CSCD 327: Relational Database Systems

Relational database design

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The Banking Schema

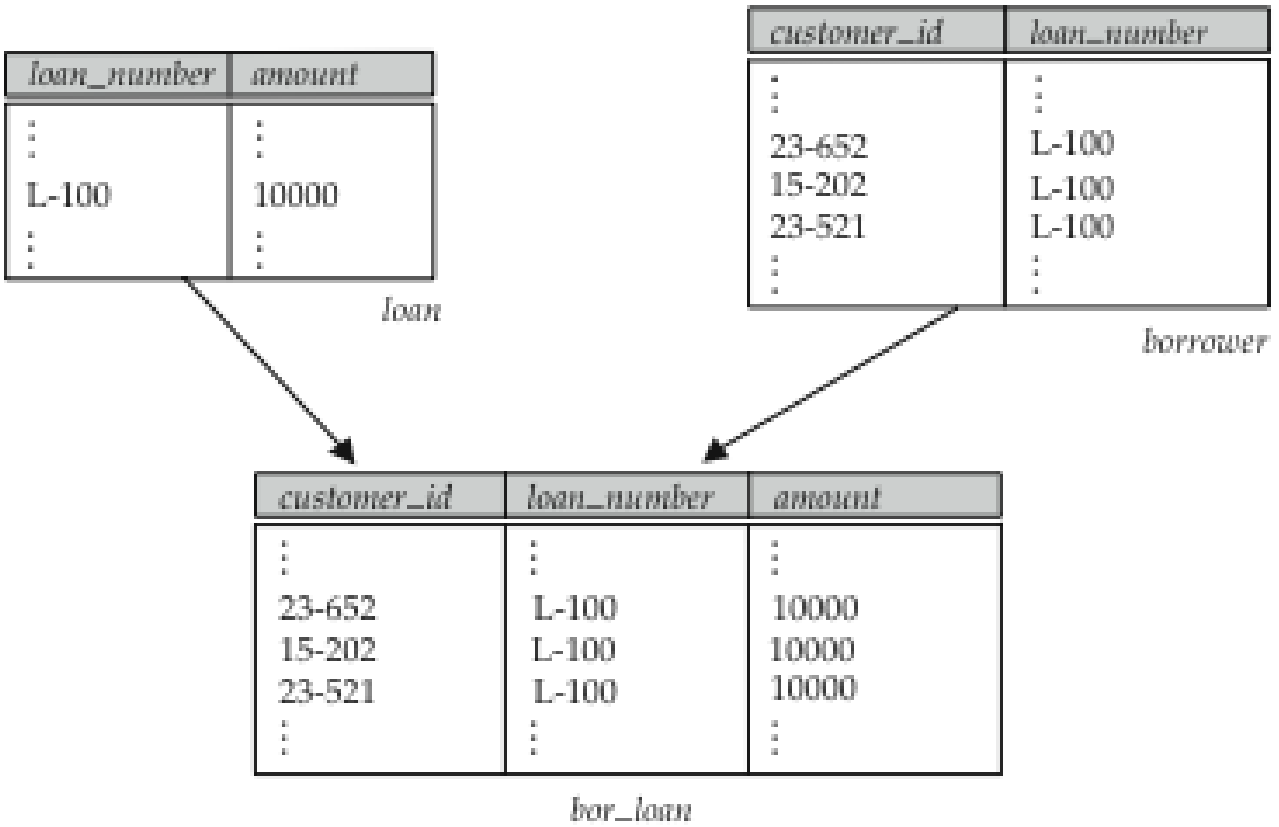
- *branch* = (*branch_name*, *branch_city*, *assets*)
- *customer* = (*customer_id*, *customer_name*, *customer_street*, *customer_city*)
- *loan* = (*loan_number*, *amount*)
- *account* = (*account_number*, *balance*)
- *employee* = (*employee_id*. *employee_name*, *telephone_number*, *start_date*)
- *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?

