

Principles of Database Systems (CS307)

Lecture 10: Normalization - Part 1

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- Most contents are from slides made by Stéphane Faroult and the authors of Database System Concepts (7th Edition).
- Their original slides have been modified to adapt to the schedule of CS307 at SUSTech.
- The slides are largely based on the slides provided by Dr. Yuxin Ma

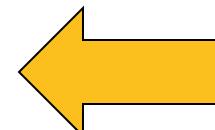
Normalization: A First Look

Design Alternatives

- In designing a database schema, we must ensure that **we avoid two major pitfalls**
 - **Redundancy:** a bad design may result in repeated information
 - E.g., store course identifier and title of a course for each course offering
 - Only store course identifier is sufficient
 - Redundant representation of information may **lead to data inconsistency among the various copies of information**
 - E.g., update is not performed on all the copies
 - **Incompleteness:** a bad design may make certain aspects of the enterprise difficult or impossible to model
 - E.g., only have entity for course offering, but without entity for courses
 - Impossible to model new courses that are not offered yet

Design Alternatives

- Avoiding bad designs is not enough
 - There may be many good designs from which we must choose
- For example, a customer who buys a product
 - The sale activity is a relationship between the customer and the product?
 - The sale activity is a relationship among the customer, the product, and the sale itself?
 - i.e., the sale can be considered as an entity
- Database design can be difficult
 - When #entities and #relationships are large
- Do we have any guidelines on how to get a good design?
 - Normal Forms (范式)!



Normalization (规范化)

- In practice, we usually just satisfy 1NF, 2NF and 3NF

	UNF (1970)	1NF (1970)	2NF (1971)	3NF (1971)	EKNF (1982)	BCNF (1974)	4NF (1977)	ETNF (2012)	5NF (1979)	DKNF (1981)	6NF (2003)
Primary key (no duplicate tuples) ^[4]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Atomic columns (cells cannot have tables as values) ^[5]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either does not begin with a proper subset of a candidate key or ends with a prime attribute (no partial functional dependencies of non-prime attributes on candidate keys) ^[5]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either begins with a superkey or ends with a prime attribute (no transitive functional dependencies of non-prime attributes on candidate keys) ^[5]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either begins with a superkey or ends with an elementary prime attribute	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	N/A
Every non-trivial functional dependency begins with a superkey	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	N/A
Every non-trivial multivalued dependency begins with a superkey	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	N/A
Every join dependency has a superkey component ^[8]	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	N/A
Every join dependency has only superkey components	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	N/A
Every constraint is a consequence of domain constraints and key constraints	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
Every join dependency is trivial	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓

First Normal Form (1NF, 第一范式)

- A relational schema R is in 1NF if the domains of all attributes of R are atomic
 - 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 CS307 that can be broken up into parts
 - However, in practice, we can also consider it atomic
 - Non-atomic values complicate storage and encourage redundant (repeated) storage of data

First Normal Form (1NF)

- Example: Non-atomic attribute

station_id	name	location
1	Luohu(罗湖)	114.11833 , 22.53111
2	Guomao(国贸)	114.11889 , 22.54
3	Laojie(老街)	114.11639 , 22.54444
4	Grand Theater(大剧院)	114.10333 , 22.54472
5	Science Museum(科学馆)	114.08972 , 22.54333
6	Huaqiang Rd(华强路)	114.07889 , 22.54306
7	Gangxia(岗厦)	114.06306 , 22.53778
8	Convention and Exhibition Center Station(会展中心)	114.05472 , 22.5375
9	Shopping Park(购物公园)	114.05472 , 22.53444
10	Xiangmihu(香蜜湖)	114.034 , 22.5417

First Normal Form (1NF)

- Another example: Starring
 - Problems: 1) Redundant names; 2) difficulties in updating/deleting a specific person; 3) extra cost in splitting names; 4) difficulties in making statistics

Movie ID	Movie Title	Country	Year	Director	Starring
0	Citizen Kane	US	1941	welles, o.	Orson Welles, Joseph Cotten
1	La règle du jeu	FR	1939	Renoir, J.	Roland Toutain, Nora Grégor, Marcel Dalio, Jean Renoir
2	North By Northwest	US	1959	HITCHCOCK, A.	Cary Grant, Eva Marie Saint, James Mason
3	Singin' in the Rain	US	1952	Donen/Kelly	Gene Kelly, Debbie Reynolds, Donald O'Connor
4	Rear Window	US	1954	Alfred Hitchcock	James Stewart, Grace Kelly

Second Normal Form (2NF, 第二范式)

- A relation satisfying 2NF must:
 - be in 1NF
 - not have any **non-prime attribute** that is dependent on any proper subset of any **candidate key** of the relation
 - A non-prime attribute of a relation is an attribute that is not a part of any candidate key of the relation
 - 不包含只依赖于 主键中部分属性 的非主属性
 - “非主属性”是指 不属于 任何候选键的属性

Second Normal Form (2NF)

