Chapter 7: Relational Database Design

Contents

The Banking Schema

- branch = (branch_name, branch_city, assets)
- customer = (customer_id, customer_name, customer_street, customer_city)
- loan = (loan_number, amount)
- account = (account_number, balance)
- employee = (employee_id. employee_name, telephone_number, start_date)
- dependent_name = (employee_id, dname)
- account_branch = (account_number, branch_name)
- loan_branch = (loan_number, branch_name)
- borrower = (customer_id, loan_number)
- depositor = (customer_id, account_number)
- cust_banker = (customer_id, employee_id, type)
- works_for = (worker_employee_id, manager_employee_id)
- payment = (loan_number, payment_number, payment_date, payment_amount)
- savings_account = (account_number, interest_rate)
- checking_account = (account_number, overdraft_amount)

Combine Schemas?

- loan

Loan_number	amount
:	:
L101	10000
:	:

- borrower

customer_id	loan_number
:	:
23-652	L101
22-353	L101
25-263	L101
:	:

- Loan_bor

customer_id	loan_number	amount
:	:	:
23-652	L101	10000
22-353	L101	10000
25-263	L101	10000
:	:	:

Repetition of information

A Combined Schema Without Repetition

Loan_number	amount
:	:
L101	10000
:	:

Loan_number	branch_name
:	:
L101	Springfield
:	:

Loan_number	amount	branch_name
:	:	:
L101	10000	springfield
⋮	⋮	⋮

What About Smaller Schemas?

- Suppose we had started with *bor_loan*. How would we know to split up (**decompose**) it into *borrower* and *loan*?
- Write a rule "if there were a schema (*loan_number*, *amount*), then *loan_number* would be a candidate key"
  - Denote as a **functional dependency**:

$$loan\_number \rightarrow amount$$

- In *bor_loan*, because *loan_number* is not a candidate key, the amount of a loan may have to be repeated. This indicates the need to decompose *bor_loan*.

What About Smaller Schemas?

Cont.

- Not all decompositions are good. Suppose we decompose *employee* into

employee1 = (employee_id, employee_name)

employee2 = (employee_name, telephone_number, start_date)

- The next slide shows how we lose information -- we cannot reconstruct the original *employee* relation -- and so, this is a lossy decomposition.

Employee_id	employee_name	telephone_number	start_date
⋮	⋮	⋮	⋮
123-45-6789	Kim	882-0000	1984-03-29
987-65-4321	Kim	869-9999	1981-02-16
⋮	⋮	⋮	⋮

employee_id	employee_name
⋮	⋮
123-45-6789	Kim
987-65-4321	Kim
⋮	⋮

employee_name	telephone_number	start_date
⋮	⋮	⋮
Kim	882-00000	1984-03-29
Kim	869-99999	1981-02-16
⋮	⋮	⋮

employee_id	employee_name
⋮	⋮
123-45-6789	Kim
987-65-4321	Kim
⋮	⋮

employee_name	telephone_number	start_date
⋮	⋮	⋮
Kim	882-00000	1984-03-29
Kim	869-99999	1981-02-16
⋮	⋮	⋮

Employee_id	employee_name	telephone_number	start_date
⋮	⋮	⋮	⋮
123-45-6789	Kim	882-0000	1984-03-29
123-45-6789	Kim	869-9999	1981-02-16
987-65-4321	Kim	869-9999	1981-02-16
987-65-4321	Kim	882-0000	1984-03-29
⋮	⋮	⋮	⋮

Lose of information

First Normal Form

- Domain is atomic if its elements are considered to be indivisible units
  - Non-atomic attributes

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

First Normal Form Cont.

- Non-atomic values complicate storage and encourage redundant (repeated) storage of data
  - Set of accounts stored with each customer, and set of owners stored with each account
  - We assume all relations are in first normal form

First Normal Form Cont.

- Atomicity is actually a property of how the elements of the domain are used
  - 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.

Goal — Devise a Theory for the Following

- Decide whether a particular relation *R* is in "good" form.
- In the case that a relation *R* is not in "good" form, decompose it into a set of relations $\{R_1, R_2, ..., R_n\}$ such that
  - each relation is in good form
  - the decomposition is a lossless-join decomposition

Goal — Devise a Theory for the Following Cont.