- Suppose we combine *borrower* and *loan* to get

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

- Result is possible repetition of information (L-100 in example below)

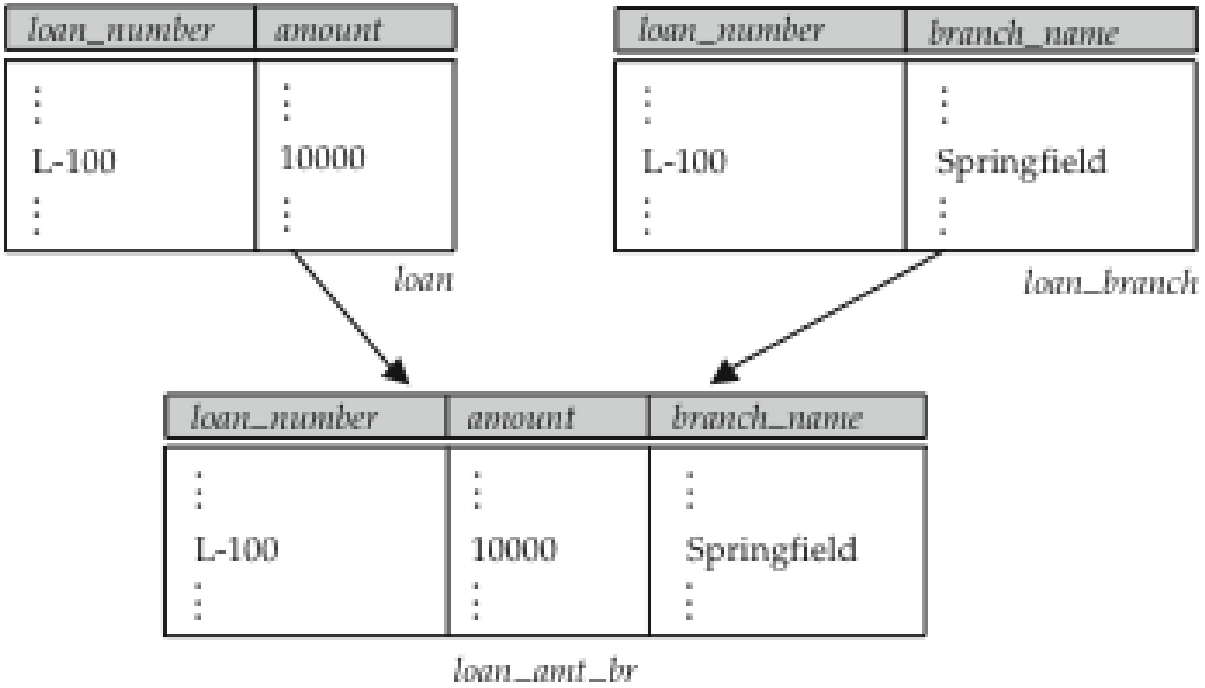


A Combined Schema Without Repetition

- Consider combining *loan_branch* and *loan*

  loan_amt_br = (*loan_number*, *amount*, *branch_name*)

- No repetition (as suggested by example below)



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**:

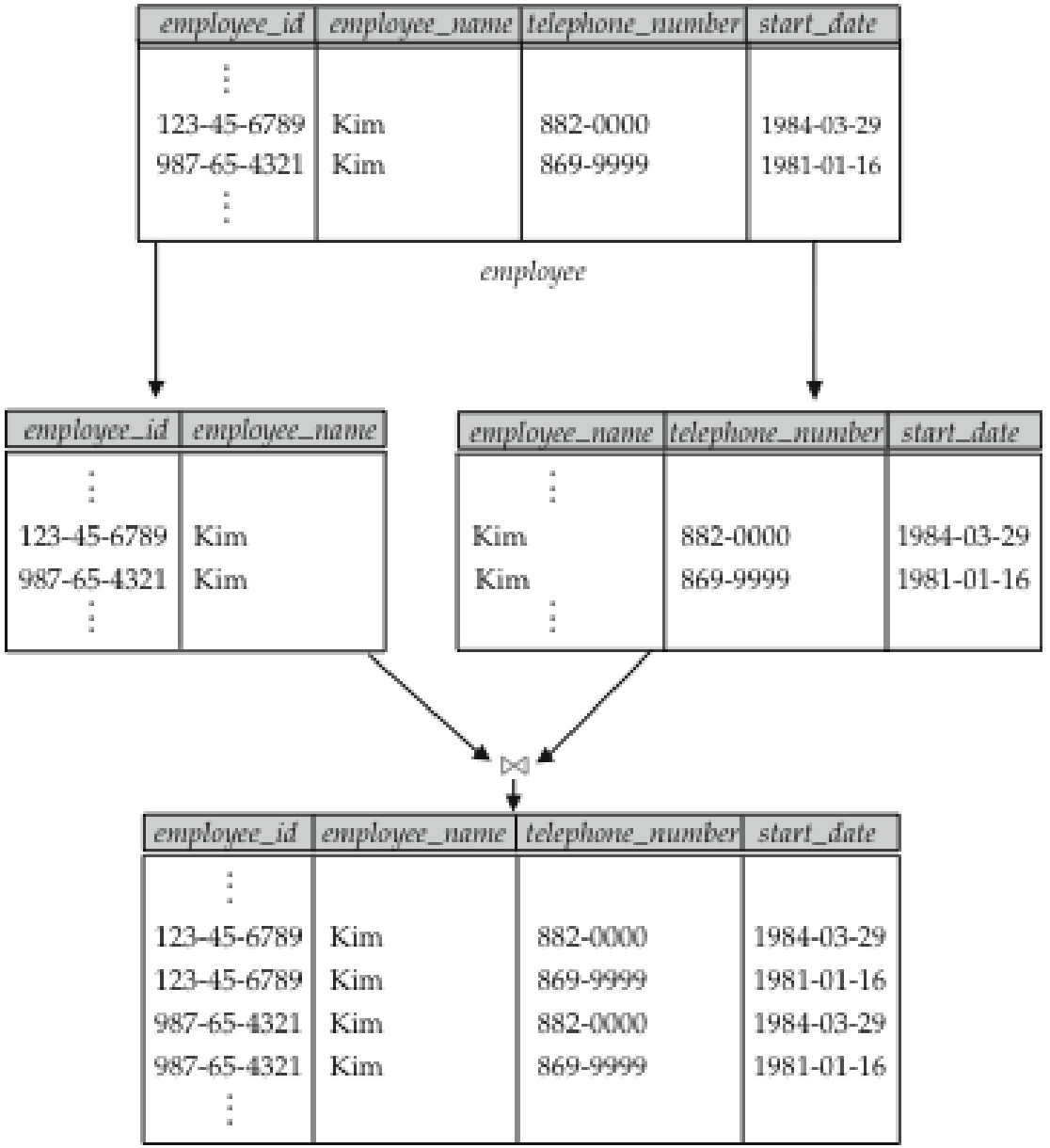
  $$loan\_number \rightarrow amount$$

- 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*.
- 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.

A Lossy Decomposition



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

Functional Dependencies

- Constraints on the set of legal relations.
- Let *R* be a relation schema

$$\alpha \subseteq R \text{ and } \beta \subseteq R$$

- 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, $A \rightarrow B$ 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 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:

  $$loan\_number \rightarrow amount$$

  but loan_number is not the super key

Functional Dependencies (Cont.)

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

First Normal Form (1NF)

- 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.

1NF Counter Example

emp_id	emp_name	emp_address	emp_mobile
101	Herschel	New Delhi	8912312390
102	Jon	Kanpur	8812121212 9900012222
103	Ron	Chennai	7778881212
104	Lester	Bangalore	9990000123 8123450987

1NF violation: Two employees (Jon & Lester) are having two mobile numbers so the company stored them in the same field as you can see in the table above.

