



Chapter 7: Normalization

Database System Concepts, 7th Ed.
©Silberschatz, Korth and Sudarshan
See www.db-book.com for conditions on re-use



Features of Good Relational Designs

- Suppose we combine *instructor* and *department* into *in_dep*, which represents the natural join on the relations *instructor* and *department*

ID	name	salary	dept_name	building	budget
22222	Einstein	95000	Physics	Watson	70000
12121	Wu	90000	Finance	Painter	120000
32343	El Said	60000	History	Painter	30000
43568	Katz	75000	Comp. Sci.	Taylor	100000
98345	Kim	80000	Elec. Eng.	Taylor	85000
76766	Crick	72000	Biology	Watson	90000
10101	Srinivasan	63000	Comp. Sci.	Taylor	100000
50385	Califert	62000	History	Painter	50000
83821	Brandt	92000	Comp. Sci.	Taylor	100000
15151	Mozart	40000	Music	Packard	80000
33456	Gold	87000	Physics	Watson	70000
76543	Singh	80000	Finance	Painter	120000

- There is repetition of information
- Need to use null values (if we add a new department with no instructors)

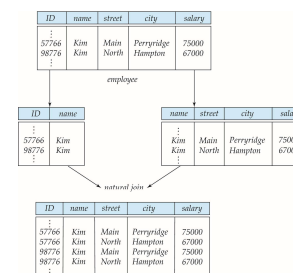
Database System Concepts - 7th Edition

7.4

©Silberschatz, Korth and Sudarshan



A Lossy Decomposition



Database System Concepts - 7th Edition

7.7

©Silberschatz, Korth and Sudarshan



Outline

- Features of Good Relational Design
- Functional Dependencies
- Decomposition Using Functional Dependencies
- Normal Forms
- Functional Dependency Theory
- Algorithms for Decomposition using Functional Dependencies
- Decomposition Using Multivalued Dependencies
- More Normal Form
- Atomic Domains and First Normal Form
- Database-Design Process
- Modeling Temporal Data

Database System Concepts - 7th Edition

7.2

©Silberschatz, Korth and Sudarshan



A Combined Schema Without Repetition

Not all combined schemas result in repetition of information

- Consider combining relations
 - sec_class(sec_id, building, room_number)* and
 - section(course_id, sec_id, semester, year)*
 into one relation
 - section(course_id, sec_id, semester, year, building, room_number)*
- No repetition in this case

Database System Concepts - 7th Edition

7.5

©Silberschatz, Korth and Sudarshan



Lossless Decomposition

- Let *R* be a relation schema and let *R*₁ and *R*₂ form a decomposition of *R*. That is *R* = *R*₁ ∪ *R*₂
- We say that the decomposition is a **lossless decomposition** if there is no loss of information by replacing *R* with the two relation schemas *R*₁ ∪ *R*₂
- Formally,

$$\Pi_{R_1}(r) \bowtie \Pi_{R_2}(r) = r$$
- And, conversely a decomposition is lossy if

$$r \subset \Pi_{R_1}(r) \bowtie \Pi_{R_2}(r)$$

Database System Concepts - 7th Edition

7.8

©Silberschatz, Korth and Sudarshan



Overview of Normalization

Database System Concepts - 7th Edition

7.3

©Silberschatz, Korth and Sudarshan



Decomposition

- The only way to avoid the repetition-of-information problem in the *in_dep* schema is to decompose it into two schemas – *instructor* and *department* schemas.
- Not all decompositions are good. Suppose we decompose

employee(ID, name, street, city, salary)
into
employee1(ID, name)
employee2(name, street, city, salary)

- The problem arises when we have two employees with the same name
- The next slide shows how we lose information – we cannot reconstruct the original *employee* relation – and so, this is a **lossy decomposition**.

Database System Concepts - 7th Edition

7.6

©Silberschatz, Korth and Sudarshan



Example of Lossless Decomposition

- Decomposition of *R* = (A, B, C)
*R*₁ = (A, B) *R*₂ = (B, C)

A	B	C
α	1	A
β	2	B

r

A	B
α	1
β	2

$\Pi_{AB}(r)$

B	C
1	A
2	B

$\Pi_{BC}(r)$


A	B	C
α	1	A
β	2	B

$\Pi_A(r) \bowtie \Pi_B(r)$

Database System Concepts - 7th Edition

7.9


©Silberschatz, Korth and Sudarshan



Normalization Theory

- Decide whether a particular relation R is in "good" form.
- If R is not in "good" form, decompose it into set of relations $\{R_1, R_2, \dots, R_n\}$ such that
 - Each relation is in good form
 - The decomposition is a **lossless decomposition**
- Our theory is based on:
 - Functional dependencies
 - Multivalued dependencies

Database System Concepts - 7th Edition 7.10 ©Berschütz, Korth and Sudarshan




Functional Dependencies Definition

- Let R be a relation schema
 $\alpha \subseteq R$ and $\beta \subseteq R$
- The **functional dependency**
 $\alpha \rightarrow \beta$
holds on R if and only if for any legal relations $r(R)$, whenever any two tuples t_1 and t_2 of r agree on the attributes α , they also agree on the attributes β . That is,

$$t_1[\alpha] = t_2[\alpha] \Rightarrow t_1[\beta] = t_2[\beta]$$
- Example: Consider $r(A,B)$ with the following instance of r .

1	4
1	5
3	7
- On this instance, $B \rightarrow A$ hold; $A \rightarrow B$ does **NOT** hold,


Database System Concepts - 7th Edition 7.13 ©Berschütz, Korth and Sudarshan



Use of Functional Dependencies

- We use functional dependencies to:
 - To test relations to see if they are legal under a given set of functional dependencies.
 - If a relation r is legal under a set F of functional dependencies, we say that r **satisfies F** .
 - To specify constraints on the set of legal relations
 - We say that F **holds on R** if all legal relations on R satisfy the set of functional dependencies F .
- Note: A specific instance of a relation schema may satisfy a functional dependency even if the functional dependency does not hold on all legal instances.
 - For example, a specific instance of *instructor* may, by chance, satisfy $name \rightarrow ID$.


Database System Concepts - 7th Edition 7.16 ©Berschütz, Korth and Sudarshan



Functional Dependencies

- Attributes of R may be dependent each other.
- For example, some of the constraints that are expected to hold in a university database are:
 - Students and instructors are uniquely identified by their ID.
 - Each student and instructor has only one name.
 - Each instructor and student is (primarily) associated with only one department.
 - Each department has only one value for its budget, and only one associated building.


Database System Concepts - 7th Edition 7.11 ©Berschütz, Korth and Sudarshan



Closure of a Set of Functional Dependencies

- Given a set F set of functional dependencies, there are certain other functional dependencies that are logically implied by F .
 - If $A \rightarrow B$ and $B \rightarrow C$, then we can infer that $A \rightarrow C$
 - etc.
- The set of all functional dependencies logically implied by F is the **closure** of F .
- We denote the **closure** of F by F^+ .


Database System Concepts - 7th Edition 7.14 ©Berschütz, Korth and Sudarshan



Trivial Functional Dependencies

- A functional dependency is **trivial** if it is satisfied by all instances of a relation
- Example:
 - $ID, name \rightarrow ID$
 - $name \rightarrow name$
- In general, $\alpha \rightarrow \beta$ is trivial if $\beta \subseteq \alpha$


Database System Concepts - 7th Edition 7.17 ©Berschütz, Korth and Sudarshan



Functional Dependencies (Cont.)