- Our theory is based on:
  - functional dependencies
  - multivalued dependencies

Functional Dependencies

- 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.*

Functional Dependencies Cont.

- 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,

$$t_1[\alpha] = t_2[\alpha] \Rightarrow t_1[\beta] = t_2[\beta]$$

Functional Dependencies Cont.

Example

- Consider $r(A,B)$ with the following instance of r

1	4
1	5
3	7

On this instance, $A \rightarrow B$ does **NOT** hold, but $B \rightarrow A$ does hold.

Functional Dependencies Cont.

- 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 Cont.

- Functional dependencies allow us to express constraints that cannot be expressed using superkeys.
- Consider the schema:

  bor_loan = (*customer_id, loan_number*, *amount*).

  We expect this functional dependency to hold:

  loan_number → *amount*

  but would not expect the following to hold:

  amount → *customer_name*

Functional Dependencies Cont.

- We use functional dependencies to:
  - test relations to see if they are legal under a given set of functional dependencies.
    - If relation *r* is legal under a set *F* of functional dependencies, we say that *r* **satisfies** *F*.
  - 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*.

Functional Dependencies Cont.

- 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.

a specific instance of *loan* may, by chance, satisfy *amount* $\rightarrow$ *customer_name*.

Functional Dependencies Cont.

- *A* functional dependency is trivial if it is satisfied by all instances of a relation

customer_name, loan_number $\rightarrow$ *customer_name*

customer_name $\rightarrow$ *customer_name*

In general, $\alpha \rightarrow \beta$ is trivial if $\beta \subseteq \alpha$

Closure of a Set of Functional Dependencies

- Given a set F 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 $A \rightarrow C$

Closure of a Set of Functional Dependencies Cont.

- The set of **all** functional dependencies logically implied by *F* is the *closure* of *F*.
- We denote the *closure* of *F* by F^+.
- F^+ is a superset of *F*.

SL(Sno, Sdept, Sloc)

F={ Sno→Sdept,Sdept→Sloc,Sno→Sloc}

Sno	Sdept	Sloc
95001	CS	A
95002	IS	B
95003	MA	C
95004	IS	B
95005	PH	B

Drawbacks

- Data redundency
- Update anomalies
- Insert anomalies
- Delete anomalies

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*

Boyce-Codd Normal Form Cont.

- Example schema *not* in BCNF:

bor_loan = (*customer_id*, *loan_number*, *amount*)

because *loan_number* $\rightarrow$ *amount* holds on *bor_loan*
but *loan_number* is not a superkey

Decomposing a Schema into BCNF

- Suppose we have a schema *R* and a non-trivial dependency $\alpha \rightarrow \beta$ causes a violation of BCNF.

  We decompose *R* into:

  - $(\alpha \cup \beta)$
  - $(R - (\beta - \alpha))$

α = *loan_number*
β = *amount*
and *bor_loan* is replaced by
$(\alpha \cup \beta)$=(*loan_number*, *amount*)
$(R - (\beta - \alpha))$ = (*customer_id*, *loan_number*)

BCNF and Dependency Preservation

- Constraints, including functional dependencies, are costly to check in practice unless they pertain to only one relation
- If it is sufficient to test only those dependencies on each individual relation of a decomposition in order to ensure that *all* functional dependencies hold, then that decomposition is *dependency preserving.*

Example

SL(Sno, Sdept, Sloc)

F={ Sno→Sdept,Sdept→Sloc,Sno→Sloc}

Sno	Sdept	Sloc
95001	CS	A
95002	IS	B
95003	MA	C
95004	IS	B
95005	PH	B

Can be divided as

ND(Sno, Sdept), NL(Sno, Sloc)

- ND

Sno	Sdept
95001	CS
95002	IS
95003	MA
95004	IS
95005	PH

- NL

Sno	Sloc
95001	A
95002	B
95003	C
95004	B
95005	B

- ND $\bowtie$ NL

Sno	Sdept	Sloc
95001	CS	A
95002	IS	B
95003	MA	C
95004	IS	B
95005	PH	B

Is a lossless decompostion,
not a dependency preserving decomposition

BCNF and Dependency Preservation Cont.

