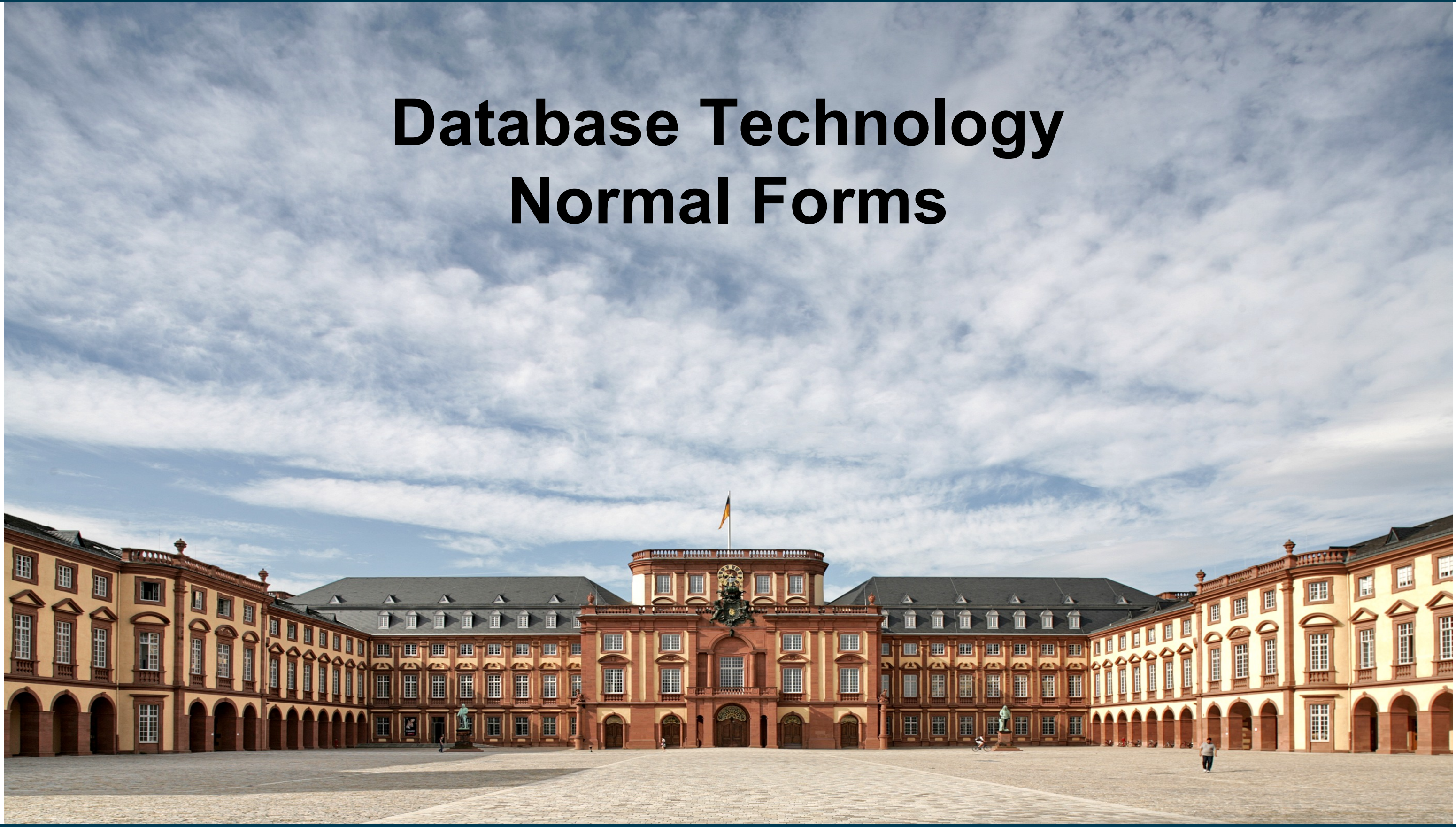
UNIVERSITÄT MANNHEIM

# Database Technology
# Normal Forms



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# Previously on Database Technology

- Designing databases with ER diagrams
  - Modeling a domain as a collection of *entities* and *relationships*
  - Entity: a “thing” or “object” in the domain
    - Described by a set of *attributes*
  - Relationship: an association among several entities
  - Represented diagrammatically by an *entity-relationship diagram*

# Today

- More about database design
  - Features of *good* Relational design
  - Atomic domains and first normal form
  - Decomposition using functional dependencies
    - 2nd, 3rd normal form, and Boyce Codd normal form
  - Decomposition using multi-valued dependencies
    - 4th normal form
  - Even more normal forms

# The Normalization Process

To the foregoing I should perhaps add the following. As far as I know, Codd himself never mentioned, in his early writings on the subject, his reasons for introducing the terminology of normal forms or normalization. But many years afterward, he did go on record with his own explanation:[33]

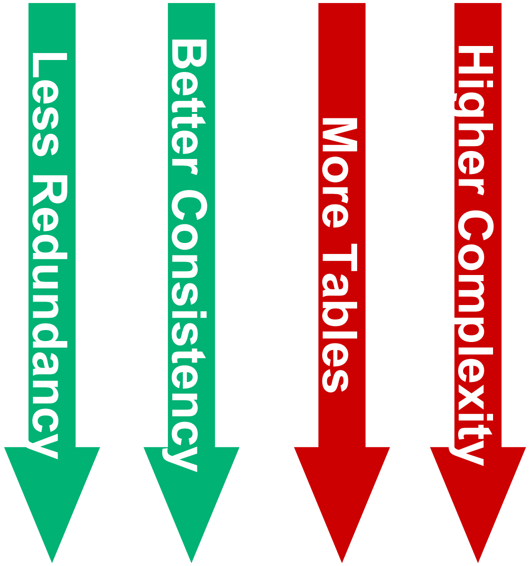
> ***Interviewer:*** *Where did "normalization" come from?*
> **Codd:** It seemed to me essential that some discipline be introduced into database design. I called it normalization because then President Nixon was talking a lot about normalizing relations with China. I figured that if he could normalize relations, so could I.

