Relational Database Design

CPS 216
Advanced Database Systems

Announcements (January 20)

- Review for Codd paper due tonight via email
  - Follow instructions on course Web site
- Reading assignment for next week (Ailamaki et al., *VLDB* 2001) has been posted
  - Due next Wednesday night
- Homework #1 assigned today
  - Expect an email regarding your DB2 account today
  - Due February 8 (in 2 ½ weeks)
- Course project will be assigned next week

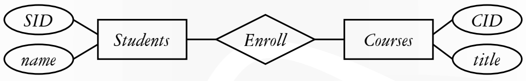
Database (schema) design

- Understand the real-world domain being modeled
- Specify it using a database design model
  - Design models are especially convenient for schema design, but are not necessarily implemented by DBMS
  - Popular ones include
    - Entity/Relationship (E/R) model
    - Object Definition Language (ODL)
- Translate the design to the data model of DBMS
  - Relational, XML, object-oriented, etc.
- Apply database design theory to check the design
- Create DBMS schema

Entity-relationship (E/R) model

- Historically very popular
  - Primarily a design model; not implemented by any major DBMS nowadays
- Can think of as a "watered-down" object-oriented design model
- E/R diagrams represent designs

E/R example



- Entity: a "thing," like a record or an object
- Entity set (rectangle): a collection of things of the same type, like a relation of tuples or a class of objects
- Relationship: an association among two or more entities
- Relationship set (diamond): a set of relationships of the same type; an association among two or more entity sets
- Attributes (ovals): properties of entities or relationships, like attributes of tuples or objects

ODL (Object Definition Language)

- Standardized by ODMG (Object Data Management Group)
  - Comes with a declarative query language OQL (Object Query Language)
  - Implemented by OODBMS (Object-Oriented DataBase Management Systems)
- Object oriented
- Based on C^{++} syntax
- Class declarations represent designs

ODL example

```
class Student {
  attribute integer SID;
  attribute string name;
  relationship Set<Course> enrolledIn inverse Course::students;
};
class Course {
  attribute string CID;
  attribute string title;
  relationship Set<Student> students inverse Student::enrolledIn;
};
```

- ❖ Easy to map them to C^{++} classes
  - ▪ ODL attributes correspond to attributes of objects; complex types are allowed
  - ▪ ODL relationships can be mapped to pointers to other objects (e.g., `Set<Course>` → set of pointers to objects of `Course` class)

Not covered in this lecture

- ❖ E/R and ODL design
- ❖ Translating E/R and ODL designs into relational designs
- ☞ Reference book (GMUW) has all the details

- ❖ Next: relational design theory

Relational model: review

- ❖ A database is a collection of relations (or tables)
- ❖ Each relation has a list of attributes (or columns)
- ❖ Each attribute has a domain (or type)
- ❖ Each relation contains a set of tuples (or rows)

Keys

- ❖ A set of attributes *K* is a key for a relation *R* if
  - ▪ In no instance of *R* will two different tuples agree on all attributes of *K*
    - • That is, *K* is a "tuple identifier"
  - ▪ No proper subset of *K* satisfies the above condition
    - • That is, *K* is minimal
- ❖ Example: *Student* (*SID*, *name*, *age*, *GPA*)
  - ▪ *SID* is a key of *Student*
  - ▪ {*SID*, *name*} is not a key (not minimal)

Schema vs. data

Student

SID	*name*	*age*	*GPA*
142	Bart	10	2.3
123	Milhouse	10	3.1
857	Lisa	8	4.3
456	Ralph	8	2.3
...	...	...	...