- Example: consider this table with the composite primary key (*station_id*, *line_id*)

station_id	english_name	chinese_name	district	line_id	line_color	operator
1	Luohu	罗湖	Luohu	1	Green	Shenzhen Metro Corporation
2	Guomao	国贸	Luohu	1	Green	Shenzhen Metro Corporation
3	Laojie	老街	Luohu	1	Green	Shenzhen Metro Corporation
4	Grand Theater	大剧院	Luohu	1	Green	Shenzhen Metro Corporation
4	Grand Theater	大剧院	Luohu	11	Purple	Shenzhen Metro Corporation
4	Grand Theater	大剧院	Luohu	2	Orange	Shenzhen Metro Corporation
3	Laojie	老街	Luohu	3	DeepSkyBlue	Shenzhen Metro No.3 Line

- The columns *line_color* and *operator* are not related to *station_id*
 - They are only related to *line_id*, which is only part of (a subset of) the primary key
- Similarly, *english_name*, *chinese_name*, and *district* are not related to *line_id*
 - They are only related to *station_id*, which is only part of (a subset of) the primary key
- 非主属性 *line_color*, *operator*, *english_name*, *chinese_name*, *district* 只依赖于主键中的部份属性

Third Normal Form (3NF, 第三范式)

- A relation satisfying 3NF must:
 - be in 2NF
 - all the attributes in a table are determined only by the candidate keys of that relation, not by any non-prime attributes
 - 所有属性 只依赖于候选键, 不依赖于任意非主属性

Third Normal Form (3NF)

- Example: Consider this table which describes the bus lines and their stops
 - Primary key (bus_line)

bus_line	station_id	chinese_name	english_name	district
B796	21	鲤鱼门	Liyumen	Nanshan
M343	21	鲤鱼门	Liyumen	Nanshan
M349	21	鲤鱼门	Liyumen	Nanshan
M250	26	坪洲	Pingzhou	Bao'an
374	61	安托山	Antuo Hill	Futian
B733	61	安托山	Antuo Hill	Futian
B828	120	临海	Linhai	Nanshan

- *station_id* depends on the primary key (*bus_line*)
- However, the columns *chinese_name*, *english_name*, and *district* depend on *station_id*, which is not the primary key.
 - They only have “*indirect/transitive*” dependence (非直接/传递依赖) on the primary key
- Problem: Data redundancy

Third Normal Form (3NF)

- Example: Consider this table which describes the bus lines and their stops
 - Primary key (*bus_line*)

bus_line	station_id	chinese_name	english_name	district
B796	21	鲤鱼门	Liyumen	Nanshan
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B733	61	安托山	Antuo Hill	Futian
B828	120	临海	Linhai	Nanshan

- Problem when not meeting 3NF:
 - Data redundancy
 - » the attributes for a station have been stored multiple times
 - Insertion and deletion anomaly
 - » inserting a new bus line with no station becomes impossible without NULLs
 - » deleting a station/bus line may also delete corresponding bus lines/stations

Normalization

- In practice, we usually just satisfy 1NF, 2NF and 3NF

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Primary key (no duplicate tuples) ^[4]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Atomic columns (cells cannot have tables as values) ^[5]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either does not begin with a proper subset of a candidate key or ends with a prime attribute (no partial functional dependencies of non-prime attributes on candidate keys) ^[5]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either begins with a superkey or ends with a prime attribute (no transitive functional dependencies of non-prime attributes on candidate keys) ^[5]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either begins with a superkey or ends with an elementary prime attribute	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	N/A
Every non-trivial functional dependency begins with a superkey	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	N/A
Every non-trivial multivalued dependency begins with a superkey	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	N/A
Every join dependency has a superkey component ^[8]	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	N/A
Every join dependency has only superkey components	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	N/A
Every constraint is a consequence of domain constraints and key constraints	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
Every join dependency is trivial	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓

(Recall) Prerequisites of Decomposition & Functional Dependency

Relation Schema and Instance

- A_1, A_2, \dots, A_n are attributes
- $R = (A_1, A_2, \dots, A_n)$ is a **relation schema**
 - Example on the right side:
instructor = ($ID, name, dept_name, salary$)
- $r(R)$ denotes a relation instance r defined over schema R
 - Or to say, the entire table on the right side
- An element t of relation r is called a **tuple**
 - ... and is represented by a row in a table

The relation schema ("R")

A_1 A_2 A_3 A_4

ID	$name$	$dept_name$	$salary$
10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	60000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
58583	Califieri	History	62000
76543	Singh	Finance	80000
76766	Crick	Biology	72000
83821	Brandt	Comp. Sci.	92000
98345	Kim	Elec. Eng.	80000

$r(R)$

A tuple

Keys

- Let $K \subseteq R$
 - K is a **superkey** of R if values for K are sufficient to identify a unique tuple of each possible relation $r(R)$
 - E.g., $\{ID\}$ and $\{ID, name\}$ are both **superkeys** of *instructor*
 - If K is a superkey, any superset K' of K where $K' \subseteq R$ is a superkey as well
 - Superkey K is a **candidate key** if K is minimal, i.e., no proper subset of K is a superkey
 - E.g., $\{ID\}$ is a candidate key for *instructor*
- One of the candidate keys is selected to be the **primary key**
 - We mark the primary key with an underline:
instructor = $(ID, name, dept_name, salary)$

<i>ID</i>	<i>name</i>	<i>dept_name</i>	<i>salary</i>
10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	60000
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instructor