# The Normalization Process

- Iteratively improve the database design
  - Rule out non-atomic values
  - Eliminate redundancies
- Iterations
  - Move database design from one normal form to the next
- In each iteration
  - The design is changed (usually: smaller, but more relations)
  - Some typical problems are eliminated

# The Normalization Process

- Levels of normalization based on the amount of redundancy in the database
- Various levels of normalization are:
  - First Normal Form (1NF)
  - Second Normal Form (2NF)
  - **Third Normal Form (3NF)**
  - **Boyce-Codd Normal Form (BCNF)**
  - Fourth Normal Form (4NF)
  - Fifth Normal Form (5NF)
  - Domain Key Normal Form (DKNF)



# Atomicity

- Consider the following relation

| ID | Name | Instructor | Programs |
|---|---|---|---|
| CS-101 | Introduction to Computer Science | Melanie Smith | CS, DS, Math, CE |
| CS-205 | Introduction to Databases | Mark Johnsson | DS, Soc |
| CS-374 | Data Mining | Mark Johnsson | CS, DS, Soc |
| MA-403 | Linear Algebra | Mary Williams | Math, CS |
| ... | ... | ... | ... |

- Task:
  - Find all courses in the DS program

# Atomicity

- Find all courses in the DS program
  - Requires processing all the strings of the *Programs* attribute
  - String processing is expensive

- Notion of *atomicity*:
  - Attribute is *atomic* (also: *scalar*) if its values are considered to be indivisible units
  - Examples of non-atomic attributes
    - Set-valued attributes (like *Programs*)
    - Composite attributes (like *Instructor*)
    - Identification numbers like CS-101 that can be broken up into (meaningful) parts

# Atomicity

- In the database, all values, also strings, are considered indivisible
- SQL queries will only return strings
  - e.g., “CS-101” or “CS, DS, Math, CE”

- If we further analyze them
  - Extract department “CS” from “CS-101”
  - Find program “DS” in “CS, DS, Math, CE”
- ...we move the semantics from the database to the application logic!

# First Normal Form

- Definition: A relational schema R is in **first normal form** if the domains of all attributes of R are atomic
- Rationale: Non-atomic values
  - complicate storage and encourage redundant storage of data
  - complicate processing of complex attributes
  - move data semantics to processing code
- From here on, we assume all relations are in first normal form

# First Normal Form – Decomposition

- Replace composite attributes by single attributes
- Replace multi-valued attributes by a new relati
  - before: R= (<u>ID</u>, …, mva)
  - after: R = (<u>ID</u>, …), $R_{mva}$ = (<u>ID</u>,mva)

| ID_dept | ID_no | Name | |
|---|---|---|---|
| CS | 101 | Introduction to Computer Science | Mela |
| CS | 205 | Introduction to Databases | Mark |
| CS | 374 | Data Mining | Mark |
| MA | 403 | Linear Algebra | Mary |
| ... | | ... | ... |

multi-attribute key

| ID_dept | ID_no | Program |
|---|---|---|
| CS | 101 | CS |
| CS | 101 | DS |
| | 101 | Math |
| | 101 | CE |
| CS | 205 | DS |
| CS | 205 | Soc |
| CS | 374 | CS |
| CS | 374 | DS |
| CS | 374 | Soc |
| MA | 403 | Math |
| MA | 403 | CS |
| ... | ... | ... |

# Functional Dependencies

- Functional dependencies
  - are a means to identify potential redundancies
  - also: a means to identify primary keys
- Definition:
  - If one set of attributes A determines another set of attributes B
  - Then B is functionally dependent on A
- Less formal:
  - If we know A, we also know B

# Functional Dependencies

- Consider the example below
- The course ID (two parts) determine
  - The course name
  - The instructor
- Functional dependency:
  - {ID_dept, ID_no} → {Name, Instructor_first, Instructor_last}

| ID_dept | ID_no | Name | Instructor_first | Instructor_last |
|---|---|---|---|---|
| CS | 101 | Introduction to Computer Science | Melanie | Smith |
| CS | 205 | Introduction to Databases | Mark | Johnsson |
| CS | 374 | Data Mining | Mark | Johnsson |
| MA | 403 | Linear Algebra | Mary | Williams |
| ... | | ... | ... | ... |

# Functional Dependencies

- Note:
  – Functional dependencies are not only determined from the data
  – But the domain knowledge

- Example: by chance, each instructor teaches only one course
  – {Instructor_first, Instructor_last} → {ID_dept, ID_no, Name}

| ID_dept | ID_no | Name | Instructor_first | Instructor_last |
|---|---|---|---|---|
| CS | 101 | Introduction to Computer Science | Melanie | Smith |
| CS | 205 | Introduction to Databases | Mark | Johnsson |
| CS | 374 | Data Mining | John | Stevens |
| MA | 403 | Linear Algebra | Mary | Williams |
| ... | | ... | ... | ... |

# True vs. False Functional Dependencies

- Functional dependencies in the data may be true or false
  - Given domain knowledge
- E.g., looking at the table below containing exactly those four entries
- What do you think about
  - {ID_no} → {First name, Last name, Birthday, Social Sec. No.}
  - {First name, Last name} → {ID_no, Birthday, Social Sec. No.}
  - {Birthday} → {ID_no, First name, Last name, Social Sec. No.}

| ID_no | First name | Last name | Birthday | Social Sec. No. |
|---|---|---|---|---|
| 101 | Melanie | Smith | 1991-12-05 | 457384723 |
| 102 | Mark | Johnsson | 1993-07-18 | 342789347 |
| 103 | Mark | Stevens | 1992-01-05 | 091238302 |
| 104 | Mary | Smith | 1991-12-04 | 123749123 |