- An instance of a relation that satisfies all such real-world constraints is called a **legal instance** of the relation;
- A legal instance of a database is one where all the relation instances are legal instances
- Constraints on the set of legal relations.
- Require that the value for a certain set of attributes determines uniquely the value for another set of attributes.
- A **functional dependency** is a generalization of the notion of a **key**.


Database System Concepts - 7th Edition 7.12 ©Berschütz, Korth and Sudarshan



Keys and Functional Dependencies

- K is a superkey for relation schema R if and only if $K \rightarrow R$
- K is a candidate key for R if and only if
 - $K \rightarrow R$, and
 - for no $\alpha \subset K$, $\alpha \rightarrow R$
- Functional dependencies allow us to express constraints that cannot be expressed using superkeys. Consider the schema:
 $in_dep(ID, name, salary, dept_name, building, budget)$.
 We expect these functional dependencies to hold:
 $dept_name \rightarrow building$
 $ID \rightarrow building$
 but would not expect the following to hold:
 $dept_name \rightarrow salary$

Database System Concepts - 7th Edition 7.15 ©Berschütz, Korth and Sudarshan




Lossless Decomposition

- We can use functional dependencies to show when certain decomposition are lossless.
- For the case of $R = (R_1, R_2)$, we require that for all possible relations r on schema R

$$r = \Pi_{R_1}(r) \bowtie \Pi_{R_2}(r)$$
- A decomposition of R into R_1 and R_2 is **lossless decomposition** if at least one of the following dependencies is in F :
 - $R_1 \cap R_2 \rightarrow R_1$
 - $R_1 \cap R_2 \rightarrow R_2$
- The above functional dependencies are a sufficient condition for lossless join decomposition; the dependencies are a necessary condition only if all constraints are functional dependencies


Database System Concepts - 7th Edition 7.18 ©Berschütz, Korth and Sudarshan



Example


- $R = (A, B, C)$
 $F = (A \rightarrow B, B \rightarrow C)$
- $R_1 = (A, B), R_2 = (B, C)$
 - Lossless decomposition:
 $R_1 \cap R_2 = (B)$ and $B \rightarrow BC$
- $R_1 = (A, B), R_2 = (A, C)$
 - Lossy decomposition:
 $R_1 \cap R_2 = (A)$ and $A \rightarrow AB$

Database System Concepts - 7th Edition 7.19 ©Berschütz, Korth and Sudarshan



Normal Forms


Database System Concepts - 7th Edition 7.22 ©Berschütz, Korth and Sudarshan



Decomposing a Schema into BCNF

- Let R be a schema R that is not in BCNF. Let $\alpha \rightarrow \beta$ be the FD that causes a violation of BCNF.
- We decompose R into:
 - $(\alpha \cup \beta)$
 - $(R - (\beta - \alpha))$
- In our example of in_dep ,
 - $\alpha = dept_name$
 - $\beta = building, budget$
 - and in_dep is replaced by
 - $(\alpha \cup \beta) = (dept_name, building, budget)$
 - $(R - (\beta - \alpha)) = (ID, name, dept_name, salary)$


Database System Concepts - 7th Edition 7.28 ©Berschütz, Korth and Sudarshan



Dependency Preservation

- Testing functional dependency constraints each time the database is updated can be costly
- It is useful to design the database in a way that constraints can be tested efficiently.
- If testing a functional dependency can be done by considering just one relation, then the cost of testing this constraint is low
- When decomposing a relation it is possible that it is no longer possible to do the testing without having to perform a Cartesian Product.
- A decomposition that makes it computationally hard to enforce functional dependency is said to be NOT **dependency preserving**.


Database System Concepts - 7th Edition 7.29 ©Berschütz, Korth and Sudarshan



Boyce-Codd Normal Form

- A relation schema R is in BCNF with respect to a set F of functional dependencies if for all functional dependencies in F of the form $\alpha \rightarrow \beta$ where $\alpha \subseteq R$ and $\beta \subseteq R$, at least one of the following holds:
 - $\alpha \rightarrow \beta$ is trivial (i.e., $\beta \subseteq \alpha$)
 - α is a superkey for R


Database System Concepts - 7th Edition 7.33 ©Berschütz, Korth and Sudarshan



Example

- $R = (A, B, C)$
 $F = (A \rightarrow B, B \rightarrow C)$
- $R_1 = (A, B), R_2 = (B, C)$
 - Lossless-join decomposition:
 $R_1 \cap R_2 = (B)$ and $B \rightarrow BC$
 - Dependency preserving
- $R_1 = (A, B), R_2 = (A, C)$
 - Lossy-join decomposition:
 $R_1 \cap R_2 = (A)$ and $A \rightarrow AB$
 - Not dependency preserving (cannot check $B \rightarrow C$ without computing $R_1 \bowtie R_2$)


Database System Concepts - 7th Edition 7.28 ©Berschütz, Korth and Sudarshan



Dependency Preservation Example

- Consider a schema:
 $dept_advisor(s_ID, i_ID, department_name)$
- With function dependencies:
 $i_ID \rightarrow dept_name$
 $s_ID, dept_name \rightarrow i_ID$
- In the above design we are forced to repeat the department name once for each time an instructor participates in a $dept_advisor$ relationship.
- To fix this, we need to decompose $dept_advisor$
- Any decomposition will not include all the attributes in $s_ID, dept_name \rightarrow i_ID$
- Thus, the composition NOT be dependency preserving


Database System Concepts - 7th Edition 7.31 ©Berschütz, Korth and Sudarshan



Boyce-Codd Normal Form (Cont.)

- Example schema that is **not** in BCNF:
 $in_dep(iD_name, salary_dept_name_building, budget)$
- because :
 - $dept_name \rightarrow building, budget$
 - holds on in_dep
 - but
 - $dept_name$ is not a superkey
- When decompose in_dep into $instructor$ and $department$
 - $instructor$ is in BCNF
 - $department$ is in BCNF


Database System Concepts - 7th Edition 7.34 ©Berschütz, Korth and Sudarshan



BCNF and Dependency Preservation

- It is not always possible to achieve both BCNF and dependency preservation
- Consider a schema:
 $dept_advisor(s_ID, i_ID, department_name)$
- With function dependencies:
 $i_ID \rightarrow dept_name$
 $s_ID, dept_name \rightarrow i_ID$
- $dept_advisor$ is not in BCNF
 - i_ID is not a superkey.
- Any decomposition of $dept_advisor$ will not include all the attributes in $s_ID, dept_name \rightarrow i_ID$
- Thus, the composition is NOT be dependency preserving


Database System Concepts - 7th Edition 7.37 ©Berschütz, Korth and Sudarshan



Third Normal Form

- A relation schema R is in **third normal form (3NF)** if for all: $\alpha \rightarrow \beta$ in F^+ at least one of the following holds:
 - $\alpha \rightarrow \beta$ is trivial (i.e., $\beta \in \alpha$)
 - α is a superkey for R
 - Each attribute A in $\beta - \alpha$ is contained in a candidate key for R .
(NOTE: each attribute may be in a different candidate key)
- If a relation is in BCNF it is in 3NF (since in BCNF one of the first two conditions above must hold).
- Third condition is a minimal relaxation of BCNF to ensure dependency preservation (will see why later).


Database System Concepts - 7th Edition 7.28 ©Berschütz, Korth and Sudarshan



Comparison of BCNF and 3NF

- Advantages to 3NF over BCNF: It is always possible to obtain a 3NF design without sacrificing losslessness or dependency preservation.
- Disadvantages to 3NF:
 - We may have to use null values to represent some of the possible meaningful relationships among data items.
 - There is the problem of repetition of information.


