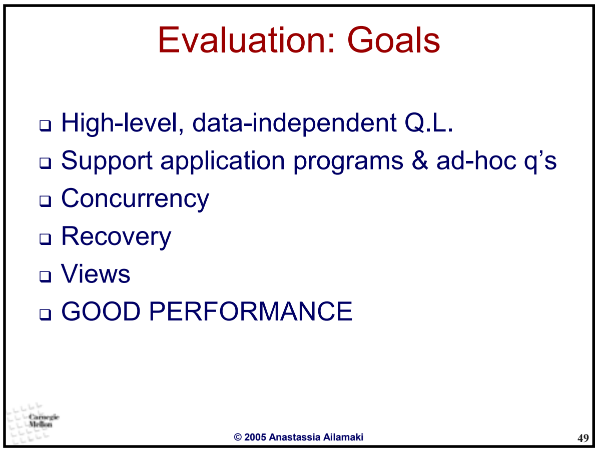
System R Summary

- RDS/RSS
- SEQUEL
- Transaction support
  - Concurrency control with hierarchical locks
  - Recovery with checkpoints, log and shadow paging
- Authorization/assertions/triggers
- Elaborate query optimizer
- Segments, images (indices), links

NEW PAPER - Break point!

Detailed Roadmap

- Intro
- Codd's paper
- System R - design
- ➡ System R - evaluation



Evaluation: Goals

- High-level, data-independent Q.L.
- Support application programs & ad-hoc q's
- Concurrency
- Recovery
- Views
- GOOD PERFORMANCE

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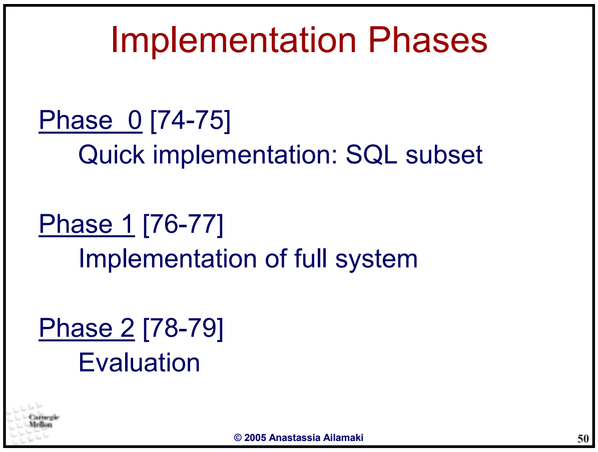

Implementation Phases

Phase 0 [74-75]
Quick implementation: SQL subset

Phase 1 [76-77]
Implementation of full system

Phase 2 [78-79]
Evaluation

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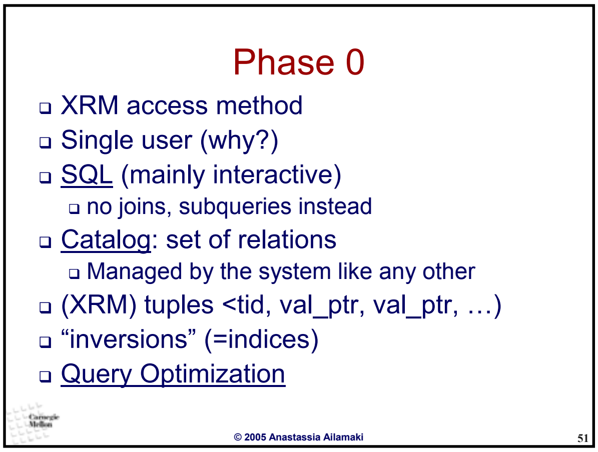

Phase 0

- XRM access method
- Single user (why?)
- SQL (mainly interactive)
  - no joins, subqueries instead
- Catalog: set of relations
  - Managed by the system like any other
- (XRM) tuples <tid, val_ptr, val_ptr, …)
- "inversions" (=indices)
- Query Optimization

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Lessons from Phase 0

- Materializing tuples is expensive
- CPU bound system - cost = aT_c + b (#I/O)
- Joins are important
- Query optimizer: should be geared to simpler queries

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Phase 1

All of the above and…

- Compilation (R. Lorie)
  - invalid modules are recompiled transparently
  - Ad-hoc queries (UFI): same treatment
- RSS paths
  - Index scan
  - Relation scan (in physical order)
  - Link scan

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Phase 1 (cont.)