Turn into 1NF

emp_id	emp_name	emp_address	emp_mobile
101	Herschel	New Delhi	8912312390
102	Jon	Kanpur	8812121212
102	Jon	Kanpur	9900012222
103	Ron	Chennai	7778881212
104	Lester	Bangalore	9990000123
104	Lester	Bangalore	8123450987

Second Normal Form (2NF)

- A table is said to be in 2NF if both the following conditions hold:
  - Table is in 1NF (First normal form)
  - No non-prime attribute is dependent on the proper subset of any candidate key of table.
    - **A non-prime attribute of a table** is an attribute that is not a part of any candidate key of the table.

2NF Counter Example

teacher_id	subject	teacher_age
111	Maths	38
111	Physics	38
222	Biology	38
333	Physics	40
333	Chemistry	40

Candidate Key: {teacher_id, subject}
Non prime attribute: teacher_age
FD: teacher_id → teacher_age
2NF violation: teacher_age depent on teacher_id, which is a proper subset of the candidate key.

Turn into 2NF

teacher_details table:

teacher_id	teacher_age
111	38
222	38
333	40

teacher_subject table:

teacher_id	subject
111	Maths
111	Physics
222	Biology
333	Physics
333	Chemistry

Third Normal Form (3NF)

- A table design is said to be in 3NF if both the following conditions hold:
  - Table must be in 2NF
  - **Transitive functional dependency** of non-prime attribute on any **super key** should be removed.
- In other words 3NF can be explained like this: A table is in 3NF if it is in 2NF and for each functional dependency α-> β at least one of the following conditions hold:
  - α is a **super key** of table
  - Each attribute in β is a prime attribute of table

3NF Counter Example

emp_id	emp_name	emp_zip	emp_state	emp_city	emp_district
1001	John	282005	UP	Agra	Dayal Bagh
1002	Ajeet	222008	TN	Chennai	M-City
1006	Lora	282007	TN	Chennai	Urrapakkam
1101	Lilly	292008	UK	Pauri	Bhagwan
1201	Steve	222999	MP	Gwalior	Ratan

Candidate Keys: {emp_id}
Non-prime attributes: all attributes except emp_id are non-prime as they are not part of any candidate keys.
Super keys: {emp_id}, {emp_id, emp_name}, {emp_id, emp_name, emp_zip}…so on
FD: emp_zip → emp_state, emp_city, emp_district
3NF violation: emp_zip is dependent on emp_id that makes non-prime attributes (emp_state, emp_city & emp_district) transitively dependent on super key (emp_id).

Turn into 3NF

employee table:

emp_id	emp_name	emp_zip
1001	John	282005
1002	Ajeet	222008
1006	Lora	282007
1101	Lilly	292008
1201	Steve	222999

employee_zip table:

emp_zip	emp_state	emp_city	emp_district
282005	UP	Agra	Dayal Bagh
222008	TN	Chennai	M-City
282007	TN	Chennai	Urrapakkam
292008	UK	Pauri	Bhagwan
222999	MP	Gwalior	Ratan

Boyce-Codd Normal Form (BCNF)

- A table is in BCNF if it is in 3NF and for each functional dependency α-> β the following condition holds:
  - α is a **super key** of table

BCNF Counter Example

Manager	Project	Branch
Brown	Mars	Chicago
Green	Jupiter	Birmingham
Green	Mars	Birmingham
Hoskins	Saturn	Birmingham
Hoskins	Venus	Birmingham

FD: Manager → Branch — each manager works in a particular branch;
FD: Project, Branch → Manager — each project has several managers, and runs on several branches; however, a project has a unique manager for each branch.
BCNF violations: manager by itself isn't a super key.

How to fix it? Coming soon….

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*.
  - For example: 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^+.
- F^+ is a superset of *F*.