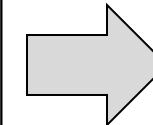
Decomposition & Functional Dependency

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*
 - There is repetition of information (e.g., building and budget)
 - Could lead to inconsistency
 - Need to use nulls (if we add a new department with no instructors)
 - In many cases, null values are troublesome, as we saw in our study of SQL

<i>ID</i>	<i>name</i>	<i>dept_name</i>	<i>salary</i>
10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	60000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
58583	Califieri	History	62000
76543	Singh	Finance	80000
76766	Crick	Biology	72000
83821	Brandt	Comp. Sci.	92000
98345	Kim	Elec. Eng.	80000

<i>dept_name</i>	<i>building</i>	<i>budget</i>
Physics	Watson	70000
Finance	Painter	120000
History	Painter	50000
Comp. Sci.	Taylor	100000
Elec. Eng.	Taylor	85000
Biology	Watson	90000
Comp. Sci.	Taylor	100000
History	Painter	50000
Comp. Sci.	Taylor	100000
Music	Packard	80000
Physics	Watson	70000
Finance	Painter	120000



<i>ID</i>	<i>name</i>	<i>salary</i>	<i>dept_name</i>	<i>building</i>	<i>budget</i>
22222	Einstein	95000	Physics	Watson	70000
12121	Wu	90000	Finance	Painter	120000
32343	El Said	60000	History	Painter	50000
45565	Katz	75000	Comp. Sci.	Taylor	100000
98345	Kim	80000	Elec. Eng.	Taylor	85000
76766	Crick	72000	Biology	Watson	90000
10101	Srinivasan	65000	Comp. Sci.	Taylor	100000
58583	Califieri	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

instructor

department

in_dep

Decomposition

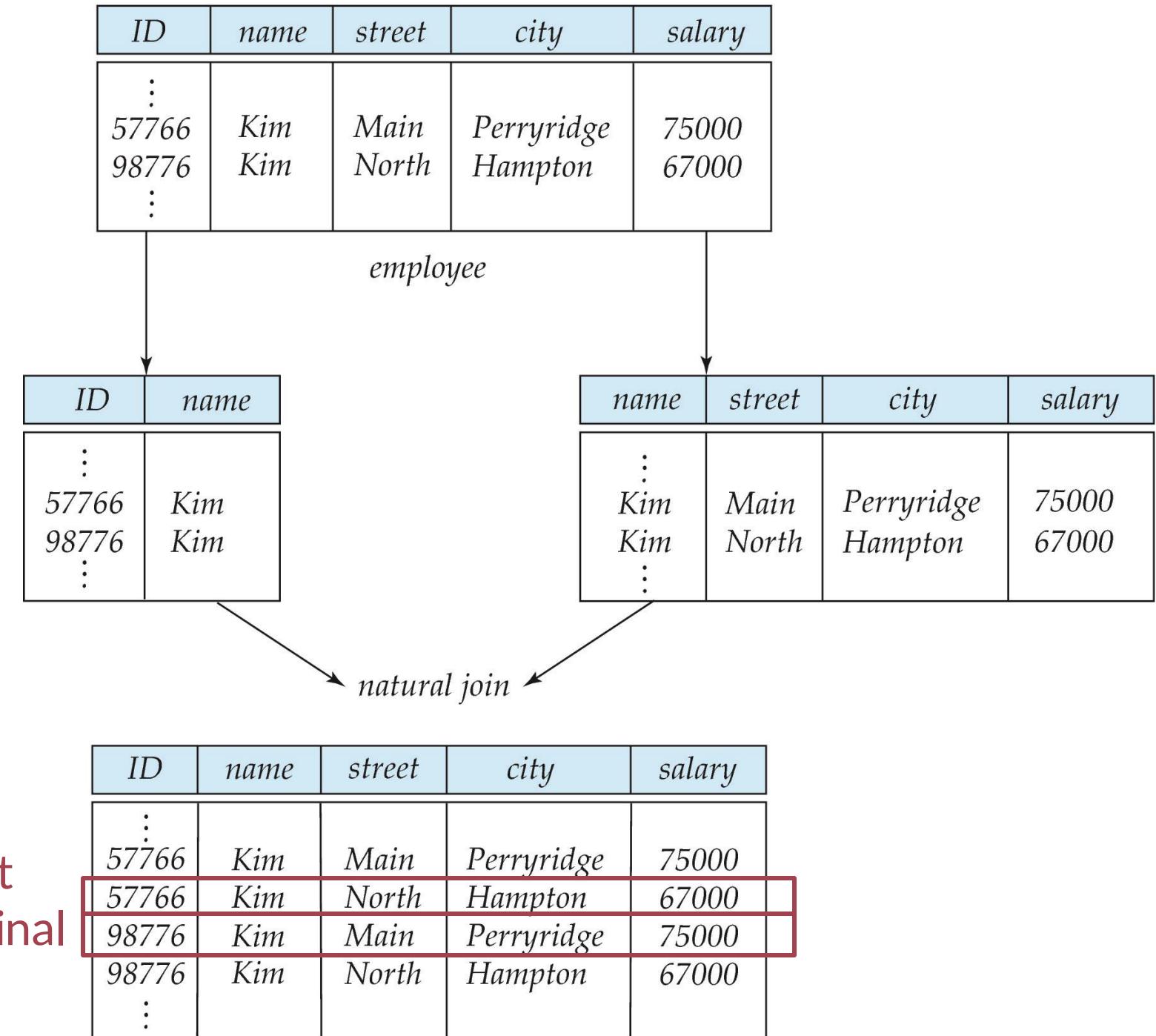
- Avoid the repetition-of-information problem
 - Decompose *in_dep* into two schemas: *instructor* and *department*
- However, not all decompositions are good
 - E.g., decompose *employee*(ID, name, street, city, salary) into:
 - *employee1*(ID, name)
 - *employee2*(name, street, city, salary)