Database System Concepts - 7th Edition 7.31 ©Berschütz, Korth and Sudarshan



How good is BCNF? (Cont.)

- There are no non-trivial functional dependencies and therefore the relation is in BCNF
- Insertion anomalies – i.e., if we add a phone 981-992-3443 to 99999, we need to add two tuples
(99999, David, 981-992-3443)
(99999, William, 981-992-3443)


Database System Concepts - 7th Edition 7.34 ©Berschütz, Korth and Sudarshan



3NF Example

- Consider a schema:
 $dept_advisor(s_ID, l_ID, dept_name)$
- With function dependencies:
 $l_ID \rightarrow dept_name$
 $s_ID, dept_name \rightarrow l_ID$
- Two candidate keys = $\{s_ID, dept_name\}$, $\{s_ID, l_ID\}$
- We have seen before that $dept_advisor$ is not in BCNF
- R , however, is in 3NF
 - $s_ID, dept_name$ is a superkey
 - $l_ID \rightarrow dept_name$ and l_ID is NOT a superkey, but:
 - $\{dept_name\} - \{l_ID\} = \{dept_name\}$ and
 - $dept_name$ is contained in a candidate key


Database System Concepts - 7th Edition 7.29 ©Berschütz, Korth and Sudarshan



Goals of Normalization

- Let R be a relation scheme with a set F of functional dependencies.
- Decide whether a relation scheme R is in "good" form.
- In the case that a relation scheme R is not in "good" form, need to decompose it into a set of relation scheme $\{R_1, R_2, \dots, R_n\}$ such that:
 - Each relation scheme is in good form
 - The decomposition is a lossless decomposition
 - Preferably, the decomposition should be dependency preserving.

Database System Concepts - 7th Edition 7.32 ©Berschütz, Korth and Sudarshan




Higher Normal Forms

- It is better to decompose $inst_info$ into:
 - $inst_child$:

ID	child_name
99999	David
99999	William
 - $inst_phone$:

ID	phone
99999	512-555-1234
99999	512-555-4321
- This suggests the need for higher normal forms, such as Fourth Normal Form (4NF), which we shall see later

Database System Concepts - 7th Edition 7.35 ©Berschütz, Korth and Sudarshan




Redundancy in 3NF

- Consider the schema R below, which is in 3NF
 - $R = \{J, K, L\}$
 - $F = \{JK \rightarrow L, L \rightarrow K\}$
 - And an instance table:

J	L	K
j_1	l_1	k_1
j_2	l_1	k_1
j_3	l_2	k_1
null	l_2	k_2

- What is wrong with the table?
 - Repetition of information
 - Need to use null values (e.g., to represent the relationship l_2, k_2 where there is no corresponding value for J)

Database System Concepts - 7th Edition 7.30 ©Berschütz, Korth and Sudarshan




How good is BCNF?

- There are database schemas in BCNF that do not seem to be sufficiently normalized
- Consider a relation
 $inst_info(ID, child_name, phone)$
 - where an instructor may have more than one phone and can have multiple children
 - Instance of $inst_info$


ID	child_name	phone
99999	David	512-555-1234
99999	David	512-555-4321
99999	William	512-555-1234
99999	William	512-555-4321

Database System Concepts - 7th Edition 7.33 ©Berschütz, Korth and Sudarshan



Functional-Dependency Theory


Database System Concepts - 7th Edition 7.36 ©Berschütz, Korth and Sudarshan



Functional-Dependency Theory Roadmap

- We now consider the formal theory that tells us which functional dependencies are implied logically by a given set of functional dependencies.
- We then develop algorithms to generate lossless decompositions into BCNF and 3NF
- We then develop algorithms to test if a decomposition is dependency-preserving


Database System Concepts - 7th Edition 7.37 ©Berschütz, Korth and Sudarshan



Example of F^+

- $R = (A, B, C, G, H, I)$
 $F = \{A \rightarrow B, A \rightarrow C, CG \rightarrow H, CG \rightarrow I, B \rightarrow H\}$
- Some members of F^+
 - $A \rightarrow H$
 - by transitivity from $A \rightarrow B$ and $B \rightarrow H$
 - $AG \rightarrow I$
 - by augmenting $A \rightarrow C$ with G , to get $AG \rightarrow CG$ and then transitivity with $CG \rightarrow I$
 - $CG \rightarrow HI$
 - by augmenting $CG \rightarrow I$ to infer $CG \rightarrow CGI$, and augmenting of $CG \rightarrow H$ to infer $CGI \rightarrow HI$, and then transitivity

Database System Concepts - 7th Edition 7.48 ©Berschütz, Korth and Sudarshan



Closure of Attribute Sets


- Given a set of attributes α , define the **closure** of α under F (denoted by α^+) as the set of attributes that are functionally determined by α under F
- Algorithm to compute α^+ , the closure of α under F

```

result :=  $\alpha$ ;
while (changes to result) do
  for each  $\beta \rightarrow \gamma$  in  $F$  do
    begin
      if  $\beta \subseteq \text{result}$  then result := result  $\cup$   $\gamma$ 
    end
  end

```


Database System Concepts - 7th Edition 7.43 ©Berschütz, Korth and Sudarshan



Closure of a Set of Functional Dependencies

- Given a set F set of functional dependencies, there are certain other functional dependencies that are logically implied by F .
 - If $A \rightarrow B$ and $B \rightarrow C$, then we can infer that $A \rightarrow C$
 - etc.
- The set of all functional dependencies logically implied by F is the **closure** of F .
- We denote the **closure** of F by F^+ .


Database System Concepts - 7th Edition 7.38 ©Berschütz, Korth and Sudarshan



Closure of Functional Dependencies (Cont.)

- Additional rules:
 - Union rule:** If $\alpha \rightarrow \beta$ holds and $\alpha \rightarrow \gamma$ holds, then $\alpha \rightarrow \beta\gamma$ holds.
 - Decomposition rule:** If $\alpha \rightarrow \beta\gamma$ holds, then $\alpha \rightarrow \beta$ holds and $\alpha \rightarrow \gamma$ holds.
 - Pseudotransitivity rule:** If $\alpha \rightarrow \beta$ holds and $\gamma\beta \rightarrow \delta$ holds, then $\alpha\gamma \rightarrow \delta$ holds.
- The above rules can be inferred from Armstrong's axioms.


Database System Concepts - 7th Edition 7.41 ©Berschütz, Korth and Sudarshan



Example of Attribute Set Closure

- $R = (A, B, C, G, H, I)$
 $F = \{A \rightarrow B, A \rightarrow C, CG \rightarrow H, CG \rightarrow I, B \rightarrow H\}$
- $(AG)^+$
 - result = AG
 - result = ABCG ($A \rightarrow C$ and $A \rightarrow B$)
 - result = ABCGH ($CG \rightarrow H$ and $CG \subseteq AGBC$)
 - result = ABCGHI ($CG \rightarrow I$ and $CG \subseteq AGBCH$)
- Is AG a candidate key?
 - Is AG a super key?
 - Does $AG \rightarrow R$? == Is $R \subseteq (AG)^+$
 - Is any subset of AG a superkey?
 - Does $A \rightarrow R$? == Is $R \subseteq (A)^+$
 - Does $G \rightarrow R$? == Is $R \subseteq (G)^+$
 - In general: check for each subset of size $n-1$


Database System Concepts - 7th Edition 7.44 ©Berschütz, Korth and Sudarshan



Closure of a Set of Functional Dependencies

- We can compute F^+ , the closure of F , by repeatedly applying **Armstrong's Axioms**:
 - Reflexive rule:** if $\beta \subseteq \alpha$, then $\alpha \rightarrow \beta$
 - Augmentation rule:** if $\alpha \rightarrow \beta$, then $\gamma\alpha \rightarrow \gamma\beta$
 - Transitivity rule:** if $\alpha \rightarrow \beta$, and $\beta \rightarrow \gamma$, then $\alpha \rightarrow \gamma$
- These rules are
 - Sound** – generate only functional dependencies that actually hold, and
 - Complete** – generate all functional dependencies that hold.

