Database design III

Functional dependencies cont.
BCNF and 3NF
MVDs and 4NF

Quiz time!

What's wrong with this schema?

```
Courses(code, period, name, teacher)
code → name
code, period → teacher

{('TDA356', 2, 'Databases', 'Niklas Broberg'),
 ('TDA356', 4, 'Databases', 'Rogardt Heldal')}
```

Redundancy!

Using FDs to detect anomalies

- Whenever X → A holds for a relation R, but X is not a key for R, then values of A will be redundantly repeated!

```
Courses(code, period, name, teacher)

{('TDA356', 2, 'Databases', 'Niklas Broberg'),
 ('TDA356', 4, 'Databases', 'Rogardt Heldal')}

code → name
code, period → teacher
```

Quiz: What kind of anomaly could this relational schema lead to?

Decomposition

```
Courses(code, period, name, teacher)
code → name
code, period → teacher
```

- Fix the problem by decomposing Courses:
  - Create one relation with the attributes from the offending FD, in this case **code** and **name**.
  - Keep the original relation, but remove all attributes from the RHS of the FD. Insert a reference from the LHS in this relation, to the key in the first.

What?

Boyce-Codd Normal Form

- A relation R is in Boyce-Codd Normal Form (BCNF) if, whenever a nontrivial FD X → A holds on R, X is a superkey of R.
  - Remember: nontrivial means A is not part of X
  - Remember: a superkey is any superset of a key (including the keys themselves).

```
Courses(code, name)
CoursePeriods(code, period, teacher)
```

BCNF violations

- We say that an FD X → A *violates* BCNF with respect to relation R if X → A holds on R, but X is not a superkey of R.

Example:

```
Courses(code, period, name, teacher)
```

code → name	violates BCNF
code, period → teacher	does not.

BCNF normalization

- Algorithm: Given a relation R and FDs F.
  1. Identify new FDs using the transitive rule, and add these to F.
  2. Look among the FDs in F for a violation X → A of BCNF w.r.t. R.
  3. Decompose R into two relations
     – One relation RX containing all the attributes in X^+.
     – The original relation R, except the values in X^+ that are not also in X (i.e. $R - X^+ + X$), and with a reference from X to X in RX.
  4. Repeat from 2 for the two new relations until there are no more violations.

Quiz!

Decompose Courses into BCNF.

```
Courses(code, period, name, teacher)
```

```
code → name
code, period → teacher
```

```
{code}+ = {code, name}
```

```
Courses(code, name)
CoursePeriods(course, period, teacher)
  course -> Courses.code
```

No BCNF violations left, so we're done!

Quiz again!

Why not use BCNF decomposition for designing database schemas? Why go via E-R diagrams?

– Decomposition doesn't handle all situations gracefully. E.g.
  - Self-relationships
  - Many-to-one vs. many-to-"exactly one"
  - Subclasses
  - Single-attribute entities

– E-R diagrams are graphical, hence easier to sell than some mathematical formulae.

Recovery

- We must be able to recover the original data after decomposition.

code	*per*	*name*	*teacher*
TDA357	2	Databases	Niklas Broberg
TDA357	4	Databases	Rogardt Heldal

code	*name*
TDA357	Databases

+

code	*per*	*teacher*
TDA357	2	Niklas Broberg
TDA357	4	Rogardt Heldal

code	*per*	*name*	*teacher*
TDA357	2	Databases	Niklas Broberg
TDA357	4	Databases	Rogardt Heldal

"Lossy join"

Let's try to split on non-existent **`code`** → **`teacher`**

code	*per*	*name*	*teacher*
TDA357	2	Databases	Niklas Broberg
TDA357	4	Databases	Rogardt Heldal

code	*teacher*
TDA357	Niklas Broberg
TDA357	Rogardt Heldal

+

code	*per*	*name*
TDA357	2	Databases
TDA357	4	Databases

What?

Lossless join

- Only if we decompose on proper dependencies can we guarantee that no facts are lost.
  – Schemas from proper translation of E-R diagrams get this "for free".
  – The BCNF decomposition algorithm guarantees lossless join.
- A decompositon that does not give lossless join is bad.