The problem arises when we have two employees with the same name

A Lossy Decomposition

- (Continue) we cannot reconstruct the original employee relation with the join operation
 - Unable to represent certain important facts about the university employee
 - We call it a **lossy decomposition**

Two “ghost” records that do NOT exist in the original table



Lossless Decomposition

- Let R be a relation schema and let R_1 and R_2 form a decomposition of R
 - That is, $R = R_1 \cup R_2$
 - The decomposition is a **lossless decomposition** if there is no loss of information by replacing R with the two relation schemas $R = R_1 \cup R_2$
- Formally, $\Pi_{R_1}(r) \bowtie \Pi_{R_2}(r) = r$
 - ... and a decomposition is lossy if $r \subset \Pi_{R_1}(r) \bowtie \Pi_{R_2}(r)$

↑
(!) proper subset
- Or to say, the two SQL queries on the right side generate identical results:



```
select * -- 1
from (select R1 from r)
      natural join
        (select R2 from r);

select * from R; -- 2
```

Normalization Theory

- 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 $\{R_1, R_2, \dots, R_n\}$ such that
 - Each relation is in good form
 - The decomposition is a lossless decomposition
- Our theory is based on:
 - Functional dependencies
 - * Multivalued dependencies (self study)
- Generate a set of relation schemas that allows us to store information without unnecessary redundancy, yet also allows us to retrieve information easily

Functional Dependencies

- There are usually a variety of **constraints** (rules) on the data in the real world
- 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
 - E.g., an instructor can have multiple departments, a student can have double major
 - But we assume that they can only have one
 - **Each department** has only one value for its budget, and only one associated building

Functional Dependencies

- 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
- Functional dependencies allow us to express constraints that we cannot express with superkeys

Definition of Functional Dependencies

- Let R be a relation schema, and $\alpha \subseteq R$ 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 ,
 - On this instance, $A \rightarrow B$ does NOT hold, but $B \rightarrow A$ does hold

A	B
1	4
1	5
3	7

Why we need functional dependency?

- Extra constraints that can help us avoid redundancy
 - $A \rightarrow B$
 - Can decompose (ID, A, B) to (ID, A) and (A, B)
 - When decomposing, pay attention to lossless decomposition and dependency preservation

ID	A	B
1	a1	b1
2	a1	b1
3	a2	b2
4	a2	b2

- In reality, extra constraints could be
 - 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

Closure (闭包) 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 $A \rightarrow C$
- 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

Keys and Functional Dependencies

- Let's see how can we (re)define the concept of “**keys**” under the language of **functional dependencies**

Keys and Functional Dependencies

- K is a **superkey** for relation schema R if and only if $\underline{K \rightarrow R}$
- K is a **candidate key** for R if and only if
 - $K \rightarrow R$, and
 - for **no** $\alpha \subset K$, $\alpha \rightarrow R$



(!) proper subset, again

Keys and Functional Dependencies

- Functional dependencies allow us to express constraints that cannot be expressed using superkeys
- E.g. Consider the schema: *inst_dept(ID, name, salary, dept_name, building, budget)*
 - We expect these functional dependencies to hold:
 $\text{dept_name} \rightarrow \text{building}$, $ID \rightarrow \text{building}$

... but would not expect the following to hold:

$\text{dept_name} \rightarrow \text{salary}$

Remember the constraints we had earlier

- 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
 - E.g., an instructor can have multiple departments, a student can have double major
 - But we assume that they can only have one
 - **Each department** has only one value for its budget, and only one associated building

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
 - For each functional dependency $\alpha \rightarrow \beta$, for all pairs of tuples t_1 and t_2 in the instance, $t_1[\alpha] = t_2[\alpha] \Rightarrow t_1[\beta] = t_2[\beta]$
 - To specify constraints on the set of legal relations
 - If all legal relations on R satisfy the set of functional dependencies F , we say that F holds on R

Use of Functional Dependencies

- Example: List some functional dependencies that the table satisfies

A	B	C	D
a1	b1	c1	d1
a1	b2	c1	d2
a2	b2	c2	d2
a2	b3	c2	d3
a3	b3	c2	d4

Use of Functional Dependencies

- Example: List some functional dependencies that the table satisfies
 - $A \rightarrow C$ (but $C \rightarrow A$ is not satisfied)
 - $D \rightarrow B$

Can you find more?