Database System Concepts - 7th Edition 7.39 ©Berschütz, Korth and Sudarshan



Procedure for Computing F^+


- To compute the closure of a set of functional dependencies F :


```

 $F^+ = F$ 
repeat
  for each functional dependency  $f$  in  $F^+$ 
    apply reflexivity and augmentation rules on  $F^+$ 
    add the resulting functional dependencies to  $F^+$ 
  for each pair of functional dependencies  $f_1$  and  $f_2$  in  $F^+$ 
    if  $f_1$  and  $f_2$  can be combined using transitivity
      then add the resulting functional dependency to  $F^+$ 
until  $F^+$  does not change any further

```
- NOTE:** We shall see an alternative procedure for this task later

Database System Concepts - 7th Edition 7.42 ©Berschütz, Korth and Sudarshan




Uses of Attribute Closure

There are several uses of the attribute closure algorithm:

- Testing for superkey:
 - To test if α is a superkey, we compute α^+ and check if α^+ contains all attributes of R .
- Testing functional dependencies
 - To check if a functional dependency $\alpha \rightarrow \beta$ holds (or, in other words, is in F^+), just check if $\beta \subseteq \alpha^+$.
 - That is, we compute α^+ by using attribute closure, and then check if it contains β .
 - Is a simple and cheap test, and very useful
- Computing closure of F
 - For each $\gamma \subseteq R$, we find the closure γ^+ , and for each $S \subseteq \gamma^+$, we output a functional dependency $\gamma \rightarrow S$.


Database System Concepts - 7th Edition 7.46 ©Berschütz, Korth and Sudarshan



Canonical Cover

- Suppose that we have a set of functional dependencies F on a relation schema. Whenever a user performs an update on the relation, the database system must ensure that the update does not violate any functional dependencies; that is, all the functional dependencies in F are satisfied in the new database state.
- If an update violates any functional dependencies in the set F , the system must roll back the update.
- We can reduce the effort spent in checking for violations by **testing a simplified set of functional dependencies that has the same closure as the given set F .**
- This simplified set is termed the **canonical cover**.
- To define canonical cover we must first define **extraneous attributes**.
 - An attribute of a functional dependency in F is **extraneous** if we can remove it without changing F^+ .


Database System Concepts - 7th Edition 7.48 ©Berschütz, Korth and Sudarshan



Extraneous Attributes

- An attribute of a functional dependency in F is **extraneous** if we can remove it without changing F^+ .
- Consider a set F of functional dependencies and the functional dependency $\alpha \rightarrow \beta$ in F .
 - Remove from the left side:** Attribute A is **extraneous** in α if
 - $A \in \alpha$ and
 - F logically implies $F' = (F - \{\alpha \rightarrow \beta\}) \cup \{(\alpha - A) \rightarrow \beta\}$.
 - Remove from the right side:** Attribute A is **extraneous** in β if
 - $A \in \beta$ and
 - The set of functional dependencies $F' = (F - \{\alpha \rightarrow \beta\}) \cup \{\alpha \rightarrow (\beta - A)\}$ logically implies F .

Database System Concepts - 7th Edition 7.49 ©Berschütz, Korth and Sudarshan




Canonical Cover

A **canonical cover** for F is a set of dependencies F_c such that

- $F^+ = F_c^+$
 - F_c logically implies all dependencies in F_c , and
 - F_c logically implies all dependencies in F , and
- No functional dependency in F_c contains an extraneous attribute, and
- Each left side of functional dependency in F_c is unique. That is, there are no two dependencies in F_c
 - $\alpha_1 \rightarrow \beta_1$ and $\alpha_2 \rightarrow \beta_2$ such that
 - $\alpha_1 = \alpha_2$


Database System Concepts - 7th Edition 7.52 ©Berschütz, Korth and Sudarshan



Extraneous Attributes

- Removing an attribute from the left side of a functional dependency could make it a stronger constraint.
 - For example, if we have $AB \rightarrow C$ and remove B , we get the possibly stronger result $A \rightarrow C$. It may be stronger because $A \rightarrow C$ logically implies $AB \rightarrow C$, but $AB \rightarrow C$ does not, on its own, logically imply $A \rightarrow C$.
- But, depending on what our set F of functional dependencies happens to be, we may be able to remove B from $AB \rightarrow C$ safely.
 - For example, suppose that
 - $F = \{AB \rightarrow C, A \rightarrow D, D \rightarrow C\}$
 - Then we can show that F logically implies $A \rightarrow C$, making extraneous in $AB \rightarrow C$.


Database System Concepts - 7th Edition 7.47 ©Berschütz, Korth and Sudarshan



Testing if an Attribute is Extraneous

- Let R be a relation schema and let F be a set of functional dependencies that hold on R . Consider an attribute in the functional dependency $\alpha \rightarrow \beta$.
- To test if attribute $A \in \beta$ is extraneous in β
 - Consider the set:
 - $F' = (F - \{\alpha \rightarrow \beta\}) \cup \{\alpha \rightarrow (\beta - A)\}$
 - check that α^+ contains A : if it does, A is extraneous in β
- To test if attribute $A \in \alpha$ is extraneous in α
 - Let $\gamma = \alpha - \{A\}$. Check if $\gamma \rightarrow \beta$ can be inferred from F .
 - Compute γ^+ using the dependencies in F
 - If γ^+ includes all attributes in β then A is extraneous in α


Database System Concepts - 7th Edition 7.50 ©Berschütz, Korth and Sudarshan



Canonical Cover

- To compute a canonical cover for F :
 - repeat**
 - Use the union rule to replace any dependencies in F of the form $\alpha_1 \rightarrow \beta_1$ and $\alpha_1 \rightarrow \beta_2$ with $\alpha_1 \rightarrow \beta_1, \beta_2$
 - Find a functional dependency $\alpha \rightarrow \beta$ in F_c with an extraneous attribute either in α or in β
 - /* Note: test for extraneous attributes done using F_c , not F^+ */
 - If an extraneous attribute is found, delete it from $\alpha \rightarrow \beta$
 - until** (F_c not change)
 - Note: Union rule may become applicable after some extraneous attributes have been deleted, so it has to be re-applied


Database System Concepts - 7th Edition 7.53 ©Berschütz, Korth and Sudarshan



Extraneous Attributes (Cont.)

- Removing an attribute from the right side of a functional dependency could make it a weaker constraint.
 - For example, if we have $AB \rightarrow CD$ and remove C , we get the possibly weaker result $AB \rightarrow D$. It may be weaker because using just $AB \rightarrow D$, we can no longer infer $AB \rightarrow C$.
- But, depending on what our set F of functional dependencies happens to be, we may be able to remove C from $AB \rightarrow CD$ safely.
 - For example, suppose that
 - $F = \{AB \rightarrow CD, A \rightarrow C\}$
 - Then we can show that even after replacing $AB \rightarrow CD$ by $AB \rightarrow D$, we can still infer $AB \rightarrow C$ and thus $AB \rightarrow CD$.