- Query optimization
  - Use statistics to calculate estimates
  - Joins
    - 2-way: nested loops or sort-merge
    - N-way: tree search on 2-way combinations

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Phase 1 (cont.)

- Locking
  - abandoned predicate locking (why?)

Phase 1 (cont.)

- Locking
  - abandoned predicate locking
    - (slow to check conflicts; locks should be in RDS)
  - Locking on physical items (hierarchies)
  - “trading” (!) and intention locks

Phase 2: Evaluation

- At IBM and customer sites for 2.5 years
- General comments
  - Enthousiastic, easy installation/reconfiguration
  - OK speed for 200Mb db, 10 conc. Users
  - slow for complex joins

Phase 2: Evaluation (cont.)

- SQL
  - ?

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Phase 2: Evaluation (cont.)

- SQL
  - Simplicity, power and data independence
  - Uniform across environments (ANSI standard)
  - User-suggested extensions (exist, like, outer join)

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Phase 2: Evaluation (cont.)

- Compilation approach ?

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Phase 2: Evaluation (cont.)

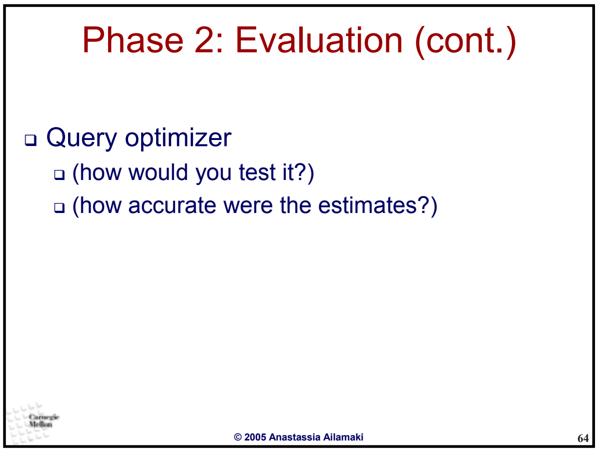
- Compilation approach was great success
  - Short, repetitive Xacts
  - Ad-hoc queries: code generation takes little time
    - Not perceivable to the user
    - Pays off after a few records have been fetched
  - Simplified design: Same approach for all queries

Phase 2: Evaluation (cont.)

- Access paths:
  - B-trees ?
  - no hashing ?
  - Links ?

Phase 2: Evaluation (cont.)

- Access paths:
  - B-trees,
  - no hashing,
  - no links
    - “essential”: unusable by optimizer, non-nav. SQL
    - “non-essential”: hard to maintain



Phase 2: Evaluation (cont.)

- Query optimizer
  - (how would you test it?)
  - (how accurate were the estimates?)

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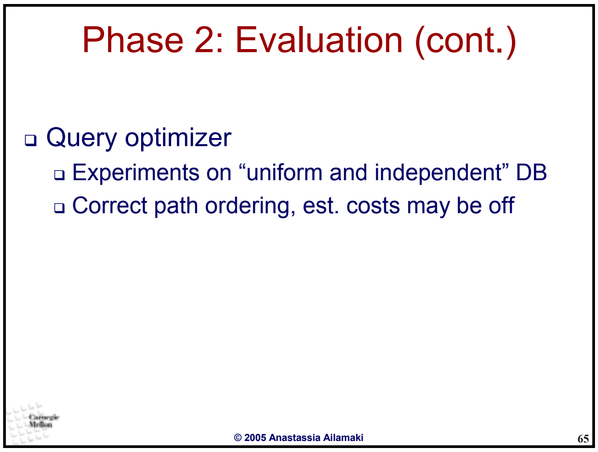

Phase 2: Evaluation (cont.)