- It is not always possible to achieve both BCNF and dependency preservation
- So, we consider a weaker normal form, known as

Third Normal Form(3NF).

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)

Third Normal Form Cont.

- 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).

Goals of Normalization

1. Let *R* be a relation schema with a set *F* of functional dependencies.
2. Decide whether a relation schema *R* is in "good" form.

Goals of Normalization Cont.

3. In the case that a relation scheme R is not in "good" form, decompose it into a set of relation scheme $\{R_1, R_2, \ldots, R_n\}$ such that
   - each relation scheme is in good form
   - the decomposition is a lossless-join decomposition
   - Preferably, the decomposition should be dependency preserving.

How good is BCNF?

- There are database schemas in BCNF that do not seem to be sufficiently normalized

Consider a database *classes* (*course*, *teacher*, *book*) such that $(c, t, b) \in$ *classes* means that *t* is qualified to teach *c*, and *b* is a required textbook for *c*

The database is supposed to list for each course the set of teachers any one of which can be the course's instructor, and the set of books, all of which are required for the course (no matter who teaches it).

- *classes*

course	*teacher*	*book*
DB	Avi	DB Concepts
DB	Avi	Ullman
DB	Hank	DB Concepts
DB	Hank	Ullman
DB	Sudarshan	DB Concepts
DB	Sudarshan	Ullman
OS	Avi	OS Concepts
OS	Avi	Stallings
OS	Pete	OS Concepts
OS	Pete	Stallings

There are no non-trivial functional dependencies and therefore the relation is in BCNF

Insertion anomalies – i.e., if Marilyn is a new teacher that can teach database, two tuples need to be inserted

(database, Marilyn, DB Concepts)
(database, Marilyn, Ullman)

Therefore, it is better to decompose *classes* into:

course	**teacher**
DB	Avi
DB	Hank
DB	Sudarshan
OS	Avi
OS	Jim

course	**book**
DB	DB Concepts
DB	Ullman
OS	OS Concepts
OS	Shaw

This suggests the need for higher normal forms, such as Fourth Normal Form (4NF), which we shall see later.

Functional-Dependency Theory

- 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

Closure of a Set of Functional Dependencies

- Given a set *F* 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 $A \rightarrow C$

- The set of all functional dependencies logically implied by *F* is the *closure* of *F*.
- We denote the *closure* of *F* by F^+.

Closure of a Set of Functional Dependencies Cont.

- We can find all of F^+ by applying Armstrong's Axioms:
  - if $\beta \subseteq \alpha$, then $\alpha \rightarrow \beta$ (**reflexivity**)
  - if $\alpha \rightarrow \beta$, then $\gamma\,\alpha \rightarrow \gamma\,\beta$ (**augmentation**)
  - if $\alpha \rightarrow \beta$, and $\beta \rightarrow \gamma$, then $\alpha \rightarrow \gamma$ (**transitivity**)

Closure of a Set of Functional Dependencies Cont.

- Armstrong's Axioms are
  - **sound** (generate only functional dependencies that actually hold) and
  - **complete** (generate all functional dependencies that hold).

Closure of a Set of Functional Dependencies Cont.

- $R = (A, B, C, G, H, I)$, $F = \{\ A \rightarrow B \quad A \rightarrow C \quad CG \rightarrow H \quad CG \rightarrow I \quad B \rightarrow H\ \}$
- 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

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 *f1*and *f2* in *F +*

    if *f1* and *f2* can be combined using transitivity

    then add the resulting functional dependency to *F +*

until *F +* does not change any further

Closure of a Set of Functional Dependencies Cont.

- We can further simplify manual computation of F^+ by using the following additional rules.
  - If $\alpha \rightarrow \beta$ holds and $\alpha \rightarrow \gamma$ holds, then $\alpha \rightarrow \beta\gamma$ holds (**union**)
  - If $\alpha \rightarrow \beta\gamma$ holds, then $\alpha \rightarrow \beta$ holds and $\alpha \rightarrow \gamma$ holds (**decomposition**)
  - If $\alpha \rightarrow \beta$ holds and $\gamma\beta \rightarrow \delta$ holds, then $\alpha\gamma \rightarrow \delta$ holds (**pseudotransitivity**)

