# NORMAL FORMS

CS121: Introduction to Relational Database Systems

Fall 2014 – Lecture 18

# Equivalent Schemas



- Many different schemas can represent a set of data
  - Which one is best?
  - What does "best" even mean?
- Main goals:
  - Representation must be complete
  - Data should not be unnecessarily redundant
  - Should be easy to manipulate the information
  - Should be easy to enforce [most] constraints

# Normal Forms



- A "good" pattern for database schemas to follow is called a <u>normal form</u>
- Several different normal forms, with different constraints
- Normal forms can be formally specified
  - Can test a schema against a normal form
  - Can transform a schema into a normal form
- Goal:
  - Design schemas that satisfy a particular normal form
  - If a schema isn't "good," transform it into an appropriate normal form

# Example Schema Design



- Schema for representing loans and borrowers:
  - *customer* relation stores customer details, including a *cust_id* primary-key attribute
  - *loan*(*loan_id*, *amount*)
  - *borrower*(*cust_id*, *loan_id*)
- Many-to-many mapping
  - A customer can have multiple loans
  - A loan can be owned by multiple customers

| loan_id | amount |
|---|---|
| … | … |
| L-100 | 10000 |
| … | … |

*loan*

| cust_id | loan_id |
|---|---|
| … | … |
| 23-652 | L-100 |
| 15-202 | L-100 |
| 23-521 | L-100 |
| … | … |

*borrower*

# Larger Schema?



- Could replace *loan* and *borrower* relations with a larger, combined relation

  *bor_loan*(*cust_id*, *loan_id*, *amount*)

| cust_id | loan_id | amount |
|---|---|---|
| … | … | … |
| 23-652 | L-100 | 10000 |
| 15-202 | L-100 | 10000 |
| 23-521 | L-100 | 10000 |
| … | … | … |

*bor_loan*

- Rationale:
  - Eliminates a join when retrieving loan amounts
- Problem: mapping between customers and loans is many-to-many
  - Multiple redundant copies of *amount* to keep in sync!

# Repeated Values



- How do we *know* that this is a problem?
  - "Because we see values that appear multiple times"
  - *This isn't a good enough reason!!!*
  - Could easily have different loans with the same amount
- A repeated value doesn't *automatically* indicate a problem…

| cust_id | loan_id | amount |
|---|---|---|
| … | … | … |
| 23-652 | L-100 | 10000 |
| 19-065 | L-205 | 10000 |
| 15-202 | L-100 | 10000 |
| 23-521 | L-100 | 10000 |
| 20-419 | L-205 | 10000 |
| … | … | … |

*bor_loan*

# Back to the Enterprise



- What are the rules of the enterprise that we are modeling?
  - "Every loan must have <u>only one</u> amount."
- In other words:
  - Every loan ID corresponds to exactly one amount.
  - If there were a schema (*loan_id*, *amount*) then *loan_id* can be a primary key.
- Specified as a <u>functional dependency</u>
  - *loan_id* $\rightarrow$ *amount*
  - *loan_id* functionally determines *amount*

# Repeated Values v2.0



- *bor_loan* relation has both *loan_id* and *amount* attributes

  *bor_loan*(<u>*cust_id*</u>, <u>*loan_id*</u>, *amount*)
- But, *loan_id* → *amount*, and *loan_id* by itself <u>can't</u> be a primary key in *bor_loan*
  - Need to support many-to-many mappings between customers and loans
  - Combination of *cust_id* and *loan_id* must be a primary key, so a particular *loan_id* value can appear multiple times
- In rows with the same *loan_id* value, *amount* will have to be repeated.