Example of BCNF decomposition:

```
CoursePeriods(course, period, teacher)
  course -> Courses.code
course, period → teacher
teacher → course
```

Two keys:
{course, period}
{teacher, period}

Violation!

Decompose:

```
Teaches(teacher, course)
  course  -> Courses.code
CoursePeriods(period, teacher)
  teacher -> Teaches.teacher
```

Quiz: What just went wrong?

```
Teaches(teacher, course)
  course  -> Courses.code
CoursePeriods(period, teacher)
  teacher -> Teaches.teacher
```

teacher	*course*
Niklas Broberg	TDA357
Rogardt Heldal	TDA357

per	*teacher*
2	Niklas Broberg
2	Rogardt Heldal

course	*per*	*teacher*
TDA357	2	Niklas Broberg
TDA357	2	Rogardt Heldal

`course, period → teacher` ??

Problem with BCNF

- Some structures cause problems for decomposition.
  - AB → C, C → B
  - Decomposing w.r.t. C → B gives two relations, containing {C,B} and {A,C} respectively. This means we can no longer enforce AB → C!
  - Intuitively, the cause of the problem is that we must split the LHS of AB → C over two different relations.
    - Not quite the full truth, but good enough.

Third Normal Form (3NF)

- 3NF is a weakening of BCNF that handles this situation.
  - An attribute is *prime* in relation R if it is a member of any key of R.
  - Non-trivial X → A violates BCNF for R if X is not a superkey of R.
  - Non-trivial X → A violates 3NF for R if X is not a superkey or R, *and A is not prime in R.*

Third Normal Form (3NF)

”A nonkey field must provide a fact about the key, the whole key and nothing but the key, so help me Codd”

Edgar F. (Ted) Codd was the inventor of the relational data model.

Different algorithm for 3NF

- Given a relation R and a set of FDs F:
  - Compute the *minimal basis* of F.
    - Minimal basis means F, except remove A → C if you have A → B and B → C.
  - Group together FDs with the same LHS.
  - For each group, create a relation with the LHS as the key.
  - If no relation contains a key of R, add one relation containing only a key of R.

Example:

```
Courses(code, period, name, teacher)
```

```
code → name
code, period → teacher
teacher → code
```

Two keys:

```
{code, period}
{teacher, period}
```

Decompose:

```
Courses(code, name)
CoursePeriods(course, period, teacher)
  course -> Courses.code
  teacher -> Teaches.name
Teaches(name, course)
  course -> Courses.code
```

CoursePeriods contains a key for the original Courses relation, so we have finished.

Earlier example revisited:

```
CoursePeriods(course, period, teacher)
  course -> Courses.code
course, period → teacher
teacher → course
```

Two keys:

```
{course, period}
{teacher, period}
```

Since all attributes are members of some key, i.e. all attributes are prime, there are no 3NF violations. Hence CoursePeriods is in 3NF.

Quiz: What's the problem now then?

3NF vs BCNF

- Three important properties of decomposition:
  1. Recovery (loss-less join)
  2. No redundancy
  3. Dependency preservation
- 3NF guarantees 1 and 3, but not 2.
- BCNF guarantees 1 and (almost) 2, but not 3.

Almost?

Example:

```
Courses(code, name, room, teacher)
```

```
code → name
```

code	name
TDA357	Databases

code	room	teacher
TDA357	VR	Niklas Broberg
TDA357	VR	Rogardt Heldal
TDA357	HC1	Niklas Broberg
TDA357	HC1	Rogardt Heldal

These two relations are in BCNF, but there's lots of redundancy!

Quiz: Why?

Let's start from the bottom…

code	room
TDA357	HC1
TDA357	VR

code	teacher
TDA357	Niklas Broberg
TDA357	Rogardt Heldal

code	room	teacher
TDA357	VR	Niklas Broberg
TDA357	VR	Rogardt Heldal
TDA357	HC1	Niklas Broberg
TDA357	HC1	Rogardt Heldal

- No redundancy before join the two independent relations
- The two starting relations are what we really want to have

Independent sets of attributes

- Partition the sets of attributes in relation R into three sets: X, Y and Z.
- If when we fix the values for one set of attributes, X, the values of another set of attributes Y are independent of the values of all other attributes Z, then we can write:

  $X \twoheadrightarrow Y$

  and, by symmetry, $X \twoheadrightarrow Z$
- This kind of statement is a *multivalued dependency* (abbreviated MVD).