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 := a;
  while (changes to result) do
    for each β → γ in F do
      begin
        if β ⊆ result then  result := result ∪ γ
      end
```

$R = (A, B, C, G, H, I)$

$F = \{A \rightarrow B \quad A \rightarrow C \quad CG \rightarrow H \quad CG \rightarrow I \quad B \rightarrow H\}$

$(AG)+$

1. result = AG
2. result = $ABCG$ $\quad (A \rightarrow C$ and $A \rightarrow B)$
3. result = $ABCGH$ $(CG \rightarrow H$ and $CG \subseteq AGBC)$
4. result = $ABCGHI(CG \rightarrow I$ and $CG \subseteq AGBCH)$

Is AG a candidate key?

Is AG a super key?

Does $AG \rightarrow R$? == Is $(AG)+ \supseteq R$

Is any subset of AG a superkey?

Does $A \rightarrow R$? == Is $(A)+ \supseteq R$

Does $G \rightarrow R$? == Is $(G)+ \supseteq R$

Uses of Attribute Closure

- Testing for superkey:
  - To test if α is a superkey, we compute α^+, and check if α^+ contains all attributes of *R*.
- 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 $\gamma \rightarrow S$.

Uses of Attribute Closure Cont.

- 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

Canonical Cover

- Sets of functional dependencies may have redundant dependencies that can be inferred from the others

  $A \rightarrow C$ is redundant in: $\{A \rightarrow B, \quad B \rightarrow C\}$

- Parts of a functional dependency may be redundant

  on RHS: $\{A \rightarrow B, \quad B \rightarrow C, \quad A \rightarrow CD\}$
  can be simplified to $\{A \rightarrow B, \quad B \rightarrow C, \quad A \rightarrow D\}$
  on LHS: $\{A \rightarrow B, \quad B \rightarrow C, \quad AC \rightarrow D\}$
  can be simplified to $\{A \rightarrow B, \quad B \rightarrow C, \quad A \rightarrow D\}$

Canonical Cover Cont.

- Intuitively, a canonical cover of F is a "minimal" set of functional dependencies equivalent to F, having no redundant dependencies or redundant parts of dependencies

Extraneous Attributes

- Consider a set F of functional dependencies and the functional dependency $\alpha \rightarrow \beta$ in F.
  - Attribute A is extraneous in α if $A \in \alpha$ and F logically implies $(F - \{\alpha \rightarrow \beta\}) \cup \{(\alpha - A) \rightarrow \beta\}$.
  - Attribute A is extraneous in β if $A \in \beta$ and the set of functional dependencies $(F - \{\alpha \rightarrow \beta\}) \cup \{\alpha \rightarrow (\beta - A)\}$ logically implies F.

Testing if an Attribute is Extraneous

- Consider a set *F* of functional dependencies and the functional dependency $\alpha \rightarrow \beta$ in *F*.
- To test if attribute $A \in \alpha$ is extraneous in α
  1. compute $(\{\alpha\} - A)^+$ using the dependencies in *F*
  2. check that $(\{\alpha\} - A)^+$ contains β; if it does, *A* is extraneous in α

Testing if an Attribute is Extraneous Cont.

- To test if attribute $A \in \beta$ is extraneous in β
  1. compute α^+ using only the dependencies in
     $F' = (F - \{\alpha \rightarrow \beta\}) \cup \{\alpha \rightarrow (\beta - A)\}$,
  2. check that α^+ contains A; if it does, A is extraneous in β

Canonical Cover Cont.

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

Algorithms to get canonical cover

repeat

Use the union rule to replace any dependencies in *F*

$\alpha_1 \rightarrow \beta_1$ and $\alpha_1 \rightarrow \beta_2$ with $\alpha_1 \rightarrow \beta_1 \beta_2$

Find a functional dependency $\alpha \rightarrow \beta$ with an extraneous attribute either in α or in β

If an extraneous attribute is found, delete it from $\alpha \rightarrow \beta$

until *F* does not change

Note: Union rule may become applicable after some extraneous attributes have been deleted, so it has to be re-applied

Example

$R = (A, B, C)$

$F = \{A \rightarrow BC \;\; B \rightarrow C \;\; A \rightarrow B \;\; AB \rightarrow C\}$

- 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
  - 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
- The canonical cover is: $A \rightarrow B \quad B \rightarrow C$