# Functional Dependencies



- Functional dependencies are *very* important in schema analysis
  - Have a *lot* to do with keys!
  - "Good" schema designs are guided by functional dependencies
  - Frequently helpful to identify them during schema design
- Can formally define functional dependencies, and reason about them
- Can also specify constraints on schemas using functional dependencies

# Another Example Schema



- A "large" schema for employee information

  *employee(<u>emp_id</u>, emp_name, phone, title, salary, start_date)*

| emp_id | emp_name | phone | title | salary | start_date |
|---|---|---|---|---|---|
| … | … | … | … | … | … |
| 123-45-6789 | Jeff | 555-1234 | CTO | 120000 | 1996-03-15 |
| 314-15-9265 | Mary | 555-3141 | CFO | 120000 | 1997-08-02 |
| 987-65-4321 | Helen | 555-9876 | Developer | 90000 | 1996-05-23 |
| 101-01-0101 | Marcus | 555-1010 | Tester | 70000 | 1995-11-04 |
| … | … | … | … | | … |

*employee*

- Employee ID is unique, but other attributes could have duplicate values

# Smaller Schemas?



- Could represent this with two smaller schemas:

  *emp_ids*(*emp_id*, *emp_name*)

  *emp_details*(*emp_name*, *phone*, *title*, *salary*, *start_date*)

| emp_id | emp_name |
|---|---|
| … | … |
| 123-45-6789 | Jeff |
| 314-15-9265 | Mary |
| 987-65-4321 | Helen |
| 101-01-0101 | Marcus |
| … | … |

*emp_ids*

| emp_name | phone | title | salary | start_date |
|---|---|---|---|---|
| … | … | … | … | … |
| Jeff | 555-1234 | CTO | 120000 | 1996-03-15 |
| Mary | 555-3141 | CFO | 120000 | 1997-08-02 |
| Helen | 555-9876 | Developer | 90000 | 1996-05-23 |
| Marcus | 555-1010 | Tester | 70000 | 1995-11-04 |
| … | … | … | | … |

*emp_details*

- Generate original employee data with a join:

  *emp_ids* ⋈ *emp_details*

- Any problems with this?

# *emp_name* is not unique!



- Joins using *emp_name* can generate invalid tuples!

| emp_id | emp_name |
|---|---|
| … | … |
| 314-15-9265 | Mary |
| 161-80-3398 | Mary |
| … | … |

*emp_ids*

| emp_name | phone | title | salary | start_date |
|---|---|---|---|---|
| … | … | … | … | … |
| Mary | 555-3141 | CFO | 120000 | 1997-08-02 |
| Mary | 555-1618 | Gofer | 25000 | 1998-01-07 |
| … | … | … | | … |

*emp_details*

*emp_ids* ⋈ *emp_details*

| emp_id | emp_name | phone | title | salary | start_date |
|---|---|---|---|---|---|
| … | … | … | … | … | … |
| 314-15-9265 | Mary | 555-1618 | Gofer | 25000 | 1998-01-07 |
| 314-15-9265 | Mary | 555-3141 | CFO | 120000 | 1997-08-02 |
| 161-80-3398 | Mary | 555-3141 | CFO | 120000 | 1997-08-02 |
| 161-80-3398 | Mary | 555-1618 | Gofer | 25000 | 1998-01-07 |
| … | … | … | … | | … |

# Bad Decompositions



- This decomposition is clearly broken
  - It can’t represent the information correctly!
- Problem: enterprise needs to support different employees with the same name
- Lossy decompositions cannot accurately represent all facts about an enterprise
- Lossless decompositions can accurately represent all facts
- “Good” schema designs will avoid lossy decompositions

# First Normal Form

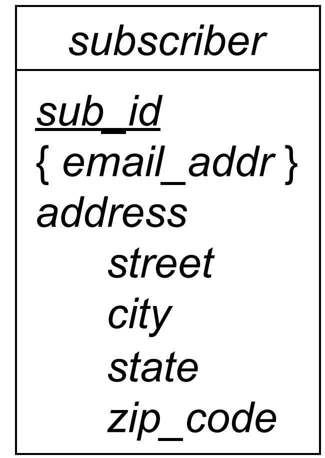


- A schema is in first normal form (1NF) if all attribute domains are atomic
  - An atomic domain has values that are indivisible units
- E-R model supports non-atomic attributes
  - Multivalued attributes
  - Composite attributes
- Relational model specifies atomic domains for attributes
  - Schemas are automatically in 1NF
  - Mapping from E-R model to relational model changes composite/multivalued attributes into an atomic form