# Towards the Second Normal Form

- Assume we have the following relation
  - The department is represented by *ID_dept* as part of the course ID
  - ...and in fully written form in the *Department* attribute
- Suppose we insert the tuple

  (CS, 102, Mathematics, Programming)

  → We can create an inconsistency!

| ID_dept | ID_no | Department | Name |
|---|---|---|---|
| CS | 101 | Computer Science | Introduction to Computer Science |
| CS | 205 | Computer Science | Introduction to Databases |
| CS | 374 | Computer Science | Data Mining |
| MA | 403 | Mathematics | Linear Algebra |
| ... | | | ... |

# Second Normal Form

- A relation is in second normal form if
  - It is in first normal form, and
  - All *nonkey* attributes are functionally dependent on the *entire* primary key
- Relation: (ID_dept, ID_no, Departmen

Violation: Department only depends on part of the primary key!

- Functional dependencies:
  - {ID_dept} → {Department}, {ID_dept, ID_no} → {Name}

| ID_dept | ID_no | Department | Name |
|---|---|---|---|
| CS | 101 | Computer Science | Introduction to Computer Science |
| CS | 205 | Computer Science | Introduction to Databases |
| CS | 374 | Computer Science | Data Mining |
| MA | 403 | Mathematics | Linear Algebra |
| ... | | | ... |

# Decomposition to Second Normal Form

- Determine the primary key PK of a relation R
- Write down all functional dependencies for the relation
- For each FD $A \rightarrow B$, where $A \subset PK$
  - Create a new Relation RB (A,B)
  - Remove B from R

Each department name now only appears once

| ID_dept | ID_no | Name |
|---|---|---|
| CS | 101 | Introduction to Computer Science |
| CS | 205 | Introduction to Databases |
| CS | 374 | Data Mining |
| MA | 403 | Linear Algebra |
| ... | | ... |

| ID_dept | Department |
|---|---|
| CS | Computer Science |
| MA | Mathematics |
| ... | |

# Decomposition to Second Normal Form

- Original problem: we could create an inconsistency by inserting

  (CS, 102, Mathematics, Programming)

- This is no longer possible: we cannot insert

  (CS, Mathematics)

  into

  (ID_dept, Department)

why?

| ID_dept | ID_no | Name |
|---|---|---|
| CS | 101 | Introduction to Computer Science |
| CS | 205 | Introduction to Databases |
| CS | 374 | Data Mining |
| MA | 403 | Linear Algebra |
| ... | | ... |

| ID_dept | Department |
|---|---|
| CS | Computer Science |
| MA | Mathematics |
| ... | |

# Lossless Join Decomposition

- Each decomposition should be lossless join
  - i.e., a natural join should reconstruct the original table
  - Consider the (wrong) example below
    - ID_dept is omitted from the first relation
  - Natural join creates cross product of both relations!

| ID_no | Name |
|---|---|
| 101 | Introduction to Computer Science |
| 205 | Introduction to Databases |
| 374 | Data Mining |
| 403 | Linear Algebra |
| | ... |

| ID_dept | Department |
|---|---|
| CS | Computer Science |
| MA | Mathematics |
| ... | |

# Further Dependencies in Relations

- Assume we had another attribute in our relation
  - i.e., the personnel ID of the instructor
- Suppose we inserted
  - (CS, 379, Web Mining, 143970, Steven, Smith)
- Is that consistent?

| ID_dept | ID_no | Name | Instr_ID | Instr_first | Instr_last |
|---|---|---|---|---|---|
| CS | 101 | Introduction to Computer Science | 143273 | Melanie | Smith |
| CS | 205 | Introduction to Databases | 143970 | Mark | Johnsson |
| CS | 374 | Data Mining | 143970 | Mark | Johnsson |
| MA | 403 | Linear Algebra | 141784 | Mary | Williams |
| ... | | ... | | ... | ... |

# Further Dependencies in Relations

- Observation 1: this relation is in 2NF
  - It is is 1NF
  - {ID_dept, ID_no} → {Name, Instr_Id, Instr_first, Instr_last} holds
  - There is no non-key attribute a for which {ID_dept} → {a} or {ID_no} → {a} holds
- Still, inconsistent inserts are possible

| ID_dept | ID_no | Name | Instr_ID | Instr_first | Instr_last |
|---|---|---|---|---|---|
| CS | 101 | Introduction to Computer Science | 143273 | Melanie | Smith |
| CS | 205 | Introduction to Databases | 143970 | Mark | Johnsson |
| CS | 374 | Data Mining | 143970 | Mark | Johnsson |
| MA | 403 | Linear Algebra | 141784 | Mary | Williams |
| ... | | ... | | ... | ... |

# Third Normal Form

- Observation 2: there is a second functional dependency
  - {Instr_ID} → {Instr_first, Instr_last}
- Definition: Third Normal Form
  - Relation is in Second Normal Form, and
  - No attribute is *transitively dependent* on the primary key

| ID_dept | ID_no | Name | Instr_ID | Instr_first | Instr_last |
|---|---|---|---|---|---|
| CS | 101 | Introduction to Computer Science | 143273 | Melanie | Smith |
| CS | 205 | Introduction to Databases | 143970 | Mark | Johnsson |
| CS | 374 | Data Mining | 143970 | Mark | Johnsson |
| MA | 403 | Linear Algebra | 141784 | Mary | Williams |
| ... | | ... | | ... | ... |

