CompSci 516
Database Systems

Lecture 5
Design Theory and Normalization

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Where are we now?

We learnt

- ✓ Relational Model and Query Languages
  - ✓ SQL, RA, RC
  - ✓ Postgres (DBMS)
  - ✓ XML (overview)
  - HW1

Next

- Database Normalization
  - (for good schema design)

Announcements

- No class or office hour on Thursday
  - Classes are canceled due to Hurricane alert
  - Make up classe/office hour to be announced later

- Reminder: HW1
  - Sakai : Resources -> HW -> HW1 folder
  - Due on 09/20 (Thurs), 11:55 pm, no late days
  - Start now!
  - Submission instructions for gradescope are updated on piazza

Reading Material

- Database normalization
  - [RG] Chapter 19.1 to 19.5, 19.6.1, 19.8 (overview)
  - [GUW] Chapter 3

Acknowledgement:
- The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.
- Some slides have been adapted from slides by Profs. Magda Balazinska, Dan Suciu, and Jun Yang

What will we learn?

- What goes wrong if we have redundant info in a database?
- Why and how should you refine a schema?
- Functional Dependencies – a new kind of integrity constraints (IC)
- Normal Forms
- How to obtain those normal forms

Example

The list of hourly employees in an organization

<u>ssn (S)</u>	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

- key = SSN

Example

The list of hourly employees in an organization

<u>ssn (S)</u>	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

- key = SSN
- Suppose for a given rating, there is only one hourly_wage value
- Redundancy in the table
- Why is redundancy bad?

Why is redundancy bad?

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

1. Redundant storage:
   - Some information is stored repeatedly
   - The rating value 8 corresponds to hourly_wage 10, which is stored three times

Why is redundancy bad?

The list of hourly employees in an organization

<u>ssn (S)</u>	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10 → 9	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

2. Update anomalies
   - If one copy of data is updated, an inconsistency is created unless all copies are similarly updated
   - Suppose you update the hourly_wage value in the first tuple using UPDATE statement in SQL -- inconsistency

Why is redundancy bad?

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

3. Insertion anomalies:
   - It may not be possible to store certain information unless some other, unrelated info is stored as well
   - We cannot insert a tuple for an employee unless we know the hourly wage for the employee's rating value

Why is redundancy bad?

The list of hourly employees in an organization

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

4. Deletion anomalies:
   - It may not be possible delete certain information without losing some other information as well
   - If we delete all tuples with a given rating value (Attishoo, Smiley, Madayan), we lose the association between that rating value and its hourly_wage value

Nulls may or may not help

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

- Does not help redundant storage or update anomalies
- May help insertion and deletion anomalies
  - can insert a tuple with null value in the hourly_wage field
  - but cannot record hourly_wage for a rating unless there is such an employee (SSN cannot be null) – same for deletion

Summary: Redundancy

Therefore,

- Redundancy arises when the schema forces an association between attributes that is “not natural”
- We want schemas that do not permit redundancy
  – at least identify schemas that allow redundancy to make an informed decision (e.g. for performance reasons)
- Null value may or may not help

- Solution?
  – decomposition of schema

Decomposition

ssn (S)	name (N)	lot (L)	rating (R)	hourly-wage (W)	hours-worked (H)
111-11-1111	Attishoo	48	8	10	40
222-22-2222	Smiley	22	8	10	30
333-33-3333	Smethurst	35	5	7	30
444-44-4444	Guldu	35	5	7	32
555-55-5555	Madayan	35	8	10	40

ssn (S)	name (N)	lot (L)	rating (R)	hours-worked (H)
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333-33-3333	Smethurst	35	5	30
444-44-4444	Guldu	35	5	32
555-55-5555	Madayan	35	8	40

rating	hourly_wage
8	10
5	7

Decompositions should be used judiciously

1. Do we need to decompose a relation?
   - Several normal forms
   - If a relation is not in one of them, may need to decompose further