- ❖ Is *name* a key of *Student*?
  - ▪ Yes? Seems reasonable for this instance
  - ▪ No! Student names are not unique in general
- ❖ Key declarations are part of the schema

More examples of keys

- ❖ *Enroll* (*SID*, *CID*)
  - ▪ {*SID*, *CID*}
- ❖ *Address* (*street_address*, *city*, *state*, *zip*)
  - ▪ {*street_address*, *city*, *state*}
  - ▪ {*street_address*, *zip*}
- ❖ *Course* (*CID*, *title*, *room*, *day_of_week*, *begin_time*, *end_time*)
  - ▪ {*CID*, *day_of_week*, *begin_time*}
  - ▪ {*CID*, *day_of_week*, *end_time*}
  - ▪ {*room*, *day_of_week*, *begin_time*}
  - ▪ {*room*, *day_of_week*, *end_time*}
  - ☞Not a good design, and we will see why later

Usage of keys

- More constraints on data, fewer mistakes
- Look up a row by its key value
  - Many selection conditions are "key = value"
- "Pointers"
  - Example: *Enroll* (*SID*, *CID*)
    - *SID* is a key of *Student*
    - *CID* is a key of *Course*
    - An *Enroll* tuple "links" a *Student* tuple with a *Course* tuple
  - Many join conditions are "key = key value stored in another table"

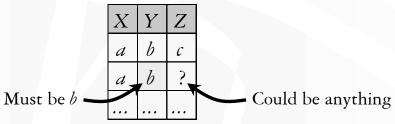
Motivation for a design theory

SID	*name*	*CID*
142	Bart	CPS216
142	Bart	CPS214
857	Lisa	CPS216
857	Lisa	CPS230
…	…	…

- Why is this design is bad?
  - This design has redundancy, because the name of a student is recorded multiple times, once for each course the student is taking
- Why is redundancy bad?
  - Wastes space, complicates updates, and promotes inconsistency
- How about a systematic approach to detecting and removing redundancy in designs?
  - Dependencies, decompositions, and normal forms

Functional dependencies

- A functional dependency (FD) has the form $X \rightarrow Y$, where X and Y are sets of attributes in a relation R
- $X \rightarrow Y$ means that whenever two tuples in R agree on all the attributes in X, they must also agree on all attributes of Y



X	Y	Z
a	b	c
a	b	?
…	…	…

FD examples

Address (*street_address*, *city*, *state*, *zip*)

- *street_address*, *city*, *state* → *zip*
- *zip* → *city*, *state*
- *zip*, *state* → *zip*?
  - This is a trivial FD
  - Trivial FD: LHS $\supseteq$ RHS
- *zip* → *state*, *zip*?
  - This is non-trivial, but not completely non-trivial
  - Completely non-trivial FD: LHS $\cap$ RHS $= \varnothing$

Keys redefined using FD's

A set of attributes K is a key for a relation R if

- $K \rightarrow$ all (other) attributes of R
  - That is, K is a "super key"
- No proper subset of K satisfies the above condition
  - That is, K is minimal

Reasoning with FD's

Given a relation R and a set of FD's $\mathcal{F}$

- Does another FD follow from $\mathcal{F}$?
  - Are some of the FD's in $\mathcal{F}$ redundant (i.e., they follow from the others)?
- Is K a key of R?
  - What are all the keys of R?

Attribute closure

- Given R, a set of FD's $\mathcal{F}$ that hold in R, and a set of attributes Z in R:
  The closure of Z (denoted Z^+) with respect to $\mathcal{F}$ is the set of all attributes functionally determined by Z
- Algorithm for computing the closure
  - Start with closure $= Z$
  - If $X \rightarrow Y$ is in $\mathcal{F}$ and X is already in the closure, then also add Y to the closure
  - Repeat until no more attributes can be added

A more complex example

StudentGrade (*SID*, *name*, *email*, *CID*, *grade*)

- $SID \rightarrow name, email$
- $email \rightarrow SID$
- $SID, CID \rightarrow grade$

☞ Not a good design, and we will see why later

Example of computing closure

- $\mathcal{F}$ includes:
  - $SID \rightarrow name, email$
  - $email \rightarrow SID$
  - $SID, CID \rightarrow grade$
- $\{ CID, email \}^+ = ?$
- $email \rightarrow SID$
  - Add *SID*; closure is now $\{ CID, email, SID \}$
- $SID \rightarrow name, email$
  - Add *name*, *email*; closure is now $\{ CID, email, SID, name \}$
- $SID, CID \rightarrow grade$
  - Add *grade*; closure is now all the attributes in *StudentGrade*