# Transitivity of Functional Dependencies

- We observe that
  - {ID_dept, ID_no} → {Instr_ID}
  - {Instr_ID} → {Instr_first, Instr_last}
- Hence, there is a *transitive* dependency of {Instr_first, Instr_last} on the primary key
- Functional dependencies are transitive by nature

| ID_dept | ID_no | Name | Instr_ID | Instr_first | Instr_last |
|---|---|---|---|---|---|
| CS | 101 | Introduction to Computer Science | 143273 | Melanie | Smith |
| CS | 205 | Introduction to Databases | 143970 | Mark | Johnsson |
| CS | 374 | Data Mining | 143970 | Mark | Johnsson |
| MA | 403 | Linear Algebra | 141784 | Mary | Williams |
| ... | | ... | | ... | ... |

# Third Normal Form: Decomposition

- Identify transitive dependency in R
  - PK $\rightarrow$ A and A $\rightarrow$ B
- Create new relation $R_A(\underline{A}, B)$
- Remove from B from R

| ID_dept | ID_no | Name | I |
|---|---|---|---|
| CS | 101 | Introduction to Computer Science | 1 |
| CS | 205 | Introduction to Databases | 1 |
| CS | 374 | Data Mining | 1 |
| MA | 403 | Linear Algebra | 141784 |
| ... | | ... | |

| Instr_ID | Instr_first | Instr_last |
|---|---|---|
| 143273 | Melanie | Smith |
| 143970 | Mark | Johnsson |
| 141784 | Mary | Williams |
| | ... | ... |

# Third Normal Form: Decomposition

- Result: the new relations are now in 3NF
- There is no transitive dependency in R
  - {Name} → {Instr_ID} and {Instr_ID} → {Name} do not hold
- There is no transitive dependency in the new relation
  - {Instr_first} → {Instr_last} and {Instr_last} → {Instr_first} do not hold

| Instr_ID | Instr_first | Instr_last |
|---|---|---|
| 143273 | Melanie | Smith |
| 143970 | Mark | Johnsson |
| 141784 | Mary | Williams |
| | ... | ... |

| ID_dept | ID_no | Name | I[illegible] |
|---|---|---|---|
| CS | 101 | Introduction to Computer Science | 1[illegible] |
| CS | 205 | Introduction to Databases | 1[illegible] |
| CS | 374 | Data Mining | 1[illegible] |
| MA | 403 | Linear Algebra | 141784 |
| ... | | ... | |

# Third Normal Form: Decomposition

- Initial problem: inconsistent insert

  (CS, 379, Web Mining, 143970, Steven, Smith)

- Now, inserting

  (143970, Steven, Smith)

  into the new relation is no longer possible!

| ID_dept | ID_no | Name | I |
|---|---|---|---|
| CS | 101 | Introduction to Computer Science | 1 |
| CS | 205 | Introduction to Databases | 1 |
| CS | 374 | Data Mining | 1 |
| MA | 403 | Linear Algebra | 141784 |
| ... | | ... | |

| Instr_ID | Instr_first | Instr_last |
|---|---|---|
| 143273 | Melanie | Smith |
| 143970 | Mark | Johnsson |
| 141784 | Mary | Williams |
| | ... | ... |

# Dependencies between Candidate Keys

- Superkeys and candidate keys:
  - 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
    - there is no $K' \subset K$ with $K' \rightarrow R$

- There may be more than one candidate key
  - Example: student_assistant(matriculation_no, social_sec_no, name, ...)
  - Each one may be equally well picked as a primary key

# Multiple Candidate Keys in 3NF

- Given this example

  student_assistant(matriculation_no, social_sec_no, name, …)

- For 3NF, we would decompose this relation
  - If we pick matriculation_no as primary key, then

    {matriculation_no} → {social_sec_no} → {name}

  - If we pick social_sec_no as primary key, then

    {social_sec_no} → {matriculation_no} → {name}

  - i.e., in any case, there is a transitive functional dependency!

# Dependencies between Candidate Keys

- Assume the following scenario
  - Departments have (one or more) secretaries
  - Secretaries work for (one or more) departments
  - Each secretary may have one phone number per department s/he works for, or just one phone number for all
  - Secretaries’ basic data (name etc.) have already been decomposed

| Institute | Secr_ID | Phone |
|---|---|---|
| CS | 0001 | 5073 |
| CS | 0002 | 5074 |
| Soc | 0001 | 6010 |
| Soc | 0003 | 6011 |
| Eng | 0003 | 6011 |
| ... | ... | ... |

# Dependencies between Candidate Keys

- Neither Institute, Secr_ID, nor Phone are a superkey
- This relation has two candidate keys
  - {Institute, Secr_ID}
  - {Institute, Phone}

| Institute | Secr_ID | Phone |
|---|---|---|
| CS | 0001 | 5073 |
| CS | 0002 | 5074 |
| Soc | 0001 | 6010 |
| Soc | 0003 | 6011 |
| Eng | 0003 | 6011 |
| ... | ... | ... |

# Dependencies between Candidate Keys

- With each candidate key as a primary key, the relation is in 3NF
- {Institute, Secr_ID}:
  - {Institute, Secr_ID} - > {Phone}
  - Neither {Institute} → {Phone} nor {Secr_ID} → {Phone} holds
  - No transitive dependency

same for
{Institute, Phone}

| Institute | Secr_ID | Phone |
|---|---|---|
| CS | 0001 | 5073 |
| CS | 0002 | 5074 |
| Soc | 0001 | 6010 |
| Soc | 0003 | 6011 |
| Eng | 0003 | 6011 |
| ... | ... | ... |

# Dependencies between Candidate Keys

- However, inconsistent inserts are still possible:

  (CS, 0001, 5075)

  if {Institute, Phone} is chosen as the primary key, or

  (Soc, 0002, 6011)

  if {Institute, Secr_ID} is chosen as the primary key

Two phone numbers for the same secretary and department

Same phone number for two secretaries

| Institute | Secr_ID | Phone |
|---|---|---|
| CS | 0001 | 5073 |
| CS | 0002 | 5074 |
| Soc | 0001 | 6010 |
| Soc | 0003 | 6011 |
| Eng | 0003 | 6011 |
| ... | ... | ... |