A	B	C	D
a1	b1	c1	d1
a1	b2	c1	d2
a2	b2	c2	d2
a2	b3	c2	d3
a3	b3	c2	d4

Use of Functional Dependencies

- 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.
- Example: we see that $room_number \rightarrow capacity$ is satisfied.
 - However, in real world, two classrooms in different buildings can have the same room number but with different room capacity
 - We prefer $\{building, room_number\} \rightarrow capacity$

<i>building</i>	<i>room_number</i>	<i>capacity</i>
Packard	101	500
Painter	514	10
Taylor	3128	70
Watson	100	30
Watson	120	50

Trivial Functional Dependencies

- A functional dependency is **trivial** if it is satisfied by all relations
- Example:
 - $ID, name \rightarrow ID$
 - $name \rightarrow name$
- In general,
 - $\alpha \rightarrow \beta$ is trivial if $\beta \subseteq \alpha$
 - i.e., $t_1[\alpha] = t_2[\alpha] \Rightarrow t_1[\beta] = t_2[\beta]$ for any tuples t_1 and t_2

Lossless Decomposition

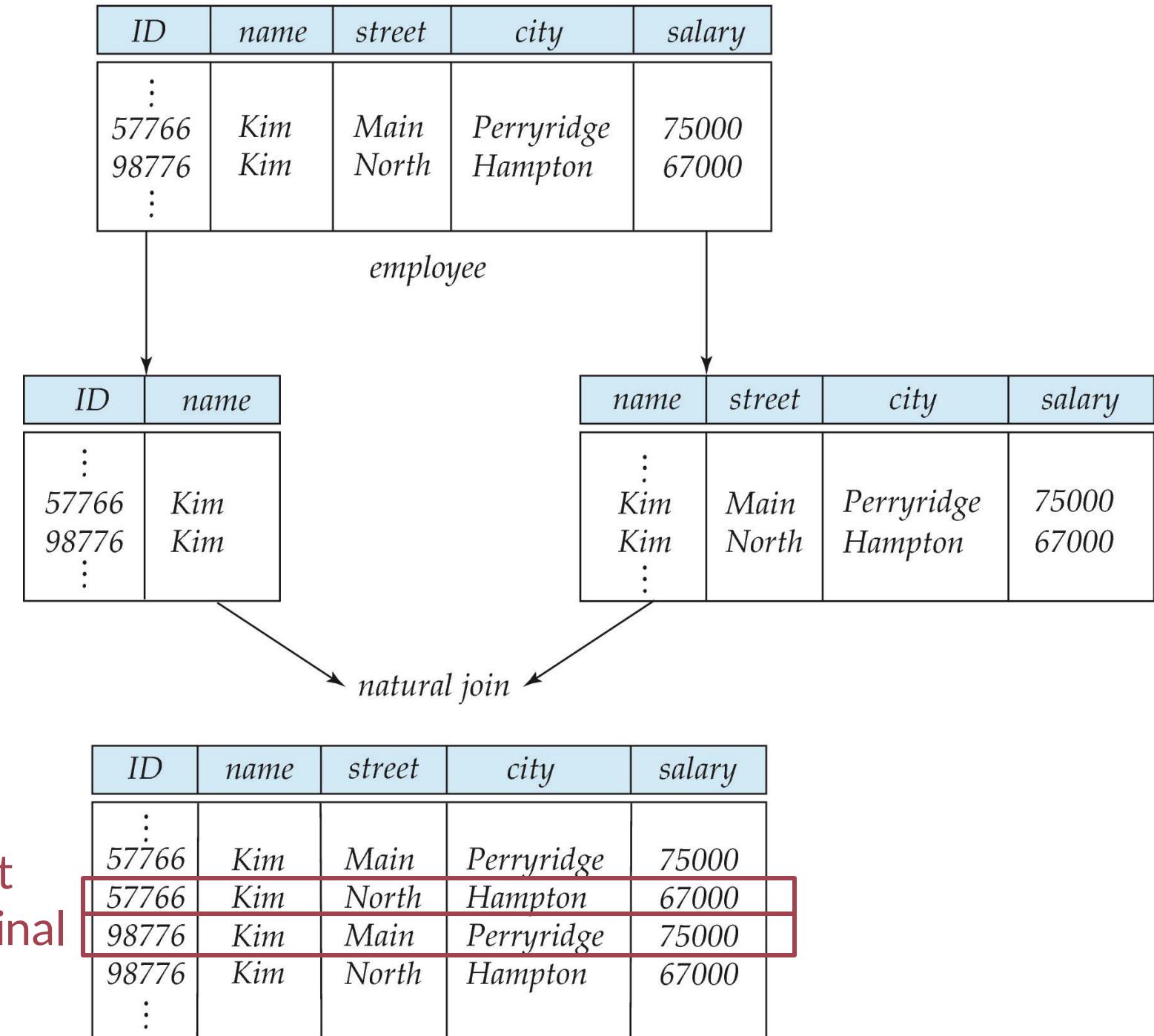
- We can use functional dependencies to show when certain decomposition are lossless
 - For the case of $R = (R_1, R_2)$, we require that for all possible relations r on schema R
$$r = \prod_{R1}(r) \bowtie \prod_{R2}(r)$$
 - A decomposition of R into R_1 and R_2 is a **lossless decomposition** if at least one of the following dependencies is in F^+ :
 - $R_1 \cap R_2 \rightarrow R_1$
 - $R_1 \cap R_2 \rightarrow R_2$