- Query optimizer
  - Experiments on “uniform and independent” DB
  - Correct path ordering, est. costs may be off

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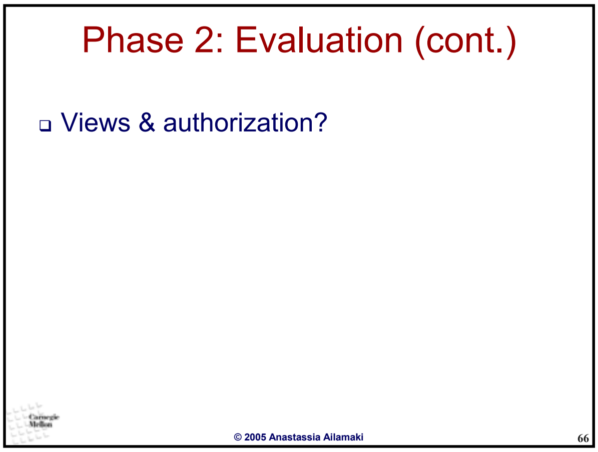

Phase 2: Evaluation (cont.)

- Views & authorization?

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Phase 2: Evaluation (cont.)

- Views & authorization: flexible & convenient

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Phase 2: Evaluation (cont.)

- Recovery
  - Shadow page algo?

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Phase 2: Evaluation (cont.)

- Recovery
  - Shadow page ⇒ performance penalties
    - (logging updates may be better)

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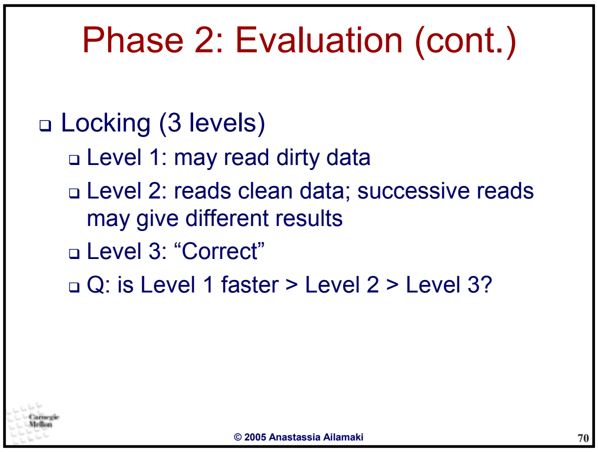

Phase 2: Evaluation (cont.)

- Locking (3 levels)
  - Level 1: may read dirty data
  - Level 2: reads clean data; successive reads may give different results
  - Level 3: “Correct”
  - Q: is Level 1 faster > Level 2 > Level 3?

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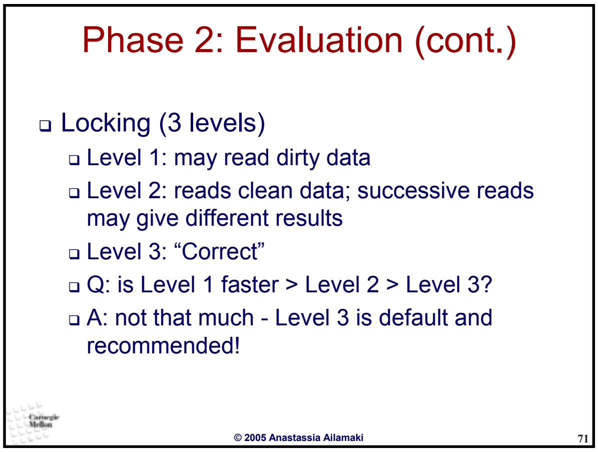

Phase 2: Evaluation (cont.)

- Locking (3 levels)
  - Level 1: may read dirty data
  - Level 2: reads clean data; successive reads may give different results
  - Level 3: “Correct”
  - Q: is Level 1 faster > Level 2 > Level 3?
  - A: not that much - Level 3 is default and recommended!