Database System Concepts - 7th Edition 7.48 ©Berschütz, Korth and Sudarshan



Examples of Extraneous Attributes

- Let $F = \{AB \rightarrow CD, A \rightarrow E, E \rightarrow C\}$
- To check if C is extraneous in $AB \rightarrow CD$, we:
 - Compute the attribute closure of AB under $F' = \{AB \rightarrow D, A \rightarrow E, E \rightarrow C\}$
 - The closure is $ABCDE$, which includes CD
 - This implies that C is extraneous

Database System Concepts - 7th Edition 7.51 ©Berschütz, Korth and Sudarshan



Example: Computing a Canonical Cover

- $R = \{A, B, C\}$
 $F = \{A \rightarrow BC, B \rightarrow C, A \rightarrow B, AB \rightarrow C\}$
- Combine $A \rightarrow BC$ and $A \rightarrow B$ into $A \rightarrow BC$
 - Set is now $\{A \rightarrow BC, B \rightarrow C, AB \rightarrow C\}$
- A is extraneous in $AB \rightarrow C$
 - Check if the result of deleting A from $AB \rightarrow C$ is implied by the other dependencies
 - Yes: in fact, $B \rightarrow C$ is already present!
 - Set is now $\{A \rightarrow BC, B \rightarrow C\}$
- C is extraneous in $A \rightarrow BC$
 - Check if $A \rightarrow C$ is logically implied by $A \rightarrow B$ and the other dependencies
 - Yes: using transitivity on $A \rightarrow B$ and $B \rightarrow C$.
 - Can use attribute closure of A in more complex cases
- The canonical cover is:
 - $A \rightarrow B$
 - $B \rightarrow C$

Database System Concepts - 7th Edition 7.54 ©Berschütz, Korth and Sudarshan

Dependency Preservation

- Let F_i be the set of dependencies F^+ that include only attributes in R_i .
 - A decomposition is **dependency preserving**, if $(F_1 \cup F_2 \cup \dots \cup F_n)^+ = F^+$
- Using the above definition, testing for dependency preservation take exponential time (generate all the functional dependencies of F^+).
- Not that if a decomposition is NOT dependency preserving then checking updates for violation of functional dependencies may require computing joins, which is expensive.

Database System Concepts - 7th Edition 7.68 ©Berschütz, Korth and Sudarshan

Testing for Dependency Preservation

$R = R_1 \bowtie R_2$
 F : functional dependencies on R

Any $\alpha \rightarrow \beta$ in F
 Let $\alpha = \alpha_1 \alpha_2, \beta = \beta_1 \beta_2$

If $\beta_1 \subseteq (\alpha_1)^+$

Then, a preserve decomposition in terms of F

No need to generate F^+ for such checking!

R1

α_1	β_1
------------	-----------

R2

α_2	β_2
------------	-----------

Database System Concepts - 7th Edition 7.68 ©Berschütz, Korth and Sudarshan

Testing for BCNF

- To check if a non-trivial dependency $\alpha \rightarrow \beta$ causes a violation of BCNF
 - compute α^+ (the attribute closure of α), and
 - verify that it includes all attributes of R ; that is, it is a superkey of R .
- Simplified test**: To check if a relation schema R is in BCNF, it suffices to check only the dependencies in the given set F for violation of BCNF, rather than checking all dependencies in F^+ .
 - If none of the dependencies in F causes a violation of BCNF, then none of the dependencies in F^+ will cause a violation of BCNF either.
- However, simplified test** using only F is incorrect when testing a relation in a decomposition of R
 - Consider $R = (A, B, C, D, E)$, with $F = \{A \rightarrow B, BC \rightarrow D\}$
 - Decompose R into $R_1 = (A, B)$ and $R_2 = (A, C, D, E)$
 - Neither of the dependencies in F contain only attributes from (A, C, D, E) so we might be misled into thinking R_2 satisfies BCNF.
 - In fact, dependency $AC \rightarrow D$ in F^+ shows R_2 is not in BCNF.

Database System Concepts - 7th Edition 7.61 ©Berschütz, Korth and Sudarshan

Dependency Preservation (Cont.)

- Let F be the set of dependencies on schema R and let R_1, R_2, \dots, R_n be a decomposition of R .
- The restriction of F to R_i is the set F_i of all functional dependencies in F^+ that include **only** attributes of R_i .
- Since all functional dependencies in a restriction involve attributes of only one relation schema, it is possible to test such a dependency for satisfaction by checking only one relation.
- Note that the definition of restriction uses all dependencies in F^+ , not just those in F .
- The set of restrictions F_1, F_2, \dots, F_n is the set of functional dependencies that can be checked efficiently.

Database System Concepts - 7th Edition 7.68 ©Berschütz, Korth and Sudarshan

Example

- $R = (A, B, C)$
 $F = \{A \rightarrow B, B \rightarrow C\}$
 Key = $\{A\}$
- R is not in BCNF
- Decomposition $R_1 = (A, B), R_2 = (B, C)$
 - R_1 and R_2 in BCNF
 - Lossless-join decomposition
 - Dependency preserving

Database System Concepts - 7th Edition 7.69 ©Berschütz, Korth and Sudarshan

Testing Decomposition for BCNF

To check if a relation R_i in a decomposition of R is in BCNF

- Either test R_i for BCNF with respect to the **restriction** of F^+ to R_i (that is, all FDs in F^+ that contain only attributes from R_i)
- Or use the original set of dependencies F that hold on R , but with the following test:
 - for every set of attributes $\alpha \subseteq R_i$, check that α^+ (the attribute closure of α) either includes no attribute of $R_i - \alpha$, or includes all attributes of R_i .
- If the condition is violated by some $\alpha \rightarrow \beta$ in F^+ , the dependency $\alpha \rightarrow (\alpha^+ - \alpha) \cap R_i$ can be shown to hold on R_i , and R_i violates BCNF.
- We use above dependency to decompose R_i .

Database System Concepts - 7th Edition 7.62 ©Berschütz, Korth and Sudarshan

Testing for Dependency Preservation

- To check if a dependency $\alpha \rightarrow \beta$ is preserved in a decomposition of R into R_1, R_2, \dots, R_n , we apply the following test (with attribute closure done with respect to F)
 - $result = \alpha$
 - repeat**
 - for each** R_i in the decomposition
 - $t = (result \cap R_i)^+ \cap R_i$
 - $result = result \cup t$
 - until** $(result$ does not change)
 - If $result$ contains all attributes in β , then the functional dependency $\alpha \rightarrow \beta$ is preserved.
- We apply the test on all dependencies in F to check if a decomposition is dependency preserving
- This procedure takes polynomial time, instead of the exponential time required to compute F^+ and $(F_1 \cup F_2 \cup \dots \cup F_n)^+$

Database System Concepts - 7th Edition 7.67 ©Berschütz, Korth and Sudarshan

Algorithm for Decomposition Using Functional Dependencies

Database System Concepts - 7th Edition 7.69 ©Berschütz, Korth and Sudarshan

BCNF Decomposition Algorithm


```

result := {R};
done := false;
compute F+;
while (not done) do
  if (there is a schema Ri in result that is not in BCNF)
    then begin
      let α → β be a nontrivial functional dependency that
        holds on Ri such that α → Ri is not in F+,
        and α ∩ β = ∅;
      result := (result - Ri) ∪ (Ri - β) ∪ (α, β);
    end
  else done := true;

```

Note: each R_i is in BCNF, and decomposition is lossless-join.