# 1NF Example



- E-R diagram for magazine subscribers
  - *address* is composite
  - *email_addr* is multivalued




- Converts to a 1NF schema:

  *subscriber*(*sub_id*, *street*, *city*, *state*, *zip_code*)

  *sub_emails*(*sub_id*, *email_addr*)
  - The conversion rules we have discussed, *automatically* convert E-R schemas into 1NF

# 1NF and Non-Atomic Attributes



- Many, but not all, SQL DBs have non-atomic types
  - Some offer support for composite attributes
  - Some offer support for multivalued attributes
  - These are SQL extensions – not portable
- As long as you steer clear of using non-atomic attributes in primary/foreign keys, can sometimes be quite useful
  - Will likely encounter them very rarely in practice, though
  - Biggest reason: DB support for list/vector column-types isn't terribly widespread, or always very easy to use

# 1NF and Non-Atomic Attributes (2)



- Composite types:
  - e.g. defining an “address” composite type
  - Can definitely be useful for making a schema clearer, as long as they aren’t used in a key!
- Multivalued types:
  - e.g. arrays, lists, sets, vectors
  - Can sometimes be useful for storing pre-computed values that aren’t expected to change frequently
  - If you are regularly issuing queries that search through or change these values, you may need to revise your schema!
    - Should probably factor non-atomic data out into a separate table

# Other Normal Forms



- Other normal forms relate to functional dependencies
- Analysis of functional dependencies shows if a schema needs decomposed
- Keys are functional dependencies too!
- Formally define functional dependencies, and reason about them
- Define normal forms in terms of functional dependencies

# Schemas and Constraints



- Keys and functional dependencies are <u>constraints</u> that a database must satisfy
  - <u>Legal</u> relations satisfy the required constraints
  - Relation doesn't contain any tuples that violate the specified constraints
- More terminology:
  - Relation schema *R*, relation *r*(*R*)
  - A set of functional dependencies *F*
  - Relation *r* <u>satisfies</u> *F* if *r* is legal
  - When we say "*F* <u>holds</u> on *R*", specifies the set of relations with *R* as their schema, that are legal with respect to *F*

# Functional Dependencies



- Formal definition of a functional dependency:
  - Given a relation schema $R$ with attribute-sets $\alpha, \beta \subseteq R$
  - The functional dependency $\alpha \rightarrow \beta$ holds on $r(R)$ if
    $\langle\ \forall\ t_1, t_2 \in r : t_1[\alpha] = t_2[\alpha] : t_1[\beta] = t_2[\beta]\ \rangle$
- In other words:
  - For all pairs of tuples $t_1$ and $t_2$ in $r$,
    if $t_1[\alpha] = t_2[\alpha]$ then $t_1[\beta] = t_2[\beta]$
  - $\alpha$ functionally determines $\beta$

# Dependencies and Superkeys



- Given relation schema $R$, a subset $K$ of $R$ can be a superkey
  - In a relation $r(R)$, no two tuples can share the same values for attributes in $K$
- Can also say: $K$ is a superkey if $K \rightarrow R$
  - The functional dependency $K \rightarrow R$ holds if
    $\langle \forall\ t_1, t_2 \in r(R) : t_1[K] = t_2[K] : t_1[R] = t_2[R] \ \rangle$
  - $t_1[R] = t_2[R]$ (or $t_1 = t_2$) means $t_1$ and $t_2$ are the same tuple
  - The superkey $K$ functionally determines the whole relation $R$
- Functional dependencies are a more general form of constraint than superkeys are.