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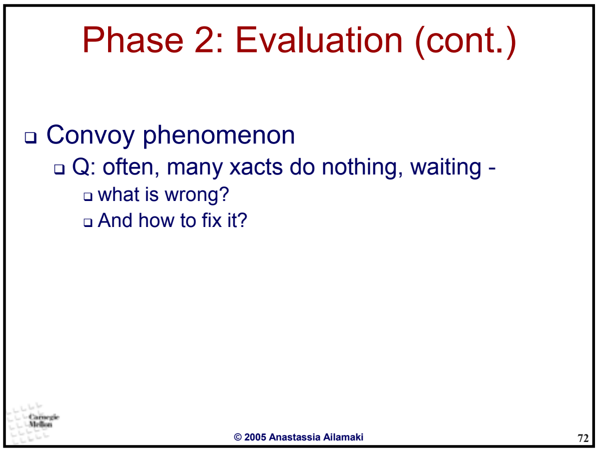

Phase 2: Evaluation (cont.)

- Convoy phenomenon
  - Q: often, many xacts do nothing, waiting -
    - what is wrong?
    - And how to fix it?

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Phase 2: Evaluation (cont.)

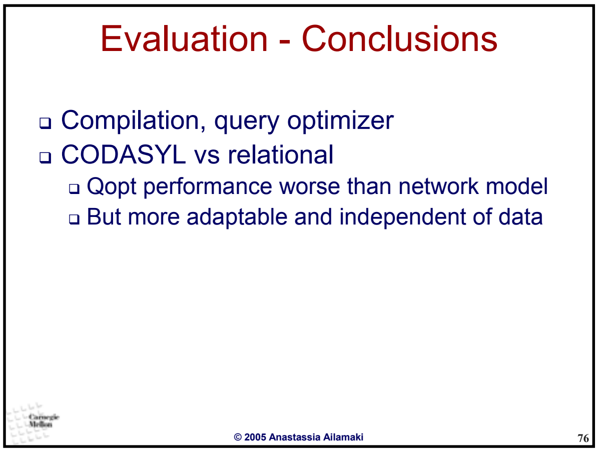
- ❑ Convoy phenomenon
  - ❑ Q: often, many xacts do nothing, waiting -
    - ❑ what is wrong?
    - ❑ And how to fix it?
  - ❑ A: Locks frequently requested / shortly released (like what?)
    - ❑ Solution: Round-robin CPU should NOT swap out job w/ high-traffic lock

Phase 2: Evaluation (cont.)

- ❑ Storing catalogs as relations: Good or bad?

Phase 2: Evaluation (cont.)

- ❑ Storing catalogs as relations: NICE!
  - ❑ Same QL for accessing everything



Evaluation - Conclusions

- Compilation, query optimizer
- CODASYL vs relational
  - Qopt performance worse than network model
  - But more adaptable and independent of data

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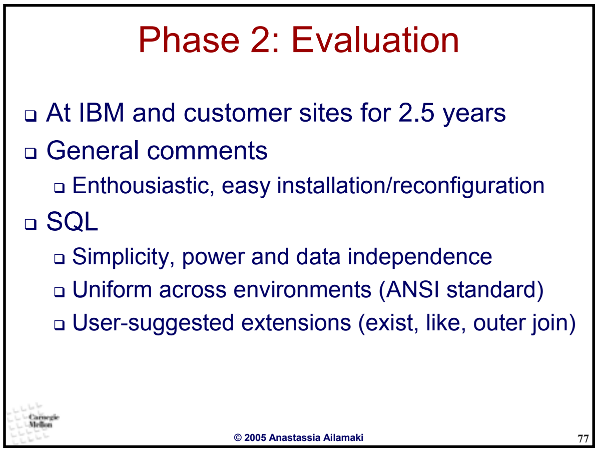

Phase 2: Evaluation

- At IBM and customer sites for 2.5 years
- General comments
  - Enthousiastic, easy installation/reconfiguration
- SQL
  - Simplicity, power and data independence
  - Uniform across environments (ANSI standard)
  - User-suggested extensions (exist, like, outer join)