Using attribute closure

Given a relation R and set of FD's $\mathcal{F}$

- Does another FD $X \rightarrow Y$ follow from $\mathcal{F}$?
  - Compute X^+ with respect to $\mathcal{F}$
  - If $Y \subseteq X^+$, then $X \rightarrow Y$ follow from $\mathcal{F}$
- Is K a key of R?
  - Compute K^+ with respect to $\mathcal{F}$
  - If K^+ contains all the attributes of R, K is a super key
  - Still need to verify that K is *minimal* (how?)

Useful rules of FD's

- Armstrong's axioms
  - Reflexivity: If $Y \subseteq X$, then $X \rightarrow Y$
  - Augmentation: If $X \rightarrow Y$, then $XZ \rightarrow YZ$ for any Z
  - Transitivity: If $X \rightarrow Y$ and $Y \rightarrow Z$, then $X \rightarrow Z$
- Rules derived from axioms
  - Splitting: If $X \rightarrow YZ$, then $X \rightarrow Y$ and $X \rightarrow Z$
  - Combining: If $X \rightarrow Y$ and $X \rightarrow Z$, then $X \rightarrow YZ$

Non-key FD's

- Consider a non-trivial FD $X \rightarrow Y$ where X is not a super key
  - Since X is not a super key, there are some attributes (say Z) that are not functionally determined by X

X	*Y*	*Z*
a	*b*	*c*1
a	*b*	*c*2
…	…	…

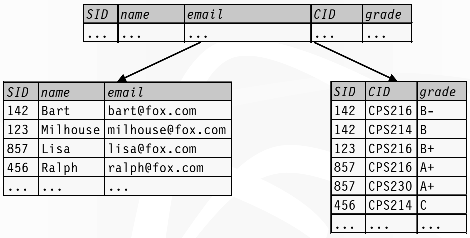
The fact that *a* is always associated with *b* is recorded in multiple rows: redundancy!

Example of redundancy

- *StudentGrade* (*SID*, *name*, *email*, *CID*, *grade*)
- *SID* → *name*, *email*

SID	*name*	*email*	*CID*	*grade*
142	Bart	bart@fox.com	CPS216	B-
142	Bart	bart@fox.com	CPS214	B
123	Milhouse	milhouse@fox.com	CPS216	B+
857	Lisa	lisa@fox.com	CPS216	A+
857	Lisa	lisa@fox.com	CPS230	A+
456	Ralph	ralph@fox.com	CPS214	C
...	...	...	...	...

Decomposition



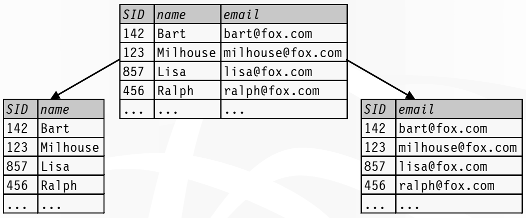
SID	*name*	*email*	*CID*	*grade*
...	...	...	...	...

SID	*name*	*email*
142	Bart	bart@fox.com
123	Milhouse	milhouse@fox.com
857	Lisa	lisa@fox.com
456	Ralph	ralph@fox.com
...	...	...

SID	*CID*	*grade*
142	CPS216	B-
142	CPS214	B
123	CPS216	B+
857	CPS216	A+
857	CPS230	A+
456	CPS214	C
...	...	...

- Eliminates redundancy
- To get back to the original relation: $\bowtie$

Unnecessary decomposition



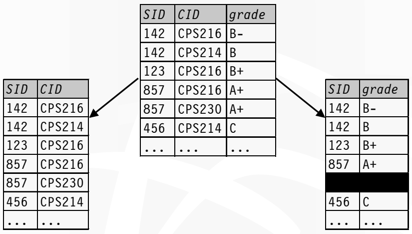
SID	*name*	*email*
142	Bart	bart@fox.com
123	Milhouse	milhouse@fox.com
857	Lisa	lisa@fox.com
456	Ralph	ralph@fox.com
...	...	...