# Dependencies between Candidate Keys

- Observation: we have different functional dependencies here
  - {Institute, Secr_ID} → {Phone}
  - {Institute, Phone} → {Secr_ID}
- None of them violate the 3NF
- These are dependencies between different candidate keys

| Institute | Secr_ID | Phone |
|---|---|---|
| CS | 0001 | 5073 |
| CS | 0002 | 5074 |
| Soc | 0001 | 6010 |
| Soc | 0003 | 6011 |
| Eng | 0003 | 6011 |
| ... | ... | ... |

# Boyce-Codd Normal Form

- Definition: A relation is in Boyce-Codd Normal Form if
  - It is in 3NF
  - There is no functional dependency between attributes that belong to different candidate keys
  - i.e., if CK $\rightarrow$ {a}, then a must not be part of a candidate key
- BCNF is equivalent to 3NF unless
  - A relation has two or more candidate keys
  - At least two of the candidate keys are composed of more than one attribute
  - The candidate keys are not disjoint, i.e., the composite candidate keys share some attributes

# Decomposition to BCNF

- Create a single relation for each composite candidate key
- Place the remaining attributes (if any) in one of the relations
  – Based on their dependency

| Institute | Secr_ID |
|---|---|
| CS | 0001 |
| CS | 0002 |
| Soc | 0001 |
| Soc | 0003 |
| Eng | 0003 |
| ... | ... |

| Institute | Phone |
|---|---|
| CS | 5073 |
| CS | 5074 |
| Soc | 6010 |
| Soc | 6011 |
| Eng | 6011 |
| ... | ... |

# Decomposition to BCNF

- Problem with inconsistent inserts:

  (CS, 0001, 5075)
  (Soc, 0002, 6011)

- This is no longer possible
  - First violates primary key in R1
  - Second violates primary key in R2

| Institute | Secr_ID |
|---|---|
| CS | 0001 |
| CS | 0002 |
| Soc | 0001 |
| Soc | 0003 |
| Eng | 0003 |
| ... | ... |

| Institute | Phone |
|---|---|
| CS | 5073 |
| CS | 5074 |
| Soc | 6010 |
| Soc | 6011 |
| Eng | 6011 |
| ... | ... |

# BCNF and Dependency Preservation

- We have lost some dependency during this decomposition
- We could try to reintroduce it
  - e.g., add a third relation (Secr_ID, Phone)
  - but this would lead to new sources of inconsistencies

| Institute | Secr_ID |
|---|---|
| CS | 0001 |
| CS | 0002 |
| Soc | 0001 |
| Soc | 0003 |
| Eng | 0003 |
| ... | ... |

| Institute | Phone |
|---|---|
| CS | 5073 |
| CS | 5074 |
| Soc | 6010 |
| Soc | 6011 |
| Eng | 6011 |
| ... | ... |

Which phone no. belongs to which secretary?

# Decomposition to BCNF

- There are still inconsistencies that BCNF does not capture
  - e.g., inserting (Soc, 0002, 5074)
- This would be captured by the third relation
  - i.e., Secr_ID, Phone
  - but at the price of additional redundancies

Same phone number
for two secretaries
in *different* departments

| Institute | Secr_ID |
|---|---|
| CS | 0001 |
| CS | 0002 |
| Soc | 0001 |
| Soc | 0003 |
| Eng | 0003 |
| ... | ... |

| Institute | Phone |
|---|---|
| CS | 5073 |
| CS | 5074 |
| Soc | 6010 |
| Soc | 6011 |
| Eng | 6011 |
| ... | ... |

| Secr_ID | Phone |
|---|---|
| 0001 | 5073 |
| 0002 | 5074 |
| 0001 | 6010 |
| 0003 | 6011 |
| ... | ... |

# Boyce-Codd NF vs. 3NF

- If decomposition does not cause any loss of information it is called a *lossless decomposition*
- If a decomposition does not cause any dependencies to be lost it is called a *dependency-preserving decomposition*
- Any relation can be decomposed in a lossless way into a collection of smaller relations that are in BCNF form
  - However, *dependency preservation* is not guaranteed
- Any table can be decomposed in a lossless way into 3NF that also preserves the dependencies
  - 3NF may be better than BCNF in some cases

# How Good is BCNF/3NF?

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

  *employee (ID, cost_center, phone)*

- where an employee may have more than one phone and can have multiple cost centers

| ID | Cost Center | Phone |
|---|---|---|
| 1000 | 10020 | 512-555-1234 |
| 1000 | 10030 | 512-555-1234 |
| 1000 | 10020 | 512-555-4321 |
| 1000 | 10030 | 512-555-4321 |

# How Good is BCNF/3NF?

- Consider a relation

  *employee (ID, cost_center, phone)*

- Functional dependency

  {ID} → {cost_center, phone}

- Superkey: {ID, cost_center, phone}
  - this would also be the primary key of the table

| ID | Cost Center | Phone |
|---|---|---|
| 1000 | 10020 | 512-555-1234 |
| 1000 | 10030 | 512-555-1234 |
| 1000 | 10020 | 512-555-4321 |
| 1000 | 10030 | 512-555-4321 |

# How Good is BCNF/3NF?

- There are database schemas in BCNF that do not seem to be sufficiently normalized
- Insertion anomaly:
  - Suppose that an employee gets a new phone number
  - That would require one insert per cost center
  - Performing only some of those inserts would cause an anomaly

This looks odd

| ID | Cost Center | Phone |
|---|---|---|
| 1000 | 10020 | 512-555-1234 |
| 1000 | 10030 | 512-555-1234 |
| 1000 | 10020 | 512-555-4321 |
| 1000 | 10030 | 512-555-4321 |