2. What are the problems with decomposition?
   - Lossless joins (soon)
   - Performance issues -- decomposition may both
     - help performance (for updates, some queries accessing part of data), or
     - hurt performance (new joins may be needed for some queries)

Functional Dependencies (FDs)

- A functional dependency (FD) $X \rightarrow Y$ holds over relation R if, for every allowable instance *r* of R:
  - i.e., given two tuples in *r*, if the X values agree, then the Y values must also agree
  - X and Y are *sets* of attributes
  - $t1 \in r,\ t2 \in r,\ \Pi_X(t1) = \Pi_X(t2)$ implies $\Pi_Y(t1) = \Pi_Y(t2)$

A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a1	b2	c2	d1
a2	b1	c3	d1

What is an FD here?

Functional Dependencies (FDs)

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  - X and Y are *sets* of attributes
  - $t1 \in r$, $t2 \in r$, $\Pi_X(t1) = \Pi_X(t2)$ implies $\Pi_Y(t1) = \Pi_Y(t2)$

A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a1	b2	c2	d1
a2	b1	c3	d1

What is an FD here?

$AB \rightarrow C$

Note that, AB is not a key

not a correct question though.. see next slide!

Functional Dependencies (FDs)

- An FD is a statement about all allowable relations
  - Must be identified based on semantics of application
  - Given some allowable instance *r1* of R, we can check if it violates some FD *f*, but we cannot tell if *f* holds over R
- K is a candidate key for R means that K $\rightarrow$R
  - denoting R = all attributes of R too
  - However, S $\rightarrow$R does not require S to be minimal
  - e.g. S can be a superkey

Example

- Consider relation obtained from Hourly_Emps:
  - Hourly_Emps (<u>ssn</u>, name, lot, rating, hourly_wage, hours_worked)

- Notation: We will denote a relation schema by listing the attributes: SNLRWH
  - Basically the set of attributes {S,N,L,R,W,H}
  - here first letter of each attribute

- FDs on Hourly_Emps:
  - ssn is the key: S → SNLRWH
  - rating determines hourly_wages: R → W

Armstrong's Axioms

- X, Y, Z are sets of attributes

- Reflexivity: If $X \supseteq Y$, 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 $X \rightarrow Z$

A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a1	b2	c2	d1
a2	b1	c3	d1

Apply these rules on $AB \rightarrow C$ and check

Armstrong's Axioms

- X, Y, Z are sets of attributes

- Reflexivity: If $X \supseteq Y$, 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 $X \rightarrow Z$

- These are sound and complete inference rules for FDs
  - sound: then only generate FDs in F^+ for F
  - complete: by repeated application of these rules, all FDs in F^+ will be generated

Additional Rules

- Follow from Armstrong's Axioms

- Union: If $X \rightarrow Y$ and $X \rightarrow Z$, then $X \rightarrow YZ$
- Decomposition: If $X \rightarrow YZ$, then $X \rightarrow Y$ and $X \rightarrow Z$

A	B	C	D
a1	b1	c1	d1
a1	b1	c1	d2
a2	b2	c2	d1
a2	b2	c2	d2

$A \rightarrow B$, $A \rightarrow C$

$A \rightarrow BC$

$A \rightarrow BC$

$A \rightarrow B$, $A \rightarrow C$

Closure of a set of FDs

- Given some FDs, we can usually infer additional FDs:
  - SSN → DEPT, and DEPT → LOT implies SSN → LOT

- An FD *f* is implied by a set of FDs *F* if *f* holds whenever all FDs in *F* hold.