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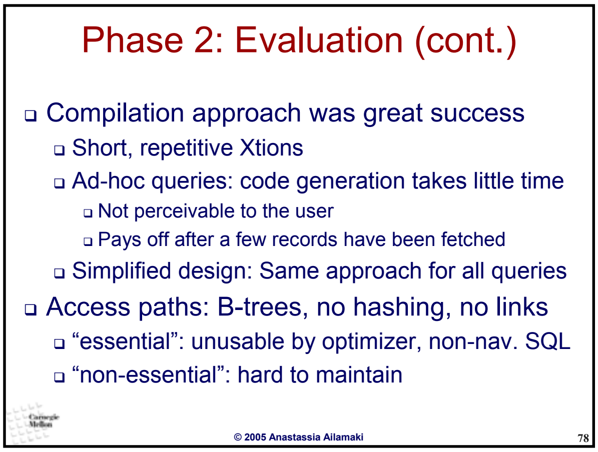

Phase 2: Evaluation (cont.)

- Compilation approach was great success
  - Short, repetitive Xtions
  - Ad-hoc queries: code generation takes little time
    - Not perceivable to the user
    - Pays off after a few records have been fetched
  - Simplified design: Same approach for all queries
- Access paths: B-trees, no hashing, no links
  - “essential”: unusable by optimizer, non-nav. SQL
  - “non-essential”: hard to maintain

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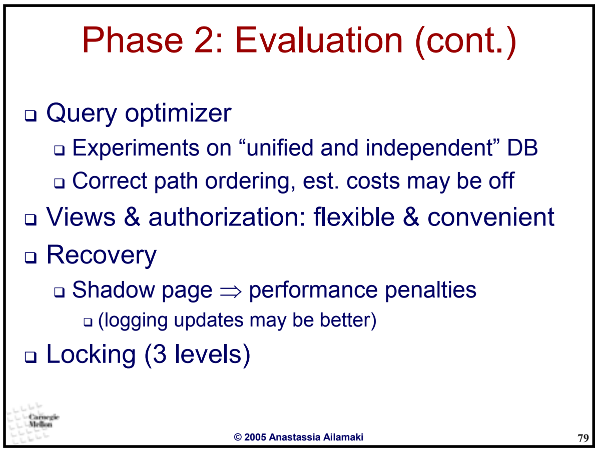
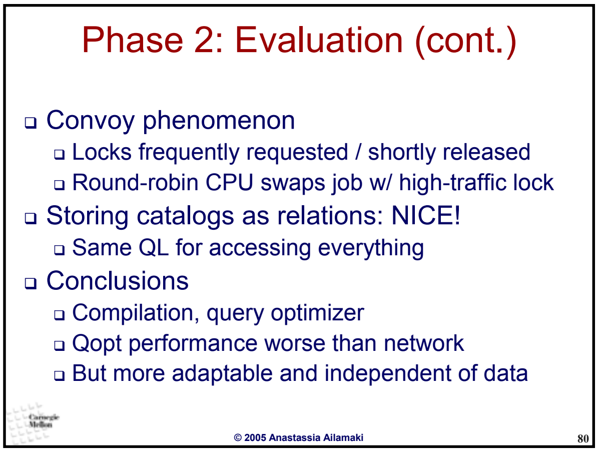


Phase 2: Evaluation (cont.)

- ❑ Query optimizer
  - ❑ Experiments on “unified and independent” DB
  - ❑ Correct path ordering, est. costs may be off
- ❑ Views & authorization: flexible & convenient
- ❑ Recovery
  - ❑ Shadow page ⇒ performance penalties
    - ❑ (logging updates may be better)
- ❑ Locking (3 levels)



Phase 2: Evaluation (cont.)

- ❑ Convoy phenomenon
  - ❑ Locks frequently requested / shortly released
  - ❑ Round-robin CPU swaps job w/ high-traffic lock
- ❑ Storing catalogs as relations: NICE!
  - ❑ Same QL for accessing everything
- ❑ Conclusions
  - ❑ Compilation, query optimizer
  - ❑ Qopt performance worse than network
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