SID	*name*
142	Bart
123	Milhouse
857	Lisa
456	Ralph
...	...

SID	*email*
142	bart@fox.com
123	milhouse@fox.com
857	lisa@fox.com
456	ralph@fox.com
...	...

- Fine: join returns the original relation
- Unnecessary: no redundancy is removed, and now *SID* is stored twice!

Bad decomposition



SID	*CID*	*grade*
142	CPS216	B-
142	CPS214	B
123	CPS216	B+
857	CPS216	A+
857	CPS230	A+
456	CPS214	C
...	...	...

SID	*CID*
142	CPS216
142	CPS214
123	CPS216
857	CPS216
857	CPS230
456	CPS214
...	...

SID	*grade*
142	B-
142	B
123	B+
857	A+
[redacted]	[redacted]
456	C
...	...

- Association between *CID* and *grade* is lost
- Join returns more rows than the original relation

Questions about decomposition

- When to decompose
- How to come up with a correct decomposition

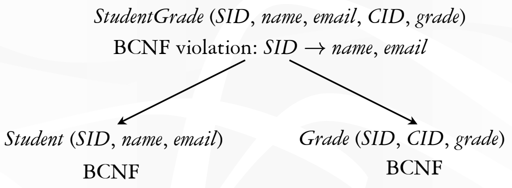
An answer: BCNF

- A relation *R* is in Boyce-Codd Normal Form if
  - For every non-trivial FD $X \rightarrow Y$ in *R*, *X* is a super key
  - That is, all FDs follow from “key → other attributes”
- When to decompose
  - As long as some relation is not in BCNF
- How to come up with a correct decomposition
  - Always decompose on a BCNF violation
  - ☞Then it is guaranteed to be a correct decomposition!

BCNF decomposition algorithm

- Find a BCNF violation
  - That is, a non-trivial FD $X \rightarrow Y$ in R where X is not a super key of R
- Decompose R into R_1 and R_2, where
  - R_1 has attributes $X \cup Y$
  - R_2 has attributes $X \cup Z$, where Z contains all attributes of R that are in neither X nor Y
- Repeat until all relations are in BCNF

BCNF decomposition example

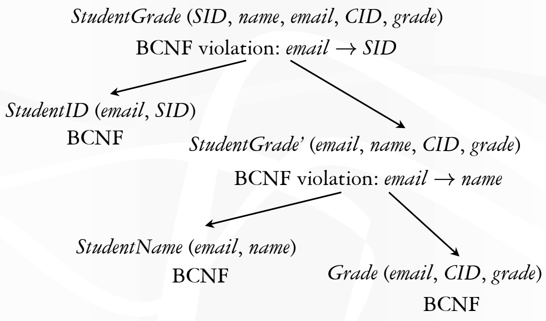


StudentGrade (*SID*, *name*, *email*, *CID*, *grade*)
BCNF violation: *SID* → *name*, *email*

Student (*SID*, *name*, *email*)
BCNF

Grade (*SID*, *CID*, *grade*)
BCNF

Another example



StudentGrade (*SID*, *name*, *email*, *CID*, *grade*)
BCNF violation: *email* → *SID*

StudentID (*email*, *SID*)
BCNF

StudentGrade' (*email*, *name*, *CID*, *grade*)
BCNF violation: *email* → *name*

StudentName (*email*, *name*)
BCNF

Grade (*email*, *CID*, *grade*)
BCNF

Recap

- Functional dependencies: generalization of keys
- Non-key functional dependencies: a source of redundancy
- BCNF decomposition: a method of removing redundancies due to FD's
- BCNF: schema in this normal form has no redundancy due to FD's
- ☞ Not covered in this lecture: many other types of dependencies (e.g., MVD) and normal forms (e.g., 4NF)
  - GMUW has all the details
  - Relational design theory was a big research area in the 1970's, but there is not much going on now