Database System Concepts - 7th Edition 7.63 ©Berschütz, Korth and Sudarshan



Example of BCNF Decomposition

- class (course_id, title, dept_name, credits, sec_id, semester, year, building, room_number, capacity, time_slot_id)
- Functional dependencies:
 - course_id → title, dept_name, credits
 - building, room_number → capacity
 - course_id, sec_id, semester, year → building, room_number, time_slot_id
- A candidate key {course_id, sec_id, semester, year}.
- BCNF Decomposition:
 - course_id → title, dept_name, credits holds
 - but course_id is not a superkey.
 - We replace class by:
 - course(course_id, title, dept_name, credits)
 - class-1 (course_id, sec_id, semester, year, building, room_number, capacity, time_slot_id)


Database System Concepts - 7th Edition 7.64 ©Berschütz, Korth and Sudarshan



3NF Example -- Relation dept_advisor

- dept_advisor (s_ID, l_ID, dept_name)
- $F = \{s_ID, dept_name \rightarrow l_ID, l_ID \rightarrow dept_name\}$
- Two candidate keys: s_ID, dept_name, and l_ID, s_ID
- R is in 3NF
 - s_ID, dept_name → l_ID s_ID
 - s_ID, dept_name is a superkey
 - l_ID → dept_name
 - dept_name is contained in a candidate key

Database System Concepts - 7th Edition 7.67 ©Berschütz, Korth and Sudarshan




3NF Decomposition Algorithm (Cont.)

Above algorithm ensures

- Each relation schema R_i is in 3NF
- Decomposition is dependency preserving and lossless-join
- Proof of correctness is at end of this presentation (click here)


Database System Concepts - 7th Edition 7.70 ©Berschütz, Korth and Sudarshan



BCNF Decomposition (Cont.)

- course is in BCNF
 - How do we know this?
- building, room_number → capacity holds on class-1
 - but (building, room_number) is not a superkey for class-1.
- We replace class-1 by:
 - classroom (building, room_number, capacity)
 - section (course_id, sec_id, semester, year, building, room_number, time_slot_id)
- classroom and section are in BCNF.


Database System Concepts - 7th Edition 7.69 ©Berschütz, Korth and Sudarshan



Testing for 3NF

- Need to check only FDs in F_c , need not check all FDs in F^+ .
- Use attribute closure to check for each dependency $\alpha \rightarrow \beta$, if α is a superkey.
- If α is not a superkey, we have to verify if each attribute in β is contained in a candidate key of R
 - This test is rather more expensive, since it involves finding candidate keys
- Testing for 3NF has been shown to be NP-hard
- Interestingly, decomposition into third normal form (described shortly) can be done in polynomial time


Database System Concepts - 7th Edition 7.68 ©Berschütz, Korth and Sudarshan



3NF Decomposition: An Example

- Relation schema:
 - cust_banker_branch = (customer_id, employee_id, branch_name, type)
- The functional dependencies for this relation schema are:
 - customer_id, employee_id → branch_name, type
 - employee_id → branch_name
 - customer_id, branch_name → employee_id
- We first compute a canonical cover
 - branch_name is extraneous in the r.h.s. of the 1st dependency
 - No other attribute is extraneous, so we get $F_c =$
 - customer_id, employee_id → type
 - employee_id → branch_name
 - customer_id, branch_name → employee_id


Database System Concepts - 7th Edition 7.71 ©Berschütz, Korth and Sudarshan



Third Normal Form

- There are some situations where
 - BCNF is not dependency preserving, and
 - efficient checking for FD violation on updates is important
- Solution: define a weaker normal form, called Third Normal Form (3NF)
 - Allows some redundancy (with resultant problems; we will see examples later)
 - But functional dependencies can be checked on individual relations without computing a join.
 - There is always a lossless-join, dependency-preserving decomposition into 3NF.

Database System Concepts - 7th Edition 7.66 ©Berschütz, Korth and Sudarshan




3NF Decomposition Algorithm

Let F_c be a canonical cover for F ;

```

i := 0;
for each functional dependency  $\alpha \rightarrow \beta$  in  $F_c$  do
  if none of the schemas  $R_j$ ,  $1 \leq j \leq i$  contains  $\alpha \beta$ 
  then begin
    i := i + 1;
     $R_i := \alpha \beta$ 
  end
end
if none of the schemas  $R_j$ ,  $1 \leq j \leq i$  contains a candidate key for R
then begin
  i := i + 1;
   $R_i :=$  any candidate key for R;
end
/* Optionally, remove redundant relations */
repeat
  if any schema  $R_i$  is contained in another schema  $R_k$ 
  then /* delete  $R_i$  */
     $R_i = R_k$ ;
    i := i - 1;
until no change
return ( $R_1, R_2, \dots, R_i$ )
  
```


Database System Concepts - 7th Edition 7.69 ©Berschütz, Korth and Sudarshan



3NF Decomposition Example (Cont.)

- The for loop generates following 3NF schema:
 - (customer_id, employee_id, type)
 - (employee_id, branch_name)
 - (customer_id, branch_name, employee_id)
- Observe that (customer_id, employee_id, type) contains a candidate key of the original schema, so no further relation schema needs be added
- At end of for loop, detect and delete schemas, such as (employee_id, branch_name), which are subsets of other schemas
 - result will not depend on the order in which FDs are considered
- The resultant simplified 3NF schema is:
 - (customer_id, employee_id, type)
 - (customer_id, branch_name, employee_id)


Database System Concepts - 7th Edition 7.72 ©Berschütz, Korth and Sudarshan



Comparison of BCNF and 3NF

- It is always possible to decompose a relation into a set of relations that are in 3NF such that:
 - The decomposition is lossless
 - The dependencies are preserved
- It is always possible to decompose a relation into a set of relations that are in BCNF such that:
 - The decomposition is lossless
 - It may not be possible to preserve dependencies.


Database System Concepts - 7th Edition 7.73 ©Berschütz, Korth and Sudarshan



Multivalued Dependencies (MVDs)

- Suppose we record names of children, and phone numbers for instructors:
 - $inst_child(ID, child_name)$
 - $inst_phone(ID, phone_number)$
- If we were to combine these schemas to get
 - $inst_info(ID, child_name, phone_number)$
- Example data:
 - (99999, David, 512-555-1234)
 - (99999, David, 512-555-4321)
 - (99999, William, 512-555-1234)
 - (99999, William, 512-555-4321)
- This relation is in BCNF
 - Why?

Database System Concepts - 7th Edition 7.76 ©Berschütz, Korth and Sudarshan



MVD (Cont.)

- Let R be a relation schema with a set of attributes that are partitioned into 3 nonempty subsets.


$$Y, Z, W$$
- We say that $Y \twoheadrightarrow Z$ (Y **multidetermines** Z) if and only if for all possible relations $r(R)$

$$\langle y_1, z_1, w_1 \rangle \in r \text{ and } \langle y_1, z_2, w_2 \rangle \in r$$
 then

$$\langle y_1, z_1, w_2 \rangle \in r \text{ and } \langle y_1, z_2, w_1 \rangle \in r$$
- Note that since the behavior of Z and W are identical it follows that

$$Y \twoheadrightarrow Z \text{ if } Y \twoheadrightarrow W$$


Database System Concepts - 7th Edition 7.79 ©Berschütz, Korth and Sudarshan



Design Goals

- Goal for a relational database design is:
 - BCNF.
 - Lossless join.
 - Dependency preservation.
- If we cannot achieve this, we accept one of
 - Lack of dependency preservation
 - Redundancy due to use of 3NF
- Interestingly, SQL does not provide a direct way of specifying functional dependencies other than superkeys. Can specify FDs using assertions, but they are expensive to test, (and currently not supported by any of the widely used databases!)
- Even if we had a dependency preserving decomposition, using SQL we would not be able to efficiently test a functional dependency whose left hand side is not a key.

