CompSci 516
Data Intensive Computing Systems

Lecture 4
Normalization

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Announcement

- Homework 1
  - Part-2 will be posted right after the class/office hour today
  - Contains the questions you have to answer
  - Due on Feb 9, 11:59 pm

Today's topic

- Database normalization
- Reading material
  - [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.

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
- 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

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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?

The list of hourly employees in an organization

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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

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111-11-1111	Attishoo	48	8	10	40
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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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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

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

Why is redundancy bad?

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
  - does not help redundant storage or update 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)
- Solution?

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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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

2. What are the problems with decomposition?
   - Lossless joins, Dependency preservations, Performance issues

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 <u>functional dependency</u> (FD) $X \rightarrow Y$ holds over relation R if, for every allowable instance *r* of R:
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a1	b1	c1	d1
a1	b1	c1	d2
a1	b2	c2	d1
a2	b1	c3	d1

What is an FD here?

$AB \rightarrow C$

Note that, AB is not a key

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
  - 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}

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

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*

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 $AB \rightarrow C$ and check

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- 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

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

$A \rightarrow BC$

$A \rightarrow BC$

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

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* → *Y* is in the closure of a set of FDs *F*

- No need to compute F^+

- Compute attribute closure of X (denoted X^+) wrt *F:*
  - Set of all attributes A such that X → A is in F^+

Computing Attribute Closure

Algorithm:

- closure = X
- Repeat until no change
  - if there is an FD $U \rightarrow V$ in F such that $U \subseteq$ closure, then closure = closure $\cup$ V
- Check if Y is in X^+

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

Normal Forms

- Question: given a schema, how to decide whether any schema refinement is needed
- 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

- Consider a relation R with 3 attributes, ABC
  - No FDs hold: There is no redundancy here – no decomposition needed
  - Given $A \rightarrow B$: 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
- Sometimes other subtle integrity constraints help detect redundancy

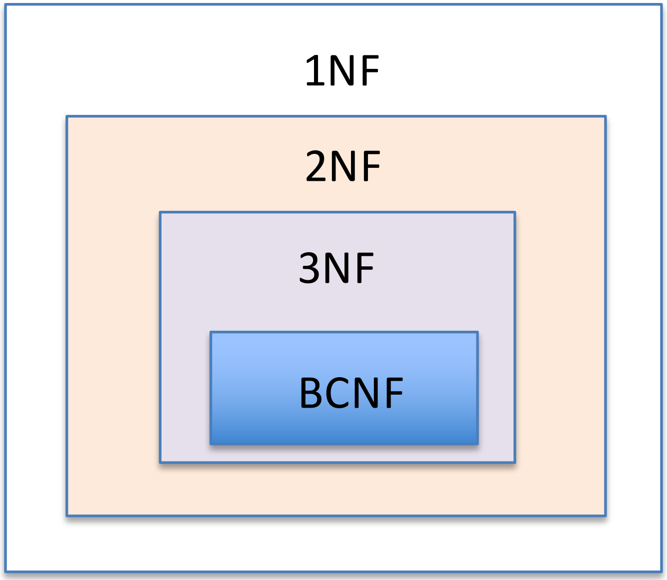
Normal Forms

R is in BCNF

$\Rightarrow$ R is in 3NF

$\Rightarrow$ R is in 2NF (a historical one)

$\Rightarrow$ 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 ϵ X (called a trivial FD), or
  - X contains a key for R
    - i.e. X is a superkey

Observations: BCNF

R is in BCNF if the only non-trivial FDs that hold over R are key constraints

- each tuple has a key and a bunch of other attributes
- No dependency in R that can be predicted using FDs alone
- If we are shown two tuples that agree upon the X value, we cannot infer the A value in one tuple from the A value in the other.
- If example relation is in BCNF, the 2 tuples must be identical, since X is a key

X	Y	A
x	y1	a
x	y2	?

Third Normal Form (3NF)

- Relation R with FDs *F* is in 3NF if, for all $X \rightarrow A$ in F^+
  - $A \in X$ (called a trivial FD), or
  - X contains a key for R, or
  - A is part of some key for R.

two conditions for BCNF

- Minimality of a key is crucial in third condition in 3NF
  - every attribute is part of some superkey (= set of all attributes)

Partial and Transitive Dependencies

If 3NF violated by $X \rightarrow A$, one of the following holds:

- X is a subset of some key K
  - We store (X, A) pairs redundantly
  - called partial dependency
  - 2NF = no partial dependency
- X is not a proper subset of any key
  - There is a chain of FDs $K \rightarrow X \rightarrow A$, which means that we cannot associate an X value with a K value unless we also associate an A value with an X value
  - Recall hourly_employee – cannot store the rating R for an employee without knowing the hourly wage
  - called transitive dependency

Observations: 3NF

- If R is in BCNF, obviously in 3NF.
- If R is in 3NF, some redundancy is possible

- Example:
  - X → A and X is not part of a key
  - Reserves(S, B, D, C), C = credit card, S → C and C → S
  - Since SBD is a key, CBD is also a key, 3NF not violated, but some redundancy

- It is a compromise, used when BCNF not achievable
  - e.g., no ``good'' decomposirion, or performance considerations
- Finding all keys of a schema and detecting if a schema is in 3NF is "NP-complete"

Decomposition of a Relation Schema

- Consider relation R contains attributes A1 ... An

- A decomposition of R consists of replacing R by two or more relations such that:
  - Each new relation schema contains a subset of the attributes of R (and no attributes that do not appear in R), and
  - Every attribute of R appears as an attribute of one of the new relations
  - E.g., Can decompose SNLRWH into SNLRH and RW

- What are the potential problems with an arbitrary decomposition?