Lossless-join Decomposition

- For the case of $R = (R_1, R_2)$, we require that for all possible relations r on schema R

$$r = \Pi_{R1}(r) \bowtie \Pi_{R2}(r)$$

- A decomposition of R into R_1 and R_2 is lossless join if and only if at least one of the following dependencies is in F^+:
  - $R_1 \cap R_2 \rightarrow R_1$
  - $R_1 \cap R_2 \rightarrow R_2$

Example

- $R = (A, B, C)$
  $F = \{A \rightarrow B, B \rightarrow C\}$
  - Can be decomposed in two different ways
- $R_1 = (A, B), \quad R_2 = (B, C)$
  - Lossless-join decomposition:

    $R_1 \cap R_2 = \{B\}$ and $B \rightarrow BC$
  - Dependency preserving
- $R_1 = (A, B), \quad R_2 = (A, C)$
  - Lossless-join decomposition:

    $R_1 \cap R_2 = \{A\}$ and $A \rightarrow AB$
  - Not dependency preserving
    (cannot check $B \rightarrow C$ without computing $R_1 \bowtie R_2$)

Dependency Preservation

- Let F_i be the set of dependencies of F^+ that include only attributes in R_i.
  - A decomposition is dependency preserving, if: $(F_1 \cup F_2 \cup \ldots \cup F_n)^+ = F^+$
  - If it is not, then checking updates for violation of functional dependencies may require computing joins, which is expensive

Testing for Dependency Preservation

- To check if a dependency $\alpha \rightarrow \beta$ is preserved in a decomposition of R into $R_1, R_2, \ldots, R_n$ we apply the following test (with attribute closure done with respect to F)
  - *result* = α
    while (changes to *result*) do
    for each R_i in the decomposition
    $t = (result \cap R_i)^+ \cap R_i$
    $result = result \cup t$
  - If *result* contains all attributes in β, then the functional dependency $\alpha \rightarrow \beta$ is preserved

Testing for Dependency Preservation

- 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 $(F_1 \cup F_2 \cup \ldots \cup F_n)^+$

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

Testing for BCNF

- To check if a non-trivial dependency $\alpha \rightarrow \beta$ causes a violation of BCNF
  1. compute α^+ (the attribute closure of α), and
  2. verify that it includes all attributes of *R*, that is, it is a superkey of *R*.

Testing for BCNF

- 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.

Testing for BCNF

- However, 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 mislead into thinking R_2 satisfies BCNF.
    - In fact, dependency $AC \rightarrow D$ in F^+ shows R_2 is not in BCNF.

Testing Decomposition for BCNF

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

BCNF Decomposition Algorithm

result := {*R* };
done := false;
compute F^+;
while (**not** *done*) **do**
if (there is a schema R_i in *result* that is not in BCNF)
then begin
let $\alpha \rightarrow \beta$ be a nontrivial functional dependency that holds on R_i such that $\alpha \rightarrow R_i$ is not in F^+,
and $\alpha \cap \beta = \emptyset$;
result := (*result* – R_i) $\cup$ (R_i – β) $\cup$ (α, β);
end
else *done* := **true;**

Example

- $R = (A, B, C)$
  $F = \{A \rightarrow B \quad B \rightarrow C\}$ Key = $\{A\}$
- R is not in BCNF ($B \rightarrow C$ but B is not superkey)
- Decomposition
  - $R_1 = (B, C)$
  - $R_2 = (A, B)$

Example of BCNF Decomposition

- Original relation *R* and functional dependency *F*

R = (*branch_name, branch_city, assets,*
customer_name, loan_number, amount)

F = {*branch_name* $\rightarrow$ *assets branch_city*
loan_number $\rightarrow$ *amount branch_name* }

Key = {*customer_name*}

Example of BCNF Decomposition

- Decomposition
  - R_1 = (*branch_name*, *branch_city*, *assets*)
  - R_2 = (*branch_name*, *customer_name*, *loan_number*, *amount*)
  - R_3 = (*branch_name*, *loan_number*, *amount*)
  - R_4 = (*customer_name*, *loan_number*)
- Final decomposition

  R_1, R_3, R_4

Third Normal Form: Motivation

- There are some situations where
  - BCNF is not dependency preserving,
  - Efficient checking for FD violation on updates is important