Database System Concepts - 7th Edition 7.74 ©Berschütz, Korth and Sudarshan




Multivalued Dependencies

- Let R be a relation schema and let $\alpha \subseteq R$ and $\beta \subseteq R$. The **multivalued dependency**

$$\alpha \twoheadrightarrow \beta$$
 holds on R if in any legal relation $r(R)$, for all pairs for tuples t_1 and t_2 in r such that $t_1[\alpha] = t_2[\alpha]$, there exist tuples t_3 and t_4 in r such that:

$$\begin{aligned} t_1[\alpha] &= t_2[\alpha] = t_3[\alpha] = t_4[\alpha] \\ t_3[\beta] &= t_1[\beta] \\ t_3[R - \beta] &= t_2[R - \beta] \\ t_4[\beta] &= t_2[\beta] \\ t_4[R - \beta] &= t_1[R - \beta] \end{aligned}$$

Database System Concepts - 7th Edition 7.77 ©Berschütz, Korth and Sudarshan




Example

- In our example:


$$\begin{aligned} ID &\twoheadrightarrow child_name \\ ID &\twoheadrightarrow phone_number \end{aligned}$$
- The above formal definition is supposed to formalize the notion that given a particular value of Y (ID) it has associated with it a set of values of Z ($child_name$) and a set of values of W ($phone_number$), and these two sets are in some sense independent of each other.
- Note:
 - If $Y \rightarrow Z$ then $Y \twoheadrightarrow Z$
 - Indeed we have (in above notation) $Z_1 = Z_2$. The claim follows.

Database System Concepts - 7th Edition 7.80 ©Berschütz, Korth and Sudarshan



Multivalued Dependencies

Database System Concepts - 7th Edition 7.75 ©Berschütz, Korth and Sudarshan




MVD -- Tabular representation

- Tabular representation of $\alpha \twoheadrightarrow \beta$

	α	β	$R - \alpha - \beta$
t_1	$a_1 \dots a_i$	$a_{i+1} \dots a_j$	$a_{j+1} \dots a_n$
t_2	$a_1 \dots a_i$	$b_{i+1} \dots b_j$	$b_{j+1} \dots b_n$
t_3	$a_1 \dots a_i$	$a_{i+1} \dots a_j$	$b_{j+1} \dots b_n$
t_4	$a_1 \dots a_i$	$b_{i+1} \dots b_j$	$a_{j+1} \dots a_n$


Database System Concepts - 7th Edition 7.78 ©Berschütz, Korth and Sudarshan



Use of Multivalued Dependencies

- We use multivalued dependencies in two ways:
 - To test relations to **determine** whether they are legal under a given set of functional and multivalued dependencies
 - To specify **constraints** on the set of legal relations. We shall concern ourselves *only* with relations that satisfy a given set of functional and multivalued dependencies.
- If a relation r fails to satisfy a given multivalued dependency, we can construct a relations r' that does satisfy the multivalued dependency by adding tuples to r .


Database System Concepts - 7th Edition 7.81 ©Berschütz, Korth and Sudarshan



Theory of MVDs

- From the definition of multivalued dependency, we can derive the following rule:
 - If $\alpha \rightarrow \beta$, then $\alpha \twoheadrightarrow \beta$
- That is, every functional dependency is also a multivalued dependency
- The **closure** D^+ of D is the set of all functional and multivalued dependencies logically implied by D .
 - We can compute D^+ from D , using the formal definitions of functional dependencies and multivalued dependencies.
 - We can manage with such reasoning for very simple multivalued dependencies, which seem to be most common in practice
 - For complex dependencies, it is better to reason about sets of dependencies using a system of inference rules (Appendix C).

Database System Concepts - 7th Edition 7.82 ©Berschütz, Korth and Sudarshan



4NF Decomposition Algorithm


```

result := {R};
done := false;
compute D+;
Let Di denote the restriction of D+ to Ri
while (not done)
  begin
    let α → β be a nontrivial multivalued dependency that holds
    on Ri such that α → Ri is not in Di and α ∩ β = ∅;
    result := (result - Ri) ∪ (Ri - β) ∪ (α, β);
  end
end
else done := true;

```

Note: each R_i is in 4NF, and decomposition is lossless-join


Database System Concepts - 7th Edition 7.88 ©Berschütz, Korth and Sudarshan



Further Normal Forms

- Join dependencies** generalize multivalued dependencies
 - lead to **project-join normal form (PJNF)** (also called **fifth normal form**)
- A class of even more general constraints, leads to a normal form called **domain-key normal form**.
- Problem with these generalized constraints: are hard to reason with, and no set of sound and complete set of inference rules exists.
- Hence rarely used


Database System Concepts - 7th Edition 7.88 ©Berschütz, Korth and Sudarshan



Fourth Normal Form

- A relation schema R is in **4NF** with respect to a set D of functional and multivalued dependencies if for all multivalued dependencies in D^+ of the form $\alpha \twoheadrightarrow \beta$, where $\alpha \subseteq R$ and $\beta \subseteq R$, at least one of the following hold:
 - $\alpha \twoheadrightarrow \beta$ is trivial (i.e., $\beta \subseteq \alpha$ or $\alpha \cup \beta = R$)
 - α is a superkey for schema R
- If a relation is in 4NF it is in BCNF


Database System Concepts - 7th Edition 7.83 ©Berschütz, Korth and Sudarshan



Example

- $R = (A, B, C, G, H, I)$
 $F = \{A \twoheadrightarrow B, B \twoheadrightarrow HI, CG \twoheadrightarrow H\}$
- R is not in 4NF since $A \twoheadrightarrow B$ and A is not a superkey for R
- Decomposition
 - a) $R_1 = (A, B)$ (R_1 is in 4NF)
 - b) $R_2 = (A, C, G, H, I)$ (R_2 is not in 4NF, decompose into R_3 and R_4)
 - c) $R_3 = (C, G, H)$ (R_3 is in 4NF)
 - d) $R_4 = (A, C, G, I)$ (R_4 is not in 4NF, decompose into R_5 and R_6)
 - $A \twoheadrightarrow B$ and $B \twoheadrightarrow HI \Rightarrow A \twoheadrightarrow HI$ (MVD transitivity), and
 - and hence $A \twoheadrightarrow I$ (MVD restriction to R_4)
 - e) $R_5 = (A, I)$ (R_5 is in 4NF)
 - f) $R_6 = (A, C, G)$ (R_6 is in 4NF)

Database System Concepts - 7th Edition 7.88 ©Berschütz, Korth and Sudarshan




Overall Database Design Process

We have assumed schema R is given

- R could have been generated when converting E-R diagram to a set of tables.
- R could have been a single relation containing *all* attributes that are of interest (called **universal relation**).
- Normalization breaks R into smaller relations.
- R could have been the result of some ad hoc design of relations, which we then test/convert to normal form.