# The *bor_loan* Relation



- *bor_loan*(*<u>cust_id</u>*, *<u>loan_id</u>*, *amount*)
  - Functional dependency: *loan_id* → *amount*
  - "Every loan has exactly one amount."
  - Every tuple in *bor_loan* with a given *loan_id* value must have the same *amount* value
- *bor_loan* also has a primary key
  - Specifies another functional dependency
  - *cust_id*, *loan_id* → *cust_id*, *loan_id*, *amount*
  - This is not a functional dependency *specifically required* by what the enterprise needs to model
    - Can be inferred from other functional dependencies in the schema

# Trivial Dependencies



- A <u>trivial</u> functional dependency is satisfied by *all* relations!
  - For a relation $R$ containing attributes $A$ and $B$,

    $A \rightarrow A$ is a trivial dependency

    $\langle\ \forall\ t_1, t_2 \in r : t_1[A] = t_2[A] : t_1[A] = t_2[A]\ \rangle$
    - Well, duh!
  - $AB \rightarrow A$ is also a trivial dependency
    - If $t_1[AB] = t_2[AB]$, then of course $t_1[A] = t_2[A]$ too!
- In general: $\alpha \rightarrow \beta$ is trivial if $\beta \subseteq \alpha$

# Closure



- Given a set of functional dependencies, we can infer other dependencies
  - Given relation schema $R(A, B, C)$
  - If $A \rightarrow B$ and $B \rightarrow C$, holds on $R$, then $A \rightarrow C$ also holds on $R$
- Given a set of functional dependencies $F$
  - $F^+$ denotes the closure of $F$
  - $F^+$ includes $F$, and all dependencies that can be inferred from $F$. ($F \subseteq F^+$)

# Boyce-Codd Normal Form



- Eliminates all redundancy that can be discovered using functional dependencies
- Given:
  - Relation schema *R*
  - Set of functional dependencies *F*
- *R* is in BCNF with respect to *F* if:
  - For all functional dependencies $\alpha \rightarrow \beta$ in $F^+$, where $\alpha \in R$ and $\beta \in R$, at least one of the following holds:
    - $\alpha \rightarrow \beta$ is a trivial dependency
    - $\alpha$ is a superkey for *R*
- A database design is in BCNF if all schemas in the design are in BCNF

# BCNF Examples



- The *bor_loan* schema isn't in BCNF

  *bor_loan*(*<u>cust_id</u>*, *<u>loan_id</u>*, *amount*)

  - *loan_id* → *amount* holds on *bor_loan*
  - This is not a trivial dependency, and *loan_id* isn't a superkey for *bor_loan*

- The *borrower* and *loan* schemas <u>are</u> in BCNF

  *borrower*(*<u>cust_id</u>*, *<u>loan_id</u>*)

  - No nontrivial dependencies hold

  *loan*(*<u>loan_id</u>*, *amount*)

  - *loan_id* → *amount* holds on *loan*
  - *loan_id* is the primary key of *loan*

# BCNF Decomposition



- If *R* is a schema not in BCNF:
  - There is at least one nontrivial functional dependency $\alpha \rightarrow \beta$ such that $\alpha$ is not a superkey for *R*
- Replace *R* with two schemas:

  $(\alpha \cup \beta)$

  $(R - (\beta - \alpha))$
    - (stated this way in case $\alpha$ and $\beta$ overlap; usually they don't)
- *The new schemas might also not be in BCNF!*
  - Repeat this decomposition process until all schemas are in BCNF

# Undoing the Damage



- For *bor_loan*, $\alpha$ = *loan_id*, $\beta$ = *amount*

  $R$ = (*cust_id*, *loan_id*, *amount*)

  ($\alpha \cup \beta$) = (*loan_id*, *amount*)

  ($R - (\beta - \alpha)$) = (*cust_id*, *loan_id*)
- Rules successfully decompose *bor_loan* back into *loan* and *borrower* schemas

# Review



- Normal forms are guidelines for what makes a database design "good"
  - Can formally specify them
  - Can transform schemas into normal forms
- Functional dependencies specify constraints between attributes in a schema
  - A more general kind of constraint than key constraints
- Covered 1NF and BCNF
  - 1NF requires all attributes to be atomic
  - BCNF uses functional dependencies to eliminate redundant data

# Next Time!



- A big question to explore:
  - Given a set of functional dependencies *F*, we need to know what dependencies can be inferred from it!
    - i.e. given *F*, how to compute $F^+$
  - BCNF needs this information, as do other normal forms
- Does Boyce-Codd Normal Form have drawbacks?
  - (yes.)
  - Motivates the development of 3rd Normal Form