# How Good is BCNF/3NF?

- There are database schemas in BCNF that do not seem to be sufficiently normalized
- It looks like decomposition into (ID, Cost Center) and (ID, Phone) would be a good idea
  - But BCNF does not suggest this
  - There is only one candidate key, i.e., {ID, Cost Center, Phone}

| ID | Cost Center | Phone |
|---|---|---|
| 1000 | 10020 | 512-555-1234 |
| 1000 | 10030 | 512-555-1234 |
| 1000 | 10020 | 512-555-4321 |
| 1000 | 10030 | 512-555-4321 |

# Fourth Normal Form

- Here, both Cost Center and Phone are multi-valued attributes
  - i.e., for each combination of ID and Cost Center, there are multiple values for Phone
  - same for combinations of ID and Phone
- Note: cost center and phone are independent from each other
  - i.e., neither {Cost Center} → {Phone} nor {Phone} → {Cost Center} holds

| ID | Cost Center | Phone |
|---|---|---|
| 1000 | 10020 | 512-555-1234 |
| 1000 | 10030 | 512-555-1234 |
| 1000 | 10020 | 512-555-4321 |
| 1000 | 10030 | 512-555-4321 |

# Fourth Normal Form

- Definition: A relation is in Fourth Normal Form if
  - it is in Boyce-Codd Normal Form
  - it does not contain more than one multi-valued attribute
    - in the sense that the multiple values are independent

| ID | Cost Center | Phone |
|---|---|---|
| 1000 | 10020 | 512-555-1234 |
| 1000 | 10030 | 512-555-1234 |
| 1000 | 10020 | 512-555-4321 |
| 1000 | 10030 | 512-555-4321 |

# Fourth Normal Form: Decomposition

- Decomposition algorithm:
  - Create a separate relation for each multi-valued attribute
  - Identify a suitable primary key
- Note: now we can safely insert a new phone number for an employee
  - Requires exactly one insert operation (as expected)
  - Does not lead to inconsistencies!

| ID | Cost Center |
|---|---|
| 1000 | 10020 |
| 1000 | 10030 |

| ID | Phone |
|---|---|
| 1000 | 512-555-1234 |
| 1000 | 512-555-4321 |

# Further Decompositions

- Consider the relation below
  - Each course is offered in different years
    - But there are additional constraints, e.g., Data Mining is only offered in the second semester
  - There might be different offerings in the same year by different lecturers
  - Although all of them are multi-valued, they are *not* independent
- Primary key: {Course, Inst_ID, Semester}

| Course | Inst_ID | Semester |
|---|---|---|
| Introduction to Computer Science | 13001 | 1st |
| Introduction to Computer Science | 13001 | 2nd |
| Data Mining | 15743 | 2nd |
| Data Mining | 14233 | 2nd |
| Linear Algebra | 14233 | 1st |
| ... | | |

# Further Decompositions

- Suppose we want to insert a third offering for data mining for the 2nd semester
  - But we do not know the instructor yet
- We cannot simply insert (Data Mining, null, 2nd)
  - Why?

| Course | Inst_ID | Semester |
|---|---|---|
| Introduction to Computer Science | 13001 | 1st |
| Introduction to Computer Science | 13001 | 2nd |
| Data Mining | 15743 | 2nd |
| Data Mining | 14233 | 2nd |
| Linear Algebra | 14233 | 1st |
| ... | | |

# Further Decompositions

- However, we could easily insert (Data Mining, 12874, 1st)
  - Although data mining is only offered for the 2nd semester
  - That knowledge is not explicit in the schema

| Course | Inst_ID | Semester |
|---|---|---|
| Introduction to Computer Science | 13001 | 1st |
| Introduction to Computer Science | 13001 | 2nd |
| Data Mining | 15743 | 2nd |
| Data Mining | 14233 | 2nd |
| Linear Algebra | 14233 | 1st |
| ... | | |

# Fifth Normal Form

- Also known as *project-join normal form (PJ/NF)*
- A relation is 5NF if
  - It is in 4NF, and
  - If it cannot be decomposed and re-joined based on the keys, without removing or adding information

| Course | Inst_ID | Semester |
|---|---|---|
| Introduction to Computer Science | 13001 | 1st |
| Introduction to Computer Science | 13001 | 2nd |
| Data Mining | 15743 | 2nd |
| Data Mining | 14233 | 2nd |
| Linear Algebra | 14233 | 1st |
| ... | | |

# Fifth Normal Form

- Decomposition into Fifth Normal Form
- For each PK with three values (A,B,C)
  - Try to decompose three relations (A,B), (B,C), (A,C)
  - Analyze whether their natural join is equivalent to (A,B,C)

| Course | Semester |
|---|---|
| Introduction to Computer Science | 1st |
| on to Computer S | |
| ng | |
| ng | |
| jebra | |
| | |

| Course | Inst_ID |
|---|---|
| Introduction to Computer Science | 13001 |
| Introduction to Computer Science | 13001 |
| Data Mining | 15743 |
| Data Mining | 14233 |
| Linear Algebra | 14233 |
| ... | |

| Inst_ID | Semester |
|---|---|
| 13001 | 1st |
| 13001 | 2nd |
| 15743 | 2nd |
| 14233 | 2nd |
| 14233 | 1st |
| | |

# Fifth Normal Form

- Suppose we want to insert a third offering for data mining for the 2nd semester
  - We can do this now by inserting into the (course, semester) relation

| Course | Semester |
|---|---|
| Introduction to Computer Science | 1st |
| ...on to Computer S... | |
| ...ng | |
| ...ng | |
| ...gebra | |
| | |

| Course | Inst_ID |
|---|---|
| Introduction to Computer Science | 13001 |
| Introduction to Computer Science | 13001 |
| Data Mining | 15743 |
| Data Mining | 14233 |
| Linear Algebra | 14233 |
| ... | |

| Inst_ID | Semester |
|---|---|
| 13001 | 1st |
| 13001 | 2nd |
| 15743 | 2nd |
| 14233 | 2nd |
| 14233 | 1st |
| | |