Problems with Decompositions

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)

→

1. SNLRH
2. RW

1. Some queries become more expensive
   – e.g., How much did sailor Joe earn? (salary = W*H) – now needs a join after decomposition

2. We may not be able to reconstruct the original relation from the decomposition
   – Fortunately, not in the SNLRWH example

3. Checking some original dependencies may require joining the instances of the decomposed relations
   – Fortunately, not in the SNLRWH example

- Tradeoff: Must consider these issues vs. redundancy

Good properties of decomposition

- Lossless join decomposition
- Dependency preserving decomposition

Lossless Join Decompositions

- Decomposition of R into X and Y is lossless-join w.r.t. a set of FDs F if, for every instance *r* that satisfies F: $\pi_X(r) \bowtie \pi_Y(r) = r$

- It is always true that $\pi_X(r) \bowtie \pi_Y(r) \subseteq r$

- In general, the other direction does not hold
  - If it does, the decomposition is lossless-join

S	P	D
s1	p1	d1
s2	p2	d2
s3	p1	d3

Decompose into SP and PD
is the decomposition lossless?

Lossless Join Decompositions

- Suppose R with FD F is decomposed into attributes R1 and R2
- The decomposition is lossless if and only if F+ contains
  - either R1 ∩ R2 → R1
  - or R1 ∩ R2 → R2
- Recall SNLRWH and FD R → W
  - Violates 3NF: R does not contain a key, W is not part of a key
  - Decompose into SNLRH and RW
  - R is common to both and R → W
  - lossless
- If X → Y, and X, Y are disjoint, then decomposing into R-Y and XY is lossless

Dependency Preserving Decomposition

- Consider CSJDPQV, C is key, JP → C and SD → P
  - Lossless decomposition: CSJDQV and SDP
  - Problem: Checking JP → C requires a join

- Dependency preserving decomposition:
  - If R is decomposed into X, Y and Z, and we enforce the FDs that hold on X, on Y and on Z, then all FDs that were given to hold on R must also hold

Projection of set of FDs F

Projection of set of FDs F:

- Suppose R is decomposed into X, Y...
- Projection of F onto X (denoted F_X) is the set of FDs $U \rightarrow V$ in F^+ such that all attributes from both U, V are in X
- Note: projection from F^+, not only F

Dependency Preserving Decomposition (formal definition)

- Decomposition of R into X and Y is **dependency preserving** if $(F_X \cup F_Y)^+ = F^+$
  - i.e., if we consider only dependencies in the closure F^+ that can be checked in X without considering Y, and in Y without considering X, these imply all dependencies in F^+
- Important to consider F^+, not only F, in this definition:

Dependency Preserving Decomposition (example)

- Example
  - ABC
  - F = {A → B, B → C, C → A}
  - F+ = {A → B, B → C, C → A, B → A, C → B, A → C}
  - ABC decomposed into AB and BC
  - Is this dependency preserving?
    - Yes! check yourself using the definition from the previous slide

- Dependency preserving does not imply lossless join
  - Check: ABC, A → B, decomposed into AB and BC
  - And vice-versa (see example on slide#38)

Algorithm: Decomposition into BCNF

- Input: relation R with FDs F

If $X \rightarrow Y$ violates BCNF, decompose R into R - Y and XY.

Repeat until all new relations are in BCNF w.r.t. the given F

- Gives a collection of relations that are
  - in BCNF
  - lossless join decomposition
  - and guaranteed to terminate
  - but a dependency-preserving decomposition may not exist (example in book)

Decomposition into BCNF (example)

- CSJDPQV, key C, F = {JP → C, SD → P, J → S}
  - To deal with SD → P, decompose into SDP, CSJDQV.
  - To deal with J → S, decompose CSJDQV into JS and CJDQV

- Note:
  - several dependencies may cause violation of BCNF
  - The order in which we pick them may lead to very different sets of relations

Other kinds of dependencies

- Multi-valued dependencies
- Join dependencies

- FDs are the most common and important
  - But these help identify redundancy that cannot be detected with FDs alone
  - Some high-level overview next

Multivalued Dependencies

Course (C)	Teacher (T)	Book (B)
Physics101	Green	Mechanics
Physics101	Green	Optics
Physics101	Brown	Mechanics
Physics101	Brown	Optics
Maths301	Green	Mechanics
Maths301	Green	Vector
Maths301	Green	Geometry

- No FDs, Key = CTB
  - Already in BCNF
- C is independent of B – called Multi-valued Dependency
  - Redundancy – won't be considered if we look at FDs only
- Redundancy can be eliminated by decomposing CTB into CT and CB

Multivalued Dependencies

Course (C)	Teacher (T)	Book (B)
Physics101	Green	Mechanics
Physics101	Green	Optics
Physics101	Brown	Mechanics
Physics101	Brown	Optics
Maths301	Green	Mechanics
Maths301	Green	Vector
Maths301	Green	Geometry

- Multi-valued Dependency
  - X →→ Y (here C →→ T)
  - in every instance, each X value is associated with a set of Y values independent of the other attributes
- Considered in 4NF

Inclusion Dependency

- Some columns are contained in other columns
  - Usually of a second relation
  - Foreign keys are one example
  - Considered in 5NF

Summary of Schema Refinement

- Functional dependencies
- Normal forms
  - (1NF, 2NF), 3NF, BCNF, (4NF, 5NF)
- Lossless join decomposition
- Dependency preserving decomposition
- BCNF decomposition algorithm

- Next topic: database internals – storage, indexing, hashing