CompSci 516
Data Intensive Computing Systems

Lecture 5
Design Theory and Normalization

Instructor: Sudeepa Roy

Announcements

- HW1 deadline:
  - Due on 09/21 (Thurs), 11:55 pm, no late days
- Project proposal deadline:
  - Preliminary idea and team members due by 09/18 (Mon) by email to the instructor
  - Proposal due on sakai by 09/25 (Mon), 11:55 pm

Today

- Finish RC from Lecture 4
  - DRC
  - More example
- Normalization

DRC: example

Sailors(sid, sname, rating, age)

Boats(bid, bname, color)

Reserves(sid, bid, day)

- Find the name and age of all sailors with a rating above 7

TRC:

$\{P \mid \exists S \in Sailors\ (S.rating > 7 \wedge P.name = S.name \wedge P.age = S.age)\}$

DRC:

$\{<N, A> \mid \exists <I, N, T, A> \in Sailors \wedge T > 7\}$

- Variables are now domain variables
- We will use use TRC
  - both are equivalent

More Examples: RC

- The famous "Drinker-Beer-Bar" example!

UNDERSTAND THE DIFFERENCE IN ANSWERS
FOR ALL FOUR DRINKERS

Acknowledgement: examples and slides by Profs. Balazinska and Suciu, and the [GUW] book

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 1

Find drinkers that frequent some bar that serves some beer they like.

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 1

Find drinkers that frequent some bar that serves some beer they like.

$Q(x) = \exists y.\ \exists z.\ Frequents(x, y) \wedge Serves(y,z) \wedge Likes(x,z)$

a shortcut for
$\{x \mid \exists F \in Frequents\ \exists S \in Serves\ \exists L \in Likes\ ((L.drinker = F.drinker) \wedge (F.bar = S.bar) \wedge (S.beer = L.beer)) \wedge (x.drinker = F.drinker)\}$

The difference is that in the first one, one variable = one attribute
in the second one, one variable = one tuple (Tuple RC)
Both are equivalent and feel free to use the one that is convenient to you

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 2

Find drinkers that frequent some bar that serves some beer they like.

$Q(x) = \exists y.\ \exists z.\ \text{Frequents}(x, y) \wedge \text{Serves}(y,z) \wedge \text{Likes}(x,z)$

Find drinkers that frequent only bars that serves some beer they like.

$Q(x) = \ldots$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 2

Find drinkers that frequent some bar that serves some beer they like.

$$Q(x) = \exists y.\ \exists z.\ \text{Frequents}(x, y) \wedge \text{Serves}(y,z) \wedge \text{Likes}(x,z)$$

Find drinkers that frequent only bars that serves some beer they like.

$$Q(x) = \forall y.\ \text{Frequents}(x, y) \Rightarrow (\exists z.\ \text{Serves}(y,z) \wedge \text{Likes}(x,z))$$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 3

Find drinkers that frequent some bar that serves some beer they like.

$$Q(x) = \exists y.\ \exists z.\ \text{Frequents}(x, y) \wedge \text{Serves}(y,z) \wedge \text{Likes}(x,z)$$

Find drinkers that frequent only bars that serves some beer they like.

$$Q(x) = \forall y.\ \text{Frequents}(x, y) \Rightarrow (\exists z.\ \text{Serves}(y,z) \wedge \text{Likes}(x,z))$$

Find drinkers that frequent some bar that serves only beers they like.

$$Q(x) = \ldots$$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 3

Find drinkers that frequent some bar that serves some beer they like.

$$Q(x) = \exists y.\ \exists z.\ \text{Frequents}(x, y) \wedge \text{Serves}(y,z) \wedge \text{Likes}(x,z)$$

Find drinkers that frequent only bars that serves some beer they like.

$$Q(x) = \forall y.\ \text{Frequents}(x, y) \Rightarrow (\exists z.\ \text{Serves}(y,z) \wedge \text{Likes}(x,z))$$

Find drinkers that frequent some bar that serves only beers they like.

$$Q(x) = \exists y.\ \text{Frequents}(x, y) \wedge \forall z.(\text{Serves}(y,z) \Rightarrow \text{Likes}(x,z))$$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 4

Find drinkers that frequent some bar that serves some beer they like.

$$Q(x) = \exists y.\ \exists z.\ \text{Frequents}(x, y) \wedge \text{Serves}(y,z) \wedge \text{Likes}(x,z)$$

Find drinkers that frequent only bars that serves some beer they like.

$$Q(x) = \forall y.\ \text{Frequents}(x, y) \Rightarrow (\exists z.\ \text{Serves}(y,z) \wedge \text{Likes}(x,z))$$

Find drinkers that frequent some bar that serves only beers they like.

