CompSci 516
Database Systems

Lecture 7
Design Theory and Normalization

Instructor: Sudeepa Roy

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Announcements (Thurs, 1/27)

- HW1 due next week 2/1 (Tues)
  - Please check out posts on Ed with updates and instructions
- Project proposal due next week 2/3 (Thurs)
  - 13 standard, 6 semi-standard, 2 open
  - consider semi-standard and open projects!
- Quiz-1 posted on Gradescope – due 2/8 (Tues)
  - Two problems only, autograded, submit as many times as you want
  - Use RATest https://ratest.cs.duke.edu/ratest/ to debug (last two problems)
  - Will demonstrate during lectures
- More quizzes will be posted soon – instructions to be posted to use "Gradiance" for online quiz
  - Will help prepare for the exam - do them early!
- If there are in-class quiz/labs, will be announced in the previous class
- No late days for quiz (gradiance closes automatically)

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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)

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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

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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

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Example

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

- key = SSN

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Example

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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?

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Why is redundancy bad? 1/4

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
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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

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Why is redundancy bad? 2/4

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 → 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

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Why is redundancy bad? 3/4

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
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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

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Why is redundancy bad? 4/4

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 to 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

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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

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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)
- Solution?

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

rating	hourly_wage
8	10
5	7

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More 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: $\bowtie$

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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!)

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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

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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 $R \subset S \bowtie T$

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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
…	…

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Functional Dependencies (FDs)

- A functional dependency (FD) X → 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 a (possible) FD here?

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

What is a (possible) FD here?

AB → C

Note that, AB is not a key

not a correct question though.. see next slide!

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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 → R
  - denoting R = all attributes of R too
  - However, S → R does not require S to be minimal
  - e.g., S can be a superkey

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Example

- Consider relation obtained from Hourly_Emps:
  - Hourly_Emps (<u>ssn</u>, name, lot, rating, hourly_wage, hours_worked)
- Use first letter of attributes for simplicity: SNLRWH
  - Basically the set of attributes {S,N,L,R,W,H}
- FDs on Hourly_Emps:
  - ssn is the key: S → SNLRWH
  - rating determines hourly_wages: R → W

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Intuitive – read yourself

Armstrong's Axioms

- X, Y, Z are sets of attributes
- Reflexivity: If X ⊇ Y, then X → Y
- Augmentation: If X → Y, then XZ → YZ for any Z
- Transitivity: If X → Y and Y → Z, then X → 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 → C and check

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Additional Rules

Intuitive – read yourself

- Follow from Armstrong's Axioms
- Union: If X → Y and X → Z, then X → YZ
- Decomposition: If X → YZ, then X → Y and X → Z

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

A → B, A → C
A → BC

A → BC
A → B, A → C

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Computing Attribute Closure

Algorithm:
- closure = X
- Repeat until no change
  - if there is an FD U → V in F such that U ⊆ closure, then closure = closure ∪ V
- Does F = {A → B, B → C, C D → E } imply A → E?
  - i.e, is A → E in the closure F^+? Equivalently, is E in A^+?

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Computing FD Closure

- 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 a given FD *X* → *Y* is in the closure of a set of FDs *F*
  - No need to compute F^+
  - Compute attribute closure of X (denoted X^+) wrt *F:*
  - Check if Y is in X^+

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Detour - RATest

- https://ratest.cs.duke.edu/ratest/
- Requires net-id
- Quiz problems (i) & (j)

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Normal Forms

- 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)
- 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

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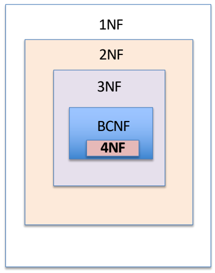
Normal Forms



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

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Boyce-Codd Normal Form (BCNF)

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

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

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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!

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BCNF decomposition example - 1

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

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BCNF decomposition example - 2

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

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Check yourself

BCNF decomposition example - 3

- 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?
  - No
- 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)

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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
…	…	…

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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 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
…	…	…

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MVD examples

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

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

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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!?

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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

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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	✌

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Another proof by chase

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

Have:

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

Need: $c_1 = c_2$

$A \to B$ $b_1 = b_2$

$B \to C$ $c_1 = c_2$

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

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Counterexample by chase

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

Have:

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

$A \twoheadrightarrow BC$ (last two rows)

Need: $b_1 = b_2$

Counterexample!

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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 → 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

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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

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4NF decomposition example

User (*uid*, *gid*, *place*)
4NF violation: *uid* ↠ *gid*

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

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
...	...

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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)

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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

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