- F^+

  = closure of F is the set of all FDs that are implied by *F*

To check if an FD belongs to a closure

- Computing the closure of a set of FDs can be expensive
  - Size of closure can be exponential in #attributes

- Typically, we just want to check if a given FD *X* → *Y* is in the closure of a set of FDs *F*

- No need to compute F^+

1. Compute attribute closure of X (denoted X^+) wrt *F:*
   - Set of all attributes A such that X → A is in F^+
2. Check if Y is in X^+

Computing Attribute Closure

Algorithm:

- closure = X
- Repeat until no change
  - if there is an FD $U \rightarrow V$ in F such that $U \subseteq$ closure, then closure = closure $\cup$ V

- Does $F = \{A \rightarrow B,\ B \rightarrow C,\ C\,D \rightarrow E\}$ imply $A \rightarrow E$?
  - i.e, is $A \rightarrow E$ in the closure F^+? Equivalently, is E in A^+?

Normal Forms

- Question: given a schema, how to decide whether any schema refinement is needed at all?
- If a relation is in a certain normal forms, it is known that certain kinds of problems are avoided/minimized
- Helps us decide whether decomposing the relation is something we want to do

FDs play a role in detecting redundancy

Example

- Consider a relation R with 3 attributes, ABC
  - No FDs hold: There is no redundancy here – no decomposition needed
  - Given A → B: Several tuples could have the same A value, and if so, they'll all have the same B value – redundancy – decomposition may be needed if A is not a key

- Intuitive idea:
  - if there is any non-key dependency, e.g. A → B, decompose!

Normal Forms

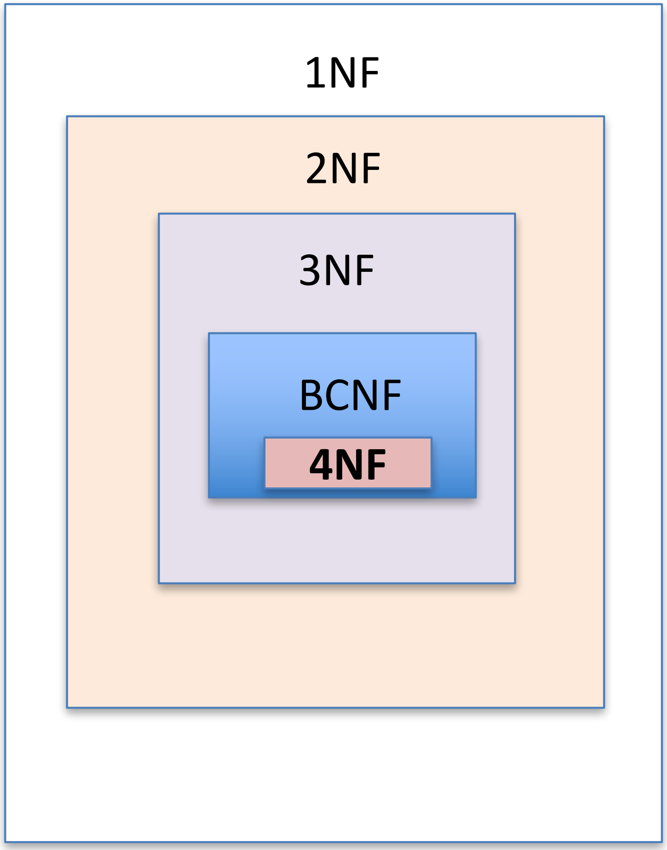
R is in 4NF

⇒ R is in BCNF

⇒ R is in 3NF

⇒ R is in 2NF (a historical one)

⇒ R is in 1NF (every field has atomic values)



Only BCNF and 4NF are covered in the class

Boyce-Codd Normal Form (BCNF)

- Relation R with FDs *F* is in BCNF if, for all $X \rightarrow A$ in F
  - $A \in X$ (called a trivial FD), or
  - X contains a key for R
    - i.e. X is a superkey

Decomposition

(on twitter)

uid	uname	twitterid	gid	fromDate
142	Bart	@BartJSimpson	dps	1987-04-19
123	Milhouse	@MilhouseVan_	gov	1989-12-17
857	Lisa	@lisasimpson	abc	1987-04-19
857	Lisa	@lisasimpson	gov	1988-09-01
456	Ralph	@ralphwiggum	abc	1991-04-25
456	Ralph	@ralphwiggum	gov	1992-09-01
…	…	…	…	…