$$Q(x) = \exists y.\ \text{Frequents}(x, y) \wedge \forall z.(\text{Serves}(y,z) \Rightarrow \text{Likes}(x,z))$$

Find drinkers that frequent only bars that serves only beer they like.

$$Q(x) = \ldots$$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

Drinker Category 4

Find drinkers that frequent some bar that serves some beer they like.

$$Q(x) = \exists y.\ \exists z.\ Frequents(x, y) \wedge Serves(y,z) \wedge Likes(x,z)$$

Find drinkers that frequent only bars that serves some beer they like.

$$Q(x) = \forall y.\ Frequents(x, y) \Rightarrow (\exists z.\ Serves(y,z) \wedge Likes(x,z))$$

Find drinkers that frequent some bar that serves only beers they like.

$$Q(x) = \exists y.\ Frequents(x, y) \wedge \forall z.(Serves(y,z) \Rightarrow Likes(x,z))$$

Find drinkers that frequent only bars that serves only beer they like.

$$Q(x) = \forall y.\ Frequents(x, y) \Rightarrow \forall z.(Serves(y,z) \Rightarrow Likes(x,z))$$

Why should we care about RC

- RC is declarative, like SQL, and unlike RA (which is operational)
- Gives foundation of database queries in first-order logic
  - you cannot express all aggregates in RC, e.g. cardinality of a relation or sum (possible in extended RA and SQL)
  - still can express conditions like “at least two tuples” (or any constant)
- RC expression may be much simpler than SQL queries
  - and easier to check for correctness than SQL
  - power to use $\forall$ and $\Rightarrow$
  - then you can systematically go to a “correct” SQL query

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to SQL

Query: Find drinkers that like some beer (so much) that they frequent all bars that serve it

$$Q(x) = \exists y.\ Likes(x, y) \wedge \forall z.(Serves(z,y) \Rightarrow Frequents(x,z))$$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to SQL

Query: Find drinkers that like some beer so much that they frequent all bars that serve it

$$Q(x) = \exists y.\ Likes(x, y) \wedge \forall z.(Serves(z,y) \Rightarrow Frequents(x,z))$$

$$\equiv \quad Q(x) = \exists y.\ Likes(x, y) \wedge \forall z.(\neg\ Serves(z,y)\ \vee\ Frequents(x,z))$$

Step 1: Replace $\forall$ with $\exists$ using de Morgan's Laws

$\forall x\ P(x)$ same as $\neg\exists x\ \neg P(x)$

$$Q(x) = \exists y.\ Likes(x, y) \wedge\ \neg\exists z.(Serves(z,y)\ \wedge\ \neg Frequents(x,z))$$

$\neg(\neg P \vee Q)$ same as $P \wedge\ \neg\ Q$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to SQL

Query: Find drinkers that like some beer so much that they frequent all bars that serve it

$$Q(x) = \exists y.\ Likes(x, y) \wedge \neg \exists z.(Serves(z,y) \wedge \neg Frequents(x,z))$$

Step 2: Translate into SQL

```
SELECT DISTINCT L.drinker
FROM Likes L
WHERE not exists
  (SELECT S.bar
   FROM Serves S
   WHERE L.beer=S.beer
        AND not exists (SELECT *
                        FROM Frequents F
                        WHERE F.drinker=L.drinker
                          AND F.bar=S.bar))
```

We will see a "methodical and correct" translation trough "safe queries" in Datalog

Summary

- You learnt three query languages for the Relational DB model
  - SQL
  - RA
  - RC
- All have their own purposes
- You should be able to write a query in all three languages and convert from one to another
  - However, you have to be careful, not all "valid" expressions in one may be expressed in another
  - {S | ¬ (S ∈ Sailors)} – infinitely many tuples – an "unsafe" query
  - More when we do "Datalog", also see Ch. 4.4 in [RG]

Where are we now?

We learnt

- ✓ Relational Model and Query Languages
  - ✓ SQL, RA, RC
  - ✓ Postgres (DBMS)
  - ✓ XML (overview)
  - HW1

Next

- Database Normalization
  - (for good schema design)

Design Theory and Normalization

Reading Material

- Database normalization
  - [RG] Chapter 19.1 to 19.5, 19.6.1, 19.8 (overview)
  - [GUW] Chapter 3

Acknowledgement:
- The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.
- Some slides have been adapted from slides by Profs. Magda Balazinska, Dan Suciu, and Jun Yang

What will we learn?

- What goes wrong if we have redundant info in a database?
- Why and how should you refine a schema?
- Functional Dependencies – a new kind of integrity constraints (IC)
- Normal Forms
- How to obtain those normal forms

Example

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

- key = SSN

Example

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
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444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

- key = SSN
- Suppose for a given rating, there is only one hourly_wage value
- Redundancy in the table
- Why is redundancy bad?