Third Normal Form: Motivation

- 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.

3NF Example

- Relation R:
  - $R = (J, K, L)$

    $F = \{JK \rightarrow L, L \rightarrow K\}$
  - Two candidate keys: JK and JL
  - R is in 3NF

    $JK \rightarrow L$ JK is a superkey

    $L \rightarrow K$ K is contained in a candidate key

Testing for 3NF

- Optimization: Need to check only FDs in *F*, need not check all FDs in F^+.
- Use attribute closure to check for each dependency $\alpha \rightarrow \beta$, if α is a superkey.

Testing for 3NF

- 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 involve 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

3NF Decomposition Algorithm

Let *Fc* be a canonical cover for *F*; $i := 0$;
for each functional dependency $\alpha \rightarrow \beta$ in *Fc* **do**
    if none of the schemas $R_j, 1 \le j \le i$ contains $\alpha\beta$
      then begin
            $i := i + 1$;
            $R_i := \alpha\beta$
          end
if none of the schemas $R_j, 1 \le j \le i$ contains a candidate key for *R*
 then begin
        $i := i + 1$;
        $R_i :=$ any candidate key for *R*;
      end
return $(R_1, R_2, ..., R_i)$

3NF Decomposition Algorithm

- Above algorithm ensures:
  - each relation schema R_i is in 3NF
  - decomposition is dependency preserving and lossless-join

3NF Decomposition: An Example

- Relation schema:

  cust_banker_branch = (*customer_id*, *employee_id*, *branch_name*, *type*)

- The functional dependencies for this relation schema are:

  1. *customer_id*, *employee_id* $\rightarrow$ *branch_name*, *type*
  2. *employee_id* $\rightarrow$ *branch_name*
  3. *customer_id*, *branch_name* $\rightarrow$ *employee_id*

3NF Decomposition: An Example

- 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* $\rightarrow$ *type*
employee_id $\rightarrow$ *branch_name*
customer_id, *branch_name* $\rightarrow$ *employee_id*

3NF Decompsition Example

- 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

3NF Decompsition Example

- If the FDs were considered in a different order, with the 2nd one considered after the 3rd,

  (*<u>employee_id</u>, branch_name*)

  would not be included in the decomposition because it is a subset of (*customer_id, branch_name, employee_id*)

3NF Decompsition Example

- Minor extension of the 3NF decomposition algorithm: 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*)

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.

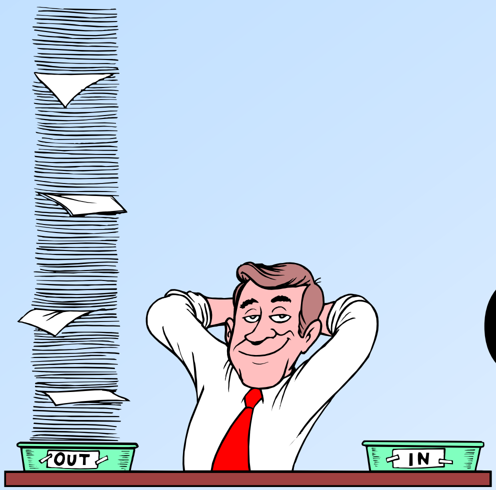
Design Goals

- 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

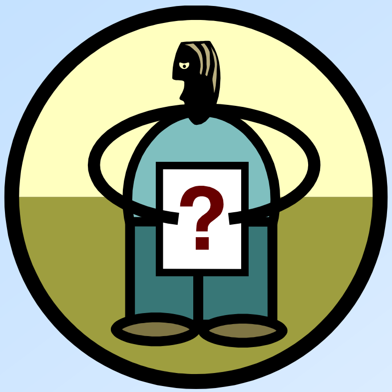
Design Goals

- 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
- 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.



Conclusions



Questions?

End of Chapter

Multivalued Dependencies (MVDs)

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

$$\alpha \rightarrow\rightarrow \beta$$

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:

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

MVD (Cont.)

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

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

course	teacher	book
DB	Avi	DB Concepts
DB	Avi	Ullman
DB	Hank	DB Concepts
DB	Hank	Ullman
DB	Sudarshan	DB Concepts
DB	Sudarshan	Ullman
OS	Avi	OS Concepts
OS	Pete	Stallings
OS	Avi	Stallings
OS	Pete	OS Concepts

Example

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

$$Y, Z, W$$

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

$$< y_1, z_1, w_1 > \in r \text{ and } < y_1, z_2, w_2 > \in r$$

then

$$< y_1, z_1, w_2 > \in r \text{ and } < y_1, z_2, w_1 > \in r$$

- Note that since the behavior of Z and W are identical it follows that

$Y \rightarrow\rightarrow Z$ if $Y \rightarrow\rightarrow W$

Example (Cont.)

- In our example:

  $$course \rightarrow\rightarrow teacher$$
  $$course \rightarrow\rightarrow book$$

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