In other words, if $R_1 \cap R_2$ forms a **superkey** for either R_1 or R_2 , the decomposition of R is a lossless decomposition

A Lossy Decomposition

- (Continue) we cannot reconstruct the original employee relation with the join operation
 - Unable to represent certain important facts about the university employee
 - We call it a **lossy decomposition**

Two “ghost” records that do NOT exist in the original table



Lossless Decomposition

- Example:
 - $in_dep (ID, name, salary, \underline{dept_name}, building, budget)$
 - ... and the decomposed schemas, *instructor* and *department*:
 - $instructor(ID, name, dept_name, salary)$
 - $department(\underline{dept_name}, building, budget)$

$instructor \cap department = dept_name$
 $dept_name \rightarrow dept_name, building, budget$

(... which means the decomposition is lossless)

Lossless Decomposition

- Another example:

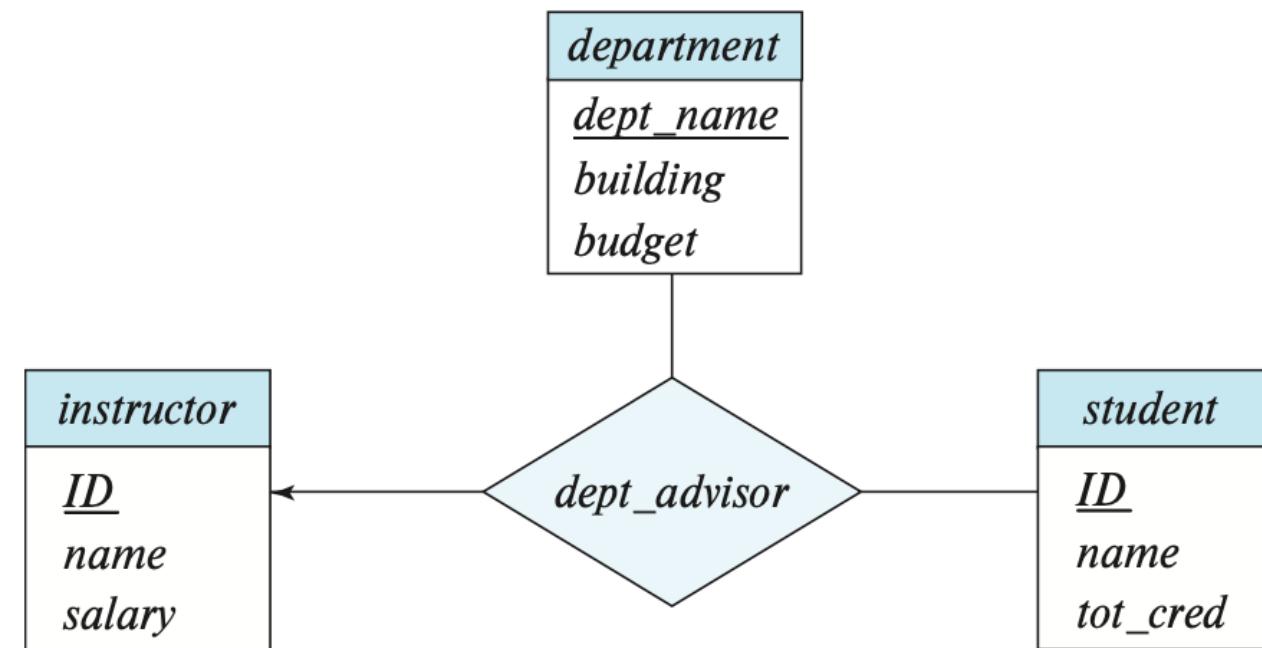
- $R = (A, B, C)$
 $F = \{A \rightarrow B, B \rightarrow C\}$
- $R_1 = (A, B), R_2 = (B, C)$
 - Lossless decomposition:
 $R_1 \cap R_2 = \{B\}$ and $B \rightarrow BC$
- $R_1 = (A, B), R_2 = (A, C)$
 - Lossless decomposition:
 $R_1 \cap R_2 = \{A\}$ and $A \rightarrow AB$
- Note:
 - $B \rightarrow BC$
is a shorthand notation for
 - $B \rightarrow \{B, C\}$

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
 - After decomposition, some functional dependency may involve multiple relation schemas and cannot be tested efficiently (as join is required)
 - After decomposing (A,B,C) to (A, B) and (B, C)
 - If we only have functional dependencies $A \rightarrow B$ and $B \rightarrow C$ (before decomposition), then the dependencies can be checked easily
 - If we also have function dependency $A \rightarrow BC$ (before decomposition), then checking it requires join
- If a functional dependency in the original relation R does not exist in any of the decomposed relations, we say it is not **dependency-preserving**
 - In the dependency preservation, every dependency must be satisfied in at least one decomposed table

Dependency Preservation

- Consider a new E-R design for relationships between students, instructors, and departments
 - An instructor can only be associated with one department
 - A student can have multiple advisors but not more than one from a given department
 - Think about double-major students