# Fifth Normal Form

- Inconsistent insert (because data mining is only offered in the 2nd semester):

  (Data Mining, 12874, 1st)

- Requires three inserts
  - We may restrict the access to (course, semester)!

| Course | Semester |
|---|---|
| Introduction to Computer Science | 1st |
| [illegible]on to Computer S[illegible] | [illegible] |
| [illegible]ng | [illegible] |
| [illegible]ng | [illegible] |
| [illegible]gebra | [illegible] |
| | |

| Course | Inst_ID |
|---|---|
| Introduction to Computer Science | 13001 |
| Introduction to Computer Science | 13001 |
| Data Mining | 15743 |
| Data Mining | 14233 |
| Linear Algebra | 14233 |
| ... | |

| Inst_ID | Semester |
|---|---|
| 13001 | 1st |
| 13001 | 2nd |
| 15743 | 2nd |
| 14233 | 2nd |
| 14233 | 1st |
| | |

# 6th Normal Form (or Domain Key Normal Form)

- Generally:
  - A relation is in DKNF when there can be no insertion or deletion anomalies in the database
  - i.e., all constraints must be encoded in the database
- Consider the employee relation below
  - Additional constraint: students may not work more than 80h

| ID | Type | Hours |
|---|---|---|
| 10032 | Lecturer | 80 |
| 10432 | Student | 40 |
| 10483 | Secretary | 160 |
| ... | ... | ... |

# 6th Normal Form (or Domain Key Normal Form)

- Recap: domain of an attribute
  - can be used to define valid ranges
- Solution:
  - Decompose into individual relations by employee type
  - Impose domain constraint on attribute *S_Hours*

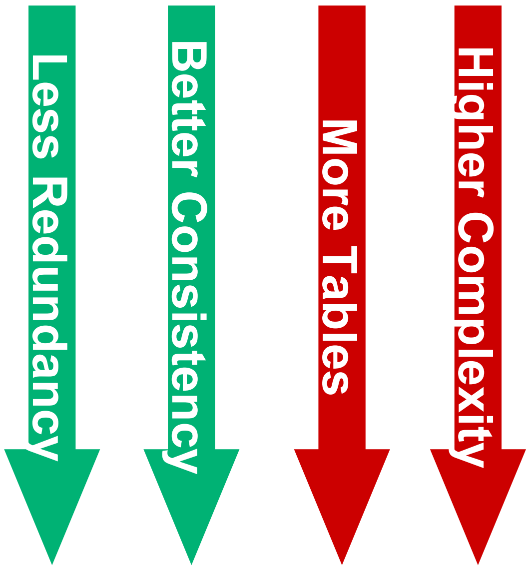
| Lecturer_ID | Hours |
|---|---|
| 10032 | 80 |
| ... | ... |

| Secretary_ID | Hours |
|---|---|
| 10483 | 160 |
| ... | ... |

| Student_ID | S_Hours |
|---|---|
| 10432 | 40 |
| ... | ... |

# Intermediate Recap

- Levels of normalization based on the amount of redundancy in the database
- Various levels of normalization are:
  - First Normal Form (1NF)
  - Second Normal Form (2NF)
  - **Third Normal Form (3NF)**
  - **Boyce-Codd Normal Form (BCNF)**
  - Fourth Normal Form (4NF)
  - Fifth Normal Form (5NF)
  - Domain Key Normal Form (DKNF)



# Incidental Denormalization

- Consider the relation below (courses and prerequisites)
  - Not normalized
  - Violates 2NF
    - Primary Key: {ID, Prereq_ID}
    - {ID} → {Name}, {Prereq_ID} → {Prereq_Name}

| ID | Name | Prereq_ID | Prereq_Name |
|---|---|---|---|
| 110 | Data Mining | 100 | Databases |
| 110 | Data Mining | 101 | Programming |
| ... | ... | ... | ... |

# Incidental Denormalization

- Normalizing to 2NF breaks this into three tables
  - Now, displaying a list of courses with prerequisites requires two joins
  - Costly in terms of performance
- Not normalizing may be better in terms of performance
  - Alternative: materialized view

The same as (ID, Name), but normalization does not tell us

| ID | Name |
|---|---|
| 110 | Data Mining |
| ... | ... |

| ID | Prereq_ID |
|---|---|
| 110 | 100 |
| 110 | 101 |
| ... | ... |

| Prereq_ID | Prereq_Name |
|---|---|
| 100 | Databases |
| 101 | Programming |
| ... | ... |

# Extreme Example

- 1NF: find non-atomic attributes


| ISBN | Author | Title | Publisher | Year |
|---|---|---|---|---|
| 978-0-857-52009-8 | Stephen Baxter,<br>Terry Pratchett | The Long Earth | Doubleday | 2012 |
| 978-0-06-206777-7 | Stephen Baxter,<br>Terry Pratchett | The Long War | Harper | 2013 |
| 978-0-575-07434-7 | Alastair Reynolds | Absolution Gap | Gollancz | 2003 |
| ... | ... | ... | ... | ... |

# Extreme Example

- 1NF: find non-atomic attributes
  - Break *ISBN* in parts (ISBN1, ISBN2, ISBN3, ISBN4, ISBN5)
  - Move *Author* to own relation
  - Break author's *Name* in parts


| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Author_First | Author_Last |
|---|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | Stephen | Baxter |
| 978 | 0 | 857 | 52009 | 8 | Terry | Pratchett |
| 978 | 0 | 06 | 206777 | 7 | Stephen | Baxter |
| | | | | | | ett |
| | | | | | | ds |

| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Title | Publisher | Year |
|---|---|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | The Long Earth | Doubleday | 2012 |
| 978 | 0 | 06 | 206777 | 7 | The Long War | Harper | 2013 |
| 978 | 0 | 575 | 07434 | 7 | Absolution Gap | Gollancz | 2003 |
| ... | ... | ... | ... | ... | ... | ... | ... |