- User id
- user name
- Twitter id
- Group id
- Joining Date (to a group)

uid	uname	twitterid
142	Bart	@BartJSimpson
123	Milhouse	@MilhouseVan_
857	Lisa	@lisasimpson
456	Ralph	@ralphwiggum
…	…	…

uid	gid	fromDate
142	dps	1987-04-19
123	gov	1989-12-17
857	abc	1987-04-19
857	gov	1988-09-01
456	abc	1991-04-25
456	gov	1992-09-01
…	…	…

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

Unnecessary decomposition

uid	*uname*	*twitterid*
142	Bart	@BartJSimpson
123	Milhouse	@MilhouseVan_
857	Lisa	@lisasimpson
456	Ralph	@ralphwiggum
…	…	…

uid	*uname*
142	Bart
123	Milhouse
857	Lisa
456	Ralph
…	…

uid	*twitterid*
142	@BartJSimpson
123	@MilhouseVan_
857	@lisasimpson
456	@ralphwiggum
…	…

- Fine: join returns the original relation
- Unnecessary: no redundancy is removed; schema is more complicated (and *uid* is stored twice!)

Bad decomposition

uid	*gid*	*fromDate*
142	dps	1987-04-19
123	gov	1989-12-17
857	abc	1987-04-19
857	gov	1988-09-01
456	abc	1991-04-25
456	gov	1992-09-01
…	…	…

uid	*gid*
142	dps
123	gov
857	abc
857	gov
456	abc
456	gov
…	…

uid	*fromDate*
142	1987-04-19
123	1989-12-17
857	1987-04-19
857	1988-09-01
456	1991-04-25
456	1992-09-01
…	…

- Association between *gid* and *fromDate* is lost
- Join returns more rows than the original relation

Lossless join decomposition

- Decompose relation R into relations S and T
  - $attrs(R) = attrs(S) \cup attrs(T)$
  - $S = \pi_{attrs(S)}(R)$
  - $T = \pi_{attrs(T)}(R)$
- The decomposition is a lossless join decomposition if, given known constraints such as FD's, we can guarantee that $R = S \bowtie T$

- $R \subseteq S \bowtie T$ or $R \supseteq S \bowtie T$?

- Any decomposition gives $R \subseteq S \bowtie T$ (why?)
  - A lossy decomposition is one with $R \subset S \bowtie T$

Loss? But I got more rows!

- "Loss" refers not to the loss of tuples, but to the loss of information
  - Or, the ability to distinguish different original relations

uid	gid	fromDate
142	dps	1987-04-19
123	gov	1989-12-17
857	abc	1988-09-01
857	gov	1987-04-19
456	abc	1991-04-25
456	gov	1992-09-01
…	…	…

No way to tell
which is the original relation

uid	gid
142	dps
123	gov
857	abc
857	gov
456	abc
456	gov
…	…

uid	fromDate
142	1987-04-19
123	1989-12-17
857	1987-04-19
857	1988-09-01
456	1991-04-25
456	1992-09-01
…	…

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

- Also gives a lossless decomposition!

BCNF decomposition example - 1

- CSJDPQV, key C, F = {JP → C, SD → P, J → S}
  - To deal with SD → P, decompose into SDP, CSJDQV.
  - To deal with J → S, decompose CSJDQV into JS and CJDQV
- Is JP → C a violation of BCNF?
- Note:
  - several dependencies may cause violation of BCNF
  - The order in which we pick them may lead to very different sets of relations
  - there may be multiple correct decompositions (can pick J → S first)

BCNF decomposition example - 2

uid → *uname*, *twitterid*
twitterid → *uid*
uid, *gid* → *fromDate*

UserJoinsGroup (*uid*, *uname*, *twitterid*, *gid*, *fromDate*)