Dependency Preservation

- *instructor*, *department*, and *student* schemas unchanged
- Consider a schema
 - *dept_advisor(s_ID, i_ID, dept_name)*
 - ... with function dependencies: (1) $i_ID \rightarrow dept_name$ (2) $s_ID, dept_name \rightarrow i_ID$
 - (1) follows “an instructor can act as an advisor for only one department”
 - (2) follows “a student may have at most one advisor for a given department”

Dependency Preservation

- *instructor*, *department*, and *student* schemas unchanged
- Consider a schema
 - *dept_advisor(s_ID, i_ID, dept_name)*
 - ... with function dependencies: (1) $i_ID \rightarrow dept_name$ (2) $s_ID, dept_name \rightarrow i_ID$
 - (1) follows “an instructor can act as an advisor for only one department”
 - (2) follows “a student may have at most one advisor for a given department”

In this design, we are forced to repeat the department name once for each time an instructor participates in a *dept_advisor* relationship.

<i>s_ID</i>	<i>i_ID</i>	<i>dept_name</i>
1	1	CS
1	2	ECE
2	1	CS
2	2	ECE

Dependency Preservation

- *instructor*, *department*, and *student* schemas unchanged
- Consider a schema
 - *dept_advisor(s_ID, i_ID, dept_name)*
 - ... with function dependencies: (1) $i_ID \rightarrow dept_name$ (2) $s_ID, dept_name \rightarrow i_ID$
 - (1) follows “an instructor can act as an advisor for only one department”
 - (2) follows “a student may have at most one advisor for a given department”

In this design, we are forced to repeat the department name once for each time an instructor participates in a *dept_advisor* relationship.

- To fix this problem, we need to decompose *dept_advisor*
 - However, any decomposition will not include all the attributes in
$$s_ID, dept_name \rightarrow i_ID$$
 - Thus, the decomposition will **NOT** be dependency-preserving
 - Redundancy reduction and dependency preservation cannot be achieved at the same time

Dependency Preservation

- Problem when not meeting dependency preservation
 - Every time the database wants to check the integrity of the functional dependency $s_ID, dept_name \rightarrow i_ID$,
the decomposed tables must be joined
 - ... where the computational cost could be very high with join operations

BCNF and 3NF

Normal Forms: Revisited

- Boyce-Codd Normal Form (BCNF)
- 3NF
- Higher-order normal forms

Normalization

- In practice, we usually just satisfy 1NF, 2NF and 3NF

	UNF (1970)	1NF (1970)	2NF (1971)	3NF (1971)	EKNF (1982)	BCNF (1974)	4NF (1977)	ETNF (2012)	5NF (1979)	DKNF (1981)	6NF (2003)
Primary key (no duplicate tuples) ^[4]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Atomic columns (cells cannot have tables as values) ^[5]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either does not begin with a proper subset of a candidate key or ends with a prime attribute (no partial functional dependencies of non-prime attributes on candidate keys) ^[5]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either begins with a superkey or ends with a prime attribute (no transitive functional dependencies of non-prime attributes on candidate keys) ^[5]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
Every non-trivial functional dependency either begins with a superkey or ends with an elementary prime attribute	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	N/A
Every non-trivial functional dependency begins with a superkey	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	N/A
Every non-trivial multivalued dependency begins with a superkey	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	N/A
Every join dependency has a superkey component ^[8]	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	N/A
Every join dependency has only superkey components	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	N/A
Every constraint is a consequence of domain constraints and key constraints	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
Every join dependency is trivial	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓

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

$$\alpha \rightarrow \beta$$

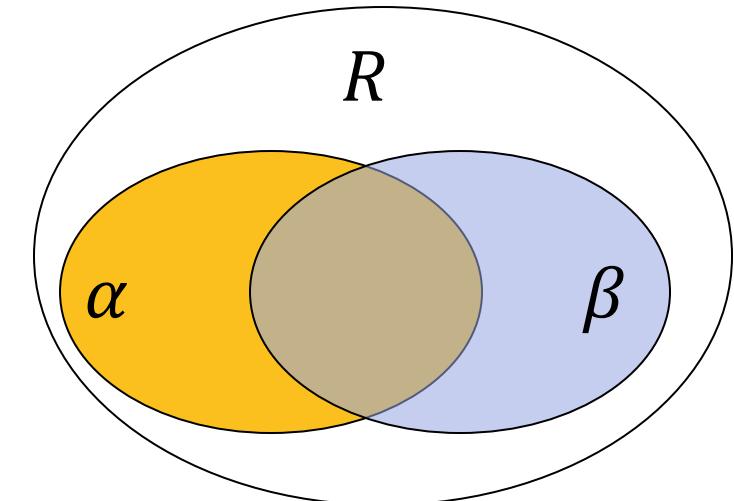
where $\alpha \subseteq R$ and $\beta \subseteq R$, at least one of the following holds:

- $\alpha \rightarrow \beta$ is **trivial** (i.e., $\beta \subseteq \alpha$)
 - α is a **superkey** for R
-
- * A database design is in BCNF if each member of the set of relation schemas that constitutes the design is in BCNF