An example

code	*room*	*teacher*
TDA357	VR	Niklas Broberg
TDA357	VR	Rogardt Heldal
TDA357	HC1	Niklas Broberg
TDA357	HC1	Rogardt Heldal

code $\twoheadrightarrow$ room
code $\twoheadrightarrow$ teacher

– room and teacher are independent multivalued attributes.
– the rooms a course uses is *independent* of the teachers on the course.
– X=code, Y=room, Z=teacher

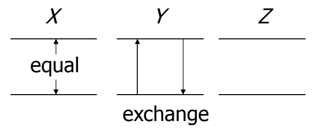
The name: multivalued dependency

- The concept that you've seen on the previous slides was given the name *multivalued dependency* by Ronald Fagin (IBM Research Laboratory) in 1977.
- The concept is about the independence of sets of multivalued attributes.
- In the VT2009 version of this course, the teacher decided to refer to this concept as "independency" (with abbreviation "IND") to emphasize this independence, and used "X $\twoheadrightarrow$ Y | Z" to show that concept relates three sets of attributes.
- I think that was a good idea! I'm happy for you to use either MVD or IND in this course.

Intuitive Definition of MVD

- An MVD $X \twoheadrightarrow Y$ is an assertion that if two tuples of a relation agree on all the attributes of X, then their components in the set of attributes Y may be swapped, and the result will be two tuples that are also in the relation.

Picture of MVD $X \twoheadrightarrow Y$ (or IND $X \twoheadrightarrow Y \mid Z$)



If two tuples have the same value for X, different values for Y and different values for the Z attributes, then there must also exist tuples where the values of Y are exchanged, otherwise Y and Z are not independent!

Implied tuples

Courses(code, name, room, teacher)

code → name

code $\twoheadrightarrow$ room
code $\twoheadrightarrow$ teacher

If we have:

code	*name*	*room*	*teacher*
TDA357	Databases	VR	Niklas Broberg
TDA357	Databases	HC1	Rogardt Heldal

we must also have:

TDA357	Databases	VR	Rogardt Heldal
TDA357	Databases	HC1	Niklas Broberg

otherwise room and teacher would not be independent!

FDs are MVDs

- Every FD is an MVD (but of course not the other way around).
  – If X $\twoheadrightarrow$ Y holds for a relation, then all possible values of Y for that X must be combined with all possible combinations of values for "all other attributes" for that X.
  – If X → A, there is only one possible value of A for that X, and it will appear in all tuples with X. Thus it will be combined with all combinations of values that exist for that X for the rest of the attributes .

Example:

code	name	room	teacher
TDA357	Databases	VR	Niklas Broberg
TDA357	Databases	VR	Rogardt Heldal
TDA357	Databases	HC1	Niklas Broberg
TDA357	Databases	HC1	Rogardt Heldal

code ↠ name — There are four possible combinations of values for the attributes **room** and **teacher**, and the only possible value for the **name** attribute, "Databases", appears in combination with all of them.

code ↠ teacher — There are two possible combinations of values for the attributes **name** and **room**, and all possible values of the attribute **teacher** appear with both of these combinations.

code ↠ room — There are two possible combinations of values for the attributes **name** and **teacher**, and all possible values of the attribute **room** appear with both of these combinations.

MVD rules

- Complementation
  - If X ↠ Y, and Z is all other attributes, then X ↠ Z.
- Splitting doesn't hold!
  - **code ↠ room, #seats**
    - **code ↠ room** does not hold, since **room** and **#seats** are not independent.
- None of the other rules for FDs hold either.

Example:

code	name	room	#seats	teacher
TDA357	Databases	VR	216	Niklas Broberg
TDA357	Databases	VR	216	Rogardt Heldal
TDA357	Databases	HC1	126	Niklas Broberg
TDA357	Databases	HC1	126	Rogardt Heldal

code ↠ room, #seats

We cannot freely swap values in the #seats and room columns, so neither

code ↠ room

or

code ↠ #seats

holds.

Fourth Normal Form

- The redundancy that comes from MVDs is not removable by putting the database schema in BCNF.
- There is a stronger normal form, called 4NF, that (intuitively) treats MVDs as FDs when it comes to decomposition, but not when determining keys of the relation.