BCNF violation: *uid* → *uname*, *twitterid*

User (*uid*, *uname*, *twitterid*)

uid → *uname*, *twitterid*
twitterid → *uid*

BCNF

Member (*uid*, *gid*, *fromDate*)

uid, *gid* → *fromDate*

BCNF

BCNF decomposition example - 3

uid → *uname*, *twitterid*
twitterid → *uid*
uid, *gid* → *fromDate*

UserJoinsGroup (*uid*, *uname*, *twitterid*, *gid*, *fromDate*)

BCNF violation: *twitterid* → *uid*

apply Armstrong's axioms and rules!

UserId (*twitterid*, *uid*)
BCNF

UserJoinsGroup' (*twitterid*, *uname*, *gid*, *fromDate*)

twitterid → *uname*
twitterid, *gid* → *fromDate*

BCNF violation: *twitterid* → *uname*

UserName (*twitterid*, *uname*)
BCNF

Member (*twitterid*, *gid*, *fromDate*)
BCNF

Recap

- Functional dependencies: a generalization of the key concept
- Non-key functional dependencies: a source of redundancy
- BCNF decomposition: a method for removing redundancies
  - BCNF decomposition is a lossless join decomposition
- BCNF: schema in this normal form has no redundancy due to FD's

BCNF = no redundancy?

- *User* (*uid*, *gid*, *place*)
  - A user can belong to multiple groups
  - A user can register places she's visited
  - Groups and places have nothing to do with other
  - FD's?
    - None
  - BCNF?
    - Yes
  - Redundancies?
    - Tons!

uid	*gid*	*place*
142	dps	Springfield
142	dps	Australia
456	abc	Springfield
456	abc	Morocco
456	gov	Springfield
456	gov	Morocco
…	…	…

Multivalued dependencies

- A multivalued dependency (MVD) has the form $X \twoheadrightarrow Y$, where X and Y are sets of attributes in a relation R
- $X \twoheadrightarrow Y$ means that whenever two rows in R agree on all the attributes of X, then we can swap their Y components and get two rows that are also in R

X	Y	Z
a	b_1	c_1
a	b_2	c_2
a	b_2	c_1
a	b_1	c_2
…	…	…

MVD examples

User (*uid*, *gid*, *place*)

- $uid \twoheadrightarrow gid$
- $uid \twoheadrightarrow place$
  - Intuition: given *uid*, attributes *gid* and *place* are "independent"
- $uid, gid \twoheadrightarrow place$
  - Trivial: LHS ∪ RHS = all attributes of R
- $uid, gid \twoheadrightarrow uid$
  - Trivial: LHS ⊇ RHS

Verify these yourself!

Complete MVD + FD rules

- FD reflexivity, augmentation, and transitivity
- MVD complementation:
  If $X \twoheadrightarrow Y$, then $X \twoheadrightarrow attrs(R) - X - Y$
- MVD augmentation:
  If $X \twoheadrightarrow Y$ and $V \subseteq W$, then $XW \twoheadrightarrow YV$
- MVD transitivity:
  If $X \twoheadrightarrow Y$ and $Y \twoheadrightarrow Z$, then $X \twoheadrightarrow Z - Y$
- Replication (FD is MVD):
  If $X \rightarrow Y$, then $X \twoheadrightarrow Y$
- Coalescence:
  If $X \twoheadrightarrow Y$ and $Z \subseteq Y$ and there is some W disjoint from Y such that $W \rightarrow Z$, then $X \rightarrow Z$

Try proving things using these!?