Why is redundancy bad?

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

1. Redundant storage:
   - Some information is stored repeatedly
   - The rating value 8 corresponds to hourly_wage 10, which is stored three times

Why is redundancy bad?

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10 → 9	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

2. Update anomalies
   - If one copy of data is updated, an inconsistency is created unless all copies are similarly updated
   - Suppose you update the hourly_wage value in the first tuple using UPDATE statement in SQL -- inconsistency

Why is redundancy bad?

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

3. Insertion anomalies:
   - It may not be possible to store certain information unless some other, unrelated info is stored as well
   - We cannot insert a tuple for an employee unless we know the hourly wage for the employee's rating value

Why is redundancy bad?

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
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444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

4. Deletion anomalies:
   - It may not be possible delete certain information without losing some other information as well
   - If we delete all tuples with a given rating value (Attishoo, Smiley, Madayan), we lose the association between that rating value and its hourly_wage value

Nulls may or may not help

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

- Does not help redundant storage or update anomalies
- May help insertion and deletion anomalies
  - can insert a tuple with null value in the hourly_wage field
  - but cannot record hourly_wage for a rating unless there is such an employee (SSN cannot be null) – same for deletion

Summary: Redundancy

Therefore,

- Redundancy arises when the schema forces an association between attributes that is "not natural"
- We want schemas that do not permit redundancy
  - at least identify schemas that allow redundancy to make an informed decision (e.g. for performance reasons)
- Null value may or may not help

- Solution?
  - decomposition of schema

Decomposition

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
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555-55-5555	Madayan	35	8	40

rating	hourly_wage
8	10
5	7

Decompositions should be used judiciously

1. Do we need to decompose a relation?
   - Several normal forms
   - If a relation is not in one of them, may need to decompose further

2. What are the problems with decomposition?
   - Lossless joins (soon)
   - Performance issues -- decomposition may both
     - help performance (for updates, some queries accessing part of data), or
     - hurt performance (new joins may be needed for some queries)

Functional Dependencies (FDs)

- A functional dependency (FD) X → Y holds over relation R if, for every allowable instance *r* of R:
  - i.e., given two tuples in *r*, if the X values agree, then the Y values must also agree
  - X and Y are *sets* of attributes
  - $t1 \in r,\ t2 \in r,\ \Pi_X(t1) = \Pi_X(t2)$ implies $\Pi_Y(t1) = \Pi_Y(t2)$

A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a1	b2	c2	d1
a2	b1	c3	d1

What is an FD here?

Functional Dependencies (FDs)

- A functional dependency (FD) X → Y holds over relation R if, for every allowable instance *r* of R:
  - i.e., given two tuples in *r*, if the X values agree, then the Y values must also agree
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A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a1	b2	c2	d1
a2	b1	c3	d1

What is an FD here?

AB → C

Note that, AB is not a key

not a correct question though.. see next slide!

Functional Dependencies (FDs)

- An FD is a statement about all allowable relations
  - Must be identified based on semantics of application
  - Given some allowable instance *r1* of R, we can check if it violates some FD *f*, but we cannot tell if *f* holds over R
- K is a candidate key for R means that K →R
  - denoting R = all attributes of R too
  - However, S →R does not require S to be minimal
  - e.g. S can be a superkey

Example

- Consider relation obtained from Hourly_Emps:
  - Hourly_Emps (ssn, name, lot, rating, hourly_wage, hours_worked)

- Notation: We will denote a relation schema by listing the attributes: SNLRWH
  - Basically the set of attributes {S,N,L,R,W,H}
  - here first letter of each attribute

- FDs on Hourly_Emps:
  - ssn is the key: S → SNLRWH
  - rating determines hourly_wages: R → W

Armstrong's Axioms

- X, Y, Z are sets of attributes

- Reflexivity: If $X \supseteq Y$, then $X \rightarrow Y$
- Augmentation: If $X \rightarrow Y$, then $XZ \rightarrow YZ$ for any Z
- Transitivity: If $X \rightarrow Y$ and $Y \rightarrow Z$, then $X \rightarrow Z$

A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a1	b2	c2	d1
a2	b1	c3	d1

Apply these rules on
AB → C and check

Armstrong's Axioms

- X, Y, Z are sets of attributes

- Reflexivity: If $X \supseteq Y$, then $X \rightarrow Y$
- Augmentation: If $X \rightarrow Y$, then $XZ \rightarrow YZ$ for any Z
- Transitivity: If $X \rightarrow Y$ and $Y \rightarrow Z$, then $X \rightarrow Z$