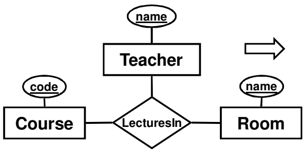
Fourth Normal Form (4NF)

- 4NF is a strengthening of BCNF to handle redundancy that comes from independence.
  - An MVD X ↠ Y is trivial for R if
    - Y is a subset of X
    - X and Y together = R
  - Non-trivial X → A violates BCNF for a relation R if X is not a superkey.
  - Non-trivial X ↠ Y violates 4NF for a relation R if X is not a superkey.
    - Note that what is (or is not) a superkey is still determined by FDs only.

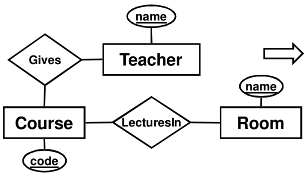
BCNF Versus 4NF

- Remember that every FD *X* -> *Y* is also an MVD, *X* ↠ *Y*.
- Thus, if *R* is in 4NF, it is certainly in BCNF.
  - This is because any BCNF violation is a 4NF violation.
- But *R* could be in BCNF and not 4NF, because MVDs are "invisible" to BCNF.

Compare with E/R




```
LecturesIn(code, teacher, room)
  code  -> Courses.code
  room -> Rooms.name
  teacher -> Teachers.name
```




```
LecturesIn(code, room)
  code -> Courses.code
  room -> Rooms.name
Gives(code, teacher)
  code -> Courses.code
  teacher -> Teachers.name
```

Normal forms

1 NF – Only simple values allowed (definition).

Problems with nonkey attributes:
2NF – (A step towards 3NF)
3NF – All nonkey attributes only depends on the whole key.

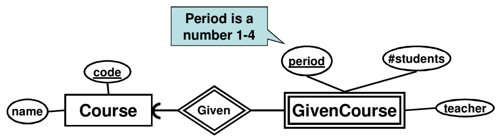
Problems within key attributes (key > 2):
4NF – Multivalued dependencies eliminated.
5NF – Other possible dependencies elimated.

Problems from nonkey attribute to key.
BCNF – Dependency from nonkey attribute to key eliminated

Constraints

- We have different kinds of constraints:
  - Dependency constraints (X → A)
    - Table structure, keys, uniqueness
  - Referential constraints
    - References (a.k.a. foreign keys)
  - Value constraints
    - E.g. a room must have a positive number of seats
  - Cardinality constraints
    - E.g. no teacher may hold more than 2 courses at the same time.

Extra constraints in E-R



The point is that the diagram should be easy to understand, and easy to implement!

Extra constraints in schemas

- No formal syntax exists. Don't let that stop you!

```
GivenCourses(course, period, teacher)
   1 ≤ period ≤ 4
```

Goals of database design

- "Map" the domain, find out what the database is intended to model.
  - The database should accept all data that is possible in reality.
  - The database should agree with reality and not accept impossible or unwanted data.
- We accomplish this by making sure that our database captures all the constraints of the domain.

The whole point of design

- The result of design should be a database schema that:
  - correctly models the domain and its constraints.
  - is easy to understand.
  - can be implemented directly in a DBMS!
    …even by someone else than the designer

Course Objectives – Design

When the course is through, you should

- Given a domain, know how to design a database that correctly models the domain and its constraints.

”We want a database that we can use for scheduling courses and lectures. This is how it’s supposed to work: …”

Exam – FDs and NFs

”A car rental company has the following, not very successful, database. They want your help to improve it. …”

- Identify all functional dependencies you expect to hold in the domain.
- Indicate which of those dependencies violate BCNF with respect to the relations in the database.
- Do a complete decomposition of the database so that the resulting relations are in BCNF.

Quiz!

Decompose Schedules into BCNF.

```
Schedules(code, name, period, numStudents, teacher,
    room, numSeats, weekday, hour)

        code → name
        code, period → #students
        code, period → teacher
        room → #seats
        code, period, weekday → hour
        code, period, weekday → room
        room, period, weekday, hour → code
```

Next Lecture

Database Construction –
SQL Data Definition Language