Read this slide after looking at the examples

An elegant solution: "chase"

- Given a set of FD's and MVD's $\mathcal{D}$, does another dependency d (FD or MVD) follow from $\mathcal{D}$?
- Procedure
  - Start with the premise of d, and treat them as "seed" tuples in a relation
  - Apply the given dependencies in $\mathcal{D}$ repeatedly
    - If we apply an FD, we infer equality of two symbols
    - If we apply an MVD, we infer more tuples
  - If we infer the conclusion of d, we have a proof
  - Otherwise, if nothing more can be inferred, we have a counterexample

TO BE CONTINUED IN LECTURE 6

Proof by chase

- In $R(A, B, C, D)$, does $A \twoheadrightarrow B$ and $B \twoheadrightarrow C$ imply that $A \twoheadrightarrow C$?

Have:	A	B	C	D
	a	b_1	c_1	d_1
	a	b_2	c_2	d_2
$A \twoheadrightarrow B$	a	b_2	c_1	d_1
	a	b_1	c_2	d_2
$B \twoheadrightarrow C$	a	b_2	c_1	d_2
	a	b_2	c_2	d_1
$B \twoheadrightarrow C$	a	b_1	c_2	d_1
	a	b_1	c_1	d_2

Need:	A	B	C	D	
	a	b_1	c_2	d_1	✌
	a	b_2	c_1	d_2	✌

Another proof by chase

- In $R(A, B, C, D)$, does $A \rightarrow B$ and $B \rightarrow C$ imply that $A \rightarrow C$?

Have:

A	B	C	D
a	b_1	c_1	d_1
a	b_2	c_2	d_2

Need:

$c_1 = c_2$ ✌

$A \rightarrow B$ $\quad b_1 = b_2$

$B \rightarrow C$ $\quad c_1 = c_2$

In general, with both MVD's and FD's, chase can generate both new tuples and new equalities

Counterexample by chase

- In $R(A, B, C, D)$, does $A \twoheadrightarrow BC$ and $CD \rightarrow B$ imply that $A \rightarrow B$?

Have:

A	B	C	D
a	b_1	c_1	d_1
a	b_2	c_2	d_2

$A \twoheadrightarrow BC$

a	b_2	c_2	d_1
a	b_1	c_1	d_2

Need:

$b_1 = b_2$ 👎

Counterexample!

4NF

- A relation R is in Fourth Normal Form (4NF) if
  - For every non-trivial MVD $X \twoheadrightarrow Y$ in R, X is a superkey
  - That is, all FD's and MVD's follow from "key $\rightarrow$ other attributes" (i.e., no MVD's and no FD's besides key functional dependencies)

- 4NF is stronger than BCNF
  - Because every FD is also a MVD

4NF decomposition algorithm

- Find a 4NF violation
  - A non-trivial MVD $X \twoheadrightarrow Y$ in R where X is not a superkey
- 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 R attributes not in X or Y)
- Repeat until all relations are in 4NF

- Almost identical to BCNF decomposition algorithm
- Any decomposition on a 4NF violation is lossless

4NF decomposition example

uid	*gid*	*place*
142	dps	Springfield
142	dps	Australia
456	abc	Springfield
456	abc	Morocco
456	gov	Springfield
456	gov	Morocco
…	…	…

User (*uid*, *gid*, *place*)

4NF violation: $uid \twoheadrightarrow gid$

Member (*uid*, *gid*)

4NF

uid	*gid*
142	dps
456	abc
456	gov
…	…

Visited (*uid*, *place*)

4NF

uid	*place*
142	Springfield
142	Australia
456	Springfield
456	Morocco
…	…

Other kinds of dependencies and normal forms

- Dependency preserving decompositions
- Join dependencies
- Inclusion dependencies
- 5NF, 3NF, 2NF
- See book if interested (not covered in class)

Summary

- Philosophy behind BCNF, 4NF:
  Data should depend on the key,
  the whole key,
  and nothing but the key!
  - You could have multiple keys though
- Redundancy is not desired typically
  - not always, mainly due to performance reasons
- Functional/multivalued dependencies – capture redundancy
- Decompositions – eliminate dependencies
- Normal forms
  - Guarantees certain non-redundancy
  - BCNF, and 4NF
- Lossless join
- How to decompose into BCNF, 4NF
- Chase