Closure of a Set of Functional Dependencies (cont.)

- Given a set *F* set of functional dependencies, there are certain other functional dependencies that are logically implied by *F*.
  - For example: 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^+.
- 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)**
- These rules are
  - sound (generate only functional dependencies that actually hold) and
  - complete (generate all functional dependencies that hold).

Example

- $R = (A, B, C, G, H, I)$
  $F = \{ A \rightarrow B$
  $A \rightarrow C$
  $CG \rightarrow H$
  $CG \rightarrow I$
  $B \rightarrow H\}$
- 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 $CG \rightarrow$ CG*I,* and augmenting of $CG \rightarrow H$ to infer $CGI \rightarrow HI,$ and then transitivity

Closure of Functional Dependencies (Cont.)

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

  The above rules can be inferred from Armstrong's axioms.

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

Example of Attribute Set Closure

- $R = (A, B, C, G, H, I)$
- $F = \{A \rightarrow B$
  $A \rightarrow C$
  $CG \rightarrow H$
  $CG \rightarrow I$
  $B \rightarrow H\}$
- $(AG)^+$
  1. $result = AG$
  2. $result = ABCG$ $(A \rightarrow C$ 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?
  1. Is AG a super key?
     1. Does $AG \rightarrow R$? == Is $(AG)^+ \supseteq R$
  2. Is any subset of AG a superkey?
     1. Does $A \rightarrow R$? == Is $(A)^+ \supseteq R$
     2. Does $G \rightarrow R$? == Is $(G)^+ \supseteq R$

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 $\gamma \rightarrow S$.

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*.
- 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.

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:

  (1) (αU β)

  (2) (*R* - (β - α))

- In our example,
  - α = *loan_number*
  - β = *amount*

  and *bor_loan* is replaced by

  (1) (αU β) = (*loan_number, amount*)

  (2) (*R* - (β - α)) = (*customer_id, loan_number*)

Lossless-join Decomposition

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

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

- 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 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 = {*loan_number, customer_name*}

- Decomposition
  - R_1 = (*branch_name, branch_city, assets*)
  - R_2 = (*branch_name, customer_name, loan_number, amount*)
  - R_{21} = (*branch_name, loan_number, amount*)
  - R_{22} = (*customer_name, loan_number*)
- Final decomposition

  R_1, R_{21}, R_{22}

Dependency Preserving

- 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***.

Dependency Preservation (cont.)

- Let F_i be the set of dependencies F^+ that include only attributes in R_i.
  - A decomposition is dependency preserving, if

    $$(F_1 \cup F_2 \cup \ldots \cup F_n)^+ = F^+$$

  - If it is not, then checking updates for violation of functional dependencies may require computing joins, which is expensive.

BCNF and Dependency Preservation

It is not always possible to get a BCNF decomposition that is dependency preserving

- $R = (J, K, L)$
  $F = \{JK \rightarrow L$
  $L \rightarrow K\}$
  Two candidate keys = JK and JL
- R is not in BCNF
- Any decomposition of R will fail to preserve

$$JK \rightarrow L$$

  This implies that testing for $JK \rightarrow L$ requires a join

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, decompose it into a set of relation scheme $\{R_1, R_2, ..., R_n\}$ such that
  - each relation scheme is in good form
  - the decomposition is a lossless-join decomposition
  - **Preferably, the decomposition should be dependency preserving.**

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
- Interestingly, SQL does not provide a direct way of specifying functional dependencies other than superkeys.

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).

How good is BCNF? (Cont.)

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

classes

- 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)

How good is BCNF? (Cont.)

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

course	*teacher*
database	Avi
database	Hank
database	Sudarshan
operating systems	Avi
operating systems	Jim

teaches

course	*book*
database	DB Concepts
database	Ullman
operating systems	OS Concepts
operating systems	Shaw

text

This suggests the need for higher normal forms, such as Fourth Normal Form (4NF), which we will not cover in this course..