Database System Concepts - 7th Edition 7.89 ©Berschütz, Korth and Sudarshan



Restriction of Multivalued Dependencies


- The restriction of D to R_i is the set D_i consisting of
 - All functional dependencies in D^+ that include only attributes of R_i
 - All multivalued dependencies of the form $\alpha \twoheadrightarrow (\beta \cap R_i)$ where $\alpha \subseteq R_i$ and $\alpha \twoheadrightarrow \beta$ is in D^+

Database System Concepts - 7th Edition 7.84 ©Berschütz, Korth and Sudarshan



Additional issues


Database System Concepts - 7th Edition 7.87 ©Berschütz, Korth and Sudarshan



ER Model and Normalization

- When an E-R diagram is carefully designed, identifying all entities correctly, the tables generated from the E-R diagram should not need further normalization.
- However, in a real (imperfect) design, there can be functional dependencies from non-key attributes of an entity to other attributes of the entity
 - Example: an *employee* entity with
 - attributes *department_name* and *building*,
 - functional dependency *department_name* → *building*
 - Good design would have made *department* an entity
- Functional dependencies from non-key attributes of a relationship set possible, but rare → most relationships are binary


Database System Concepts - 7th Edition 7.86 ©Berschütz, Korth and Sudarshan



Denormalization for Performance

- May want to use non-normalized schema for performance
- For example, displaying *prereqs* along with *course_id*, and *title* requires join of *course* with *prereq*
- Alternative 1: Use denormalized relation containing attributes of *course* as well as *prereq* with all above attributes
 - faster lookup
 - extra space and extra execution time for updates
 - extra coding work for programmer and possibility of error in extra code
- Alternative 2: use a materialized view defined a *course* \bowtie *prereq*
 - Benefits and drawbacks same as above, except no extra coding work for programmer and avoids possible errors


Database System Concepts - 7th Edition 7.81 ©Berschütz, Korth and Sudarshan



Modeling Temporal Data (Cont.)

- In practice, database designers may add start and end time attributes to relations
 - E.g., *course(course_id, course_title)* is replaced by *course(course_id, course_title, start, end)*
 - Constraint: no two tuples can have overlapping valid times
 - Hard to enforce efficiently
- Foreign key references may be to current version of data, or to data at a point in time
 - E.g., student transcript should refer to course information at the time the course was taken


Database System Concepts - 7th Edition 7.84 ©Berschütz, Korth and Sudarshan



Correctness of 3NF Decomposition Algorithm

- 3NF decomposition algorithm is dependency preserving (since there is a relation for every FD in F_c)
- Decomposition is lossless
 - A candidate key (C) is in one of the relations R_i in decomposition
 - Closure of candidate key under F_c must contain all attributes in R
 - Follow the steps of attribute closure algorithm to show there is only one tuple in the join result for each tuple in R_i

Database System Concepts - 7th Edition 7.87 ©Berschütz, Korth and Sudarshan




Other Design Issues

- Some aspects of database design are not caught by normalization
- Examples of bad database design, to be avoided:

Instead of *earnings* (*company_id, year, amount*), use


 - earnings_2004, earnings_2005, earnings_2006*, etc., all on the schema (*company_id, earnings*).
 - Above are in BCNF, but make querying across years difficult and needs new table each year
 - company_year* (*company_id, earnings_2004, earnings_2005, earnings_2006*)
 - Also in BCNF, but also makes querying across years difficult and requires new attribute each year.
 - Is an example of a **crosstab**, where values for one attribute become column names
 - Used in spreadsheets, and in data analysis tools

Database System Concepts - 7th Edition 7.82 ©Berschütz, Korth and Sudarshan



End of Chapter 7


Database System Concepts - 7th Edition 7.85 ©Berschütz, Korth and Sudarshan



Correctness of 3NF Decomposition Algorithm (Cont.)

- Claim: if a relation R_i is in the decomposition generated by the above algorithm, then R_i satisfies 3NF.
- Proof:
 - Let R_i be generated from the dependency $\alpha \rightarrow \beta$
 - Let $\gamma \rightarrow B$ be any non-trivial functional dependency on R_i (We need only consider FDs whose right-hand side is a single attribute.)
 - Now, B can be in either β or α but not in both. Consider each case separately.


Database System Concepts - 7th Edition 7.88 ©Berschütz, Korth and Sudarshan



Modeling Temporal Data


- Temporal data** have an association time interval during which the data are *valid*.
- A **snapshot** is the value of the data at a particular point in time
- Several proposals to extend ER model by adding valid time to
 - attributes, e.g., address of an instructor at different points in time
 - entities, e.g., time duration when a student entity exists
 - relationships, e.g., time during which an instructor was associated with a student as an advisor.
- But no accepted standard
- Adding a temporal component results in functional dependencies like *ID* \rightarrow *street, city* not holding, because the address varies over time
- A **temporal functional dependency** $X \rightarrow Y$ holds on schema R if the functional dependency $X \rightarrow Y$ holds on all snapshots for all legal instances $r(R)$.

Database System Concepts - 7th Edition 7.83 ©Berschütz, Korth and Sudarshan



Proof of Correctness of 3NF Decomposition Algorithm

Database System Concepts - 7th Edition 7.86 ©Berschütz, Korth and Sudarshan



Correctness of 3NF Decomposition (Cont.)

- Case 1: if B in β :
 - If γ is a superkey, the 2nd condition of 3NF is satisfied
 - Otherwise α must contain some attribute not in γ
 - Since $\gamma \rightarrow B$ is in F^+ it must be derivable from F_c by using attribute closure on γ .
 - Attribute closure not have used $\alpha \rightarrow \beta$. If it had been used, α must be contained in the attribute closure of γ , which is not possible, since we assumed γ is not a superkey.
 - Now, using $\alpha \rightarrow (\beta - B)$ and $\gamma \rightarrow B$, we can derive $\alpha \rightarrow B$ (since $\gamma \subseteq \alpha \beta$, and $B \notin \gamma$ since $\gamma \rightarrow B$ is non-trivial)
 - Then, B is extraneous in the right-hand side of $\alpha \rightarrow \beta$, which is not possible since $\alpha \rightarrow \beta$ is in F_c .
 - Thus, if B is in β then γ must be a superkey, and the second condition of 3NF must be satisfied.

Database System Concepts - 7th Edition 7.89 ©Berschütz, Korth and Sudarshan



Correctness of 3NF Decomposition (Cont.)

- Case 2: B is in α .
 - Since α is a candidate key, the third alternative in the definition of 3NF is trivially satisfied.
 - In fact, we cannot show that γ is a superkey.
 - This shows exactly why the third alternative is present in the definition of 3NF.
- Q.E.D.



First Normal Form

- Domain is **atomic** if its elements are considered to be indivisible units
 - Examples of non-atomic domains:
 - Set of names, composite attributes
 - Identification numbers like CS101 that can be broken up into parts
- A relational schema R is in **first normal form** if the domains of all attributes of R are atomic
- Non-atomic values complicate storage and encourage redundant (repeated) storage of data
 - Example: Set of accounts stored with each customer, and set of owners stored with each account
 - We assume all relations are in first normal form (and revisit this in Chapter 22: Object Based Databases)



First Normal Form (Cont.)

- Atomicity is actually a property of how the elements of the domain are used.
 - Example: Strings would normally be considered indivisible
 - Suppose that students are given roll numbers which are strings of the form CS0012 or EE1127
 - If the first two characters are extracted to find the department, the domain of roll numbers is not atomic.
 - Doing so is a bad idea: leads to encoding of information in application program rather than in the database.