- These are sound and complete inference rules for FDs
  - sound: then only generate FDs in F^+ for F
  - complete: by repeated application of these rules, all FDs in F^+ will be generated

Additional Rules

- Follow from Armstrong's Axioms

- Union: If $X \rightarrow Y$ and $X \rightarrow Z$, then $X \rightarrow YZ$
- Decomposition: If $X \rightarrow YZ$, then $X \rightarrow Y$ and $X \rightarrow Z$

A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a2	b2	c2	d1
a2	b2	c2	d2

$A \rightarrow B, A \rightarrow C$
$A \rightarrow BC$

$A \rightarrow BC$
$A \rightarrow B, A \rightarrow C$

Closure of a set of FDs

- Given some FDs, we can usually infer additional FDs:
  - SSN → DEPT, and DEPT → LOT implies SSN → LOT

- An FD *f* is implied by a set of FDs *F* if *f* holds whenever all FDs in *F* hold.

- F^+

  = closure of F is the set of all FDs that are implied by *F*

To check if an FD belongs to a closure

- Computing the closure of a set of FDs can be expensive
  - Size of closure can be exponential in #attributes

- Typically, we just want to check if a given FD $X \rightarrow Y$ is in the closure of a set of FDs F

- No need to compute F^+

1. Compute attribute closure of X (denoted X^+) wrt *F:*
   - Set of all attributes A such that $X \rightarrow A$ is in F^+
2. Check if Y is in X^+

Computing Attribute Closure

Algorithm:

- closure = X
- Repeat until no change
  - if there is an FD U → V in F such that U ⊆ closure, then closure = closure ∪ V

- Does F = {A → B, B → C, C D → E } imply A → E?
  - i.e, is A → E in the closure F^+? Equivalently, is E in A^+?

Normal Forms

- Question: given a schema, how to decide whether any schema refinement is needed at all?
- If a relation is in a certain normal forms, it is known that certain kinds of problems are avoided/minimized
- Helps us decide whether decomposing the relation is something we want to do

FDs play a role in detecting redundancy

Example

- Consider a relation R with 3 attributes, ABC
  - No FDs hold: There is no redundancy here – no decomposition needed
  - Given A → B: Several tuples could have the same A value, and if so, they'll all have the same B value – redundancy – decomposition may be needed if A is not a key

- Intuitive idea:
  - if there is any non-key dependency, e.g. A → B, decompose!

Normal Forms

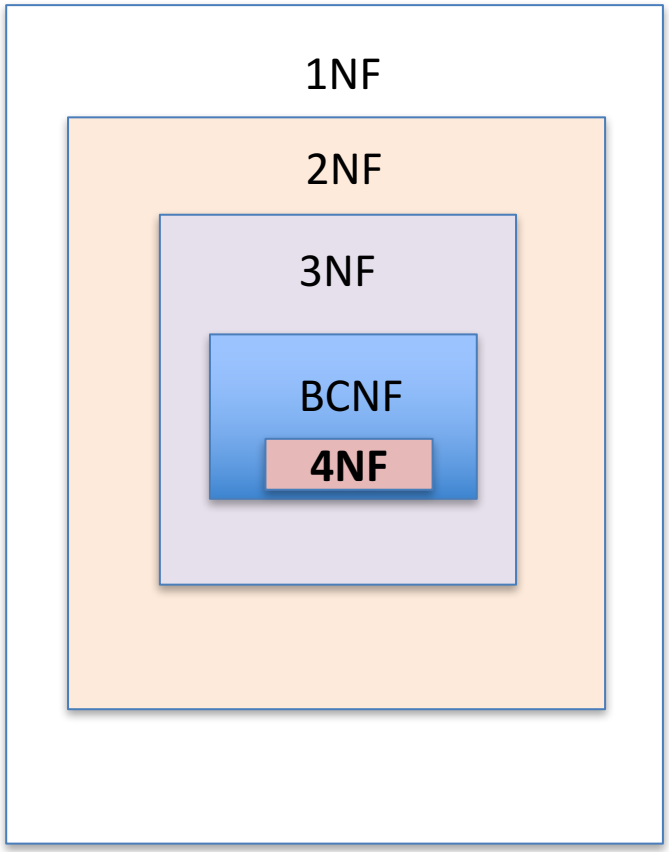
R is in 4NF

⇒ R is in BCNF

⇒ R is in 3NF

⇒ R is in 2NF (a historical one, not covered)

⇒ R is in 1NF (every field has atomic values)



Definitions next

Boyce-Codd Normal Form (BCNF)

- Relation R with FDs *F* is in BCNF if, for all X → A in F
  - A ∈ X (called a trivial FD), or
  - X contains a key for R
    - i.e. X is a superkey

Next lecture: BCNF decomposition algorithm