Use of Multivalued Dependencies

- We use multivalued dependencies in two ways:
  1. To test relations to determine whether they are legal under a given set of functional and multivalued dependencies
  2. To specify constraints on the set of legal relations. We shall thus 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*.

Theory of MVDs

- From the definition of multivalued dependency, we can derive the following rule:
  - If $\alpha \rightarrow \beta$, then $\alpha \rightarrow\rightarrow \beta$

  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 (see Appendix C).

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 $\alpha \rightarrow\rightarrow \beta$, where $\alpha \subseteq R$ and $\beta \subseteq R$, at least one of the following hold:
  - $\alpha \rightarrow\rightarrow \beta$ 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

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

    $\alpha \rightarrow\rightarrow (\beta \cap R_i)$

    where $\alpha \subseteq R_i$ and $\alpha \rightarrow\rightarrow \beta$ is in D^+

4NF Decomposition Algorithm

result: = {*R*};
done := false;
compute D^+;
Let D_i denote the restriction of D^+ to R_i
while (**not** *done*)
if (there is a schema $\mathbf{R}_i$ in *result* that is not in 4NF)
then
begin
let $\alpha \rightarrow\rightarrow \beta$ be a nontrivial multivalued dependency that holds
on R_i such that $\alpha \rightarrow R_i$ is not in D_i, and $\alpha \cap \beta = \phi$;
result := (*result* - R_i) $\cup$ (R_i - β) $\cup$ (α, β);
end
else *done*:= true;

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

Example

- $R = (A, B, C, G, H, I)$

  $F = \{ A \rightarrow\rightarrow B$

  $B \rightarrow\rightarrow HI$

  $CG \rightarrow\rightarrow H \}$
- R is not in 4NF since $A \rightarrow\rightarrow B$ 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)

  c) $R_3 = (C, G, H)$ (R_3 is in 4NF)

  d) $R_4 = (A, C, G, I)$ (R_4 is not in 4NF)
- Since $A \rightarrow\rightarrow B$ and $B \rightarrow\rightarrow HI$, $A \rightarrow\rightarrow HI$, $A \rightarrow\rightarrow I$

  e) $R_5 = (A, I)$ (R_5 is in 4NF)

  f) $R_6 = (A, C, G)$ (R_6 is in 4NF)

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

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.

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_number* and *department_address*, and a functional dependency *department_number* → *department_address*
  - 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

Denormalization for Performance

- May want to use non-normalized schema for performance
- For example, displaying *customer_name* along with *account_number* and *balance* requires join of *account* with *depositor*
- Alternative 1: Use denormalized relation containing attributes of *account* as well as *depositor* 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 as
  account $\bowtie$ depositor
  - Benefits and drawbacks same as above, except no extra coding work for programmer and avoids possible errors

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

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 a customer at different points in time
  - entities, e.g. time duration when an account exists
  - relationships, e.g. time during which a customer owned an account
- But no accepted standard
- Adding a temporal component results in functional dependencies like

  $$customer\_id \rightarrow customer\_street, customer\_city$$

  not to hold, because the address varies over time
- A *temporal functional dependency* $X \xrightarrow{\tau} Y$ holds on schema *R* if the functional dependency $X \rightarrow Y$ holds on all snapshots for all legal instances r (*R*)

Modeling Temporal Data (Cont.)

- In practice, database designers may add start and end time attributes to relations
  - E.g. *course*(*course_id*, *course_title*) → *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

End of Chapter