Boyce-Codd Normal Form

- Example schema that is **not** in BCNF:
 - $in_dep (ID, name, salary, \underline{dept_name}, building, budget)$
Because,
 $\underline{dept_name} \rightarrow building, budget$
 - holds in in_dep , however, dept_name is not a **superkey**
 - ... where $\{ID, dept_name\}$ is
 - When decompose in_dept into *instructor* and *department*
 - *instructor* is in BCNF
 - $instructor (ID, name, \underline{dept_name}, salary)$
 - No functional dependencies without having ID on the left, except trivial ones
 - *department* is in BCNF
 - $department (\underline{dept_name}, building, budget)$

Decomposing a Schema into BCNF



- Let R be a schema R that is not in BCNF
- Let $\alpha \rightarrow \beta$ be the functional dependency that causes a violation of BCNF
 - We decompose R into:
 - $(\alpha \cup \beta)$
 - $(R - (\beta - \alpha))$
 - Keep decomposing until all relation schemas are in BCNF
 - Notice that $(\alpha \cup \beta) \cap (R - (\beta - \alpha)) = \alpha$, and $\alpha \rightarrow \beta$, so lossless decomposition
- Example: *in_dep* (ID, name, salary, dept_name, building, budget)
 - $\alpha = \text{dept_name}$, $\beta = \text{building}, \text{budget}$
 - Thus, *in_dep* is replaced by:
 - $(\alpha \cup \beta) = (\text{dept_name}, \text{building}, \text{budget})$
 - $(R - (\beta - \alpha)) = (\text{ID}, \text{name}, \text{dept_name}, \text{salary})$

Decomposing a Schema into BCNF

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

BCNF and Dependency Preservation

- It is not always possible to **achieve** both BCNF and dependency preservation
- Consider the schema (that we have visited before)
 - *dept_advisor(s_ID, i_ID, dept_name)*
 - with function dependencies: (1) $i_ID \rightarrow dept_name$ (2) $s_ID, dept_name \rightarrow i_ID$
 - (1) follows “an instructor can act as an advisor for only one department”
 - (2) follows “a student may have at most one advisor for a given department”
 - Superkeys $\{s_ID, i_ID\}, \{s_ID, dept_name\}$
 - *dept_advisor* is not in BCNF since for $i_ID \rightarrow dept_name$, i_ID is not a superkey
 - Although (2) satisfies the conditions of BCNF

BCNF and Dependency Preservation

- It is not always possible to **achieve** both BCNF and dependency preservation
- Consider the schema (that we have visited before)
 - *dept_advisor(s_ID, i_ID, dept_name)*
 - with function dependencies: (1) $i_ID \rightarrow dept_name$ (2) $s_ID, dept_name \rightarrow i_ID$
 - Superkeys $\{s_ID, i_ID\}, \{s_ID, dept_name\}$
 - *dept_advisor* is not in BCNF since for $i_ID \rightarrow dept_name$, i_ID is not a superkey
- To fix this problem, we need to decompose *dept_advisor* into
 - (s_ID, i_ID) and $(i_ID, dept_name)$, both in BCNF
 - However, the decomposition will not include all the attributes in (2)
 - Thus, the decomposition will **NOT** be **dependency-preserving**
 - Can check (1) without any join
 - But checking (2) requires computing the join of the decomposed relations

Third Normal Form (3NF)

- Relax the constraints of BCNF to ensure dependency preservation
- A relation schema R is in **third normal form (3NF)** if for all

$$\alpha \rightarrow \beta \text{ in } F^+$$

at least one of the following holds:

- $\alpha \rightarrow \beta$ is trivial (i.e., $\beta \subseteq \alpha$)
 - α is a superkey for R
 - Each attribute A in $\beta - \alpha$ is contained in a candidate key for R
- Notes
 - Each attribute A 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)
 - The third condition above is a minimal relaxation of BCNF to ensure dependency preservation
 - It can ensure that every schema has a dependency-preserving decomposition into 3NF
 - Seems unintuitive. It will become more clear later when we talk about decomposition to 3NF

3NF Example

- Consider the schema (that we have visited before)
 - $\text{dept_advisor}(s_ID, i_ID, \text{dept_name})$
 - ... with function dependencies: (1) $i_ID \rightarrow \text{dept_name}$ (2) $s_ID, \text{dept_name} \rightarrow i_ID$
 - We have two candidate keys: $\{s_ID, \text{dept_name}\}$ and $\{s_ID, i_ID\}$
- dept_advisor is not in BCNF, but it can be in 3NF
 - $\{s_ID, \text{dept_name}\}$ is a superkey
 - $i_ID \rightarrow \text{dept_name}$ and i_ID is NOT a superkey (which violates BCNF), but:
 - α is i_ID , β is dept_name
 - $\{\text{dept_name}\} - \{i_ID\} = \{\text{dept_name}\}$
 - dept_name is contained in a candidate key ($\rightarrow \{s_ID, \text{dept_name}\}$)

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:
- Problems in this table:
 - Repetition of information
 - Row 1-3: L and K
 - Need to use nulls
 - Row 4: Represent the relationship l_2, k_2 with no corresponding value for J

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

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 **nulls** to represent some of the possible meaningful relationships among data items
 - There is a problem of potential repetition of information

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