# Extreme Example

- Functional dependencies on partial key
  - Relation book: publisher only depends on ISBN1, ISBN2, ISBN3
  - Violation of 2NF

| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Author_First | Author_Last |
|---|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | Stephen | Baxter |
| 978 | 0 | 857 | 52009 | 8 | Terry | Pratchett |
| 978 | 0 | 06 | 206777 | 7 | Stephen | Baxter |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ett |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ds |

| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Title | Publisher | Year |
|---|---|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | The Long Earth | Doubleday | 2012 |
| 978 | 0 | 06 | 206777 | 7 | The Long War | Harper | 2013 |
| 978 | 0 | 575 | 07434 | 7 | Absolution Gap | Gollancz | 2003 |
| ... | ... | ... | ... | ... | ... | ... | ... |

# Extreme Example

- Functional dependencies on partial key
  - Relation book: publisher only depends on ISBN1, ISBN2, ISBN3
  - Violation of 2NF
  - Resolution: move publisher to own relation

| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Author_First | Author_Last |
|---|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | Stephen | Baxter |
| 978 | 0 | 857 | 520 | | | |
| 978 | 0 | 06 | 206 | | | |

| ISBN1 | ISBN2 | ISBN3 | Publisher |
|---|---|---|---|
| 978 | 0 | 857 | Doubleday |
| | | | Harper |
| | | | Gollancz |
| | | | ... |

| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Title | Year |
|---|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | The Long Earth | 2012 |
| 978 | 0 | 06 | 206777 | 7 | The Long War | 2013 |
| 978 | 0 | 575 | 07434 | 7 | Absolution Gap | 2003 |
| ... | ... | ... | ... | ... | ... | ... |

# Extreme Example

- Observation: we still store the authors' names multiple times
  - DKNF would create author as a single table
  - Note: we need an artificial key

| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Author_ID |
|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | 1 |
| 978 | 0 | 857 | 52009 | 8 | 2 |
| 978 | 0 | 06 | | | |

| ISBN1 | ISBN2 | ISBN3 | Publisher |
|---|---|---|---|
| | | | Doubleday |

| ISBN1 | ISBN2 | ISBN3 | ISBN4 | ISBN5 | Title | Year |
|---|---|---|---|---|---|---|
| 978 | 0 | 857 | 52009 | 8 | Th | |
| 978 | 0 | 06 | 206777 | 7 | Th | |
| 978 | 0 | 575 | 07434 | 7 | Ab | |
| ... | ... | ... | ... | ... | ... | |

| Author_ID | Author_First | Author_Last |
|---|---|---|
| 1 | Stephen | Baxter |
| 2 | Terry | Pratchett |
| 3 | Alastair | Reynolds |
| ... | ... | |

# Extreme Example

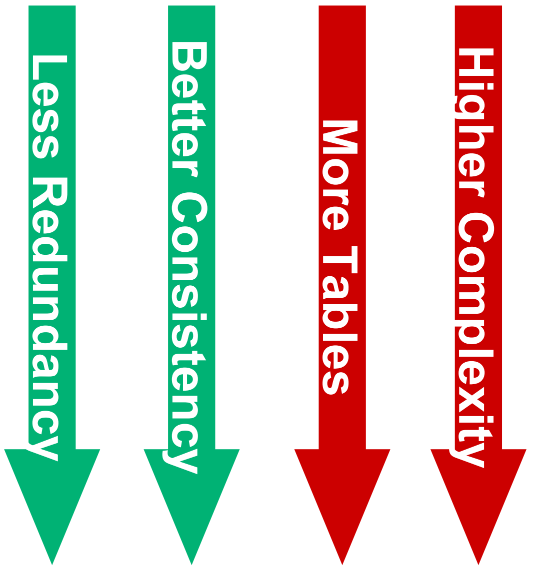
- Normalizing broke a relatively small table into four
- Discussion
  - Is it useful to break the ISBN?
  - Which of the three additional tables do we actually need?
  - Notion of atomicity/scalarity can be very subtle

# ER Models vs. Normal Forms

- Note: the relation between authors and books is an n:m relation
- ER models
  - n:m relations are represented by their own table in the database
- Normalization
  - ultimately creates a table for the n:m relation, too

# The Normalization Process

- Levels of normalization based on the amount of redundancy in the database
- Various levels of normalization are:
  - First Normal Form (1NF)
  - Second Normal Form (2NF)
  - **Third Normal Form (3NF)**
  - **Boyce-Codd Normal Form (BCNF)**
  - Fourth Normal Form (4NF)
  - Fifth Normal Form (5NF)
  - Domain Key Normal Form (DKNF)



# Normal Forms in a Nutshell

- Notions:
  - 1NF: based on atomic/scalar values
  - 2NF, 3NF, BCNF: based on keys and functional dependencies
  - 4NF: based on keys and multi-valued dependencies
  - 5NF: based on join dependencies
  - DKNF: based on domain definitions

- In practice
  - 3NF/BCNF is most used
  - The other NFs are rather of academic interest
    - e.g., 3NF relations that are not 4NF are rather rare

# Trade-Offs

- Normalization is a trade-off
- Pro:
  - Avoid inconsistencies
  - Reduce storage
- Con:
  - Increase complexity
  - Decrease performance
- 3NF vs. BCNF
  - Pro: more inconsistencies avoided
  - Con: some dependencies lost

# Summary

- How to obtain a *good* database design
  - Avoiding redundancy
  - Avoiding inconsistency
- Normalization
  - Step-by-step modification of your database design
  - Successively refines the design
- Caveat
  - Normalization until the bitter end also has shortcomings…
  - Never lose the use cases out of sight

# Questions?