Relational Database Design Theory

Introduction to Databases

CompSci 316 Fall 2019

DUKE
COMPUTER SCIENCE

Announcements (Mon. Sep. 9)

- Gradiance ER due this Wednesday
- Gradiance FD and MVD assigned
- Homework 1 due next Monday (11:59pm)
  - RA debugger for Problem 1 available at `https://ratest.cs.duke.edu/`
- Course project description posted
  - Read it!
  - "Mixer" in a week and a half
  - Milestone 1 right after fall break
  - Teamwork required: 5 people per team on average

Motivation

uid	*uname*	*gid*
142	Bart	dps
123	Milhouse	gov
857	Lisa	abc
857	Lisa	gov
456	Ralph	abc
456	Ralph	gov
…	…	…

- Why is *UserGroup* (*uid*, *uname*, *gid*) a bad design?
  -
    - Leads to ______________________________ anomalies
- Wouldn't it be nice to have 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 in Y

X	Y	Z
a	b	c
a	b	?
…	…	…

Must be b

Could be anything

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 ⊇ RHS
- *zip* → *state*, *zip*?
  - This is non-trivial, but not completely non-trivial
  - Completely non-trivial FD: LHS ∩ RHS = ∅

Redefining "keys" 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 $\{A_1, A_2, \ldots\}$ functionally determined by Z (that is, $Z \rightarrow A_1 A_2 \ldots$)
- 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 new attributes can be added

A more complex example

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

Assume that there is a 1-1 correspondence between our users and Twitter accounts

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

Not a good design, and we will see why shortly

Example of computing closure

$\mathcal{F}$ includes:

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

- $\{gid, twitterid\}^+$ = ?
- *twitterid* → *uid*
  - Add *uid*
  - Closure grows to { *gid*, *twitterid*, *uid* }
- *uid* → *uname*, *twitterid*
  - Add *uname*, *twitterid*
  - Closure grows to { *gid*, *twitterid*, *uid*, *uname* }
- *uid*, *gid* → *fromDate*
  - Add *fromDate*
  - Closure is now all attributes in *UserJoinsGroup*

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 $X \rightarrow Y$ follows 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?)

Rules of FD's

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

☞Using these rules, you can prove or disprove an FD given a set of FDs

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
…	…	…

That a should be mapped to b is recorded multiple times: redundancy, update/insertion/deletion anomaly

Example of redundancy

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

- *uid* → *uname*, *twitterid*

(… plus other FD's)

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
…	…	…	…	…

Decomposition

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
…	…	…	…	…

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:

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
…	…

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
…	…

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 $R = S \bowtie T$

- 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
…	…

Questions about decomposition

- When to decompose
- How to come up with a correct decomposition (i.e., lossless join decomposition)

An answer: BCNF

- A relation R is in Boyce-Codd Normal Form if
  - For every non-trivial FD $X \to Y$ 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 (details next)

  ☞Then it is guaranteed to be a lossless join 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

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

Another example

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

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

BCNF violation: *twitterid → uid*

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

Why is BCNF decomposition lossless

Given non-trivial $X \to Y$ in R where X is not a super key of R, need to prove:

- Anything we project always comes back in the join:

$$R \subseteq \pi_{XY}(R) \bowtie \pi_{XZ}(R)$$

  - Sure; and it doesn't depend on the FD
- Anything that comes back in the join must be in the original relation:

$$R \supseteq \pi_{XY}(R) \bowtie \pi_{XZ}(R)$$

  - Proof will make use of the fact that $X \to Y$

Recap

- Functional dependencies: a generalization of the key concept
- Non-key functional dependencies: a source of redundancy
- BCNF decomposition: a method for removing redundancies
  - BNCF 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?
  - BCNF?
  - Redundancies?

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

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 $X \twoheadrightarrow Y$

Try proving things using these!?

- Coalescence:
  If $X \twoheadrightarrow Y$ and $Z \subseteq Y$ and there is some W disjoint from Y such that $W \rightarrow Z$, then $X \rightarrow Z$

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

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: $c_1 = c_2$ ✌

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

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

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	b_2	c_2	d_1
a	b_1	c_1	d_2

$A \twoheadrightarrow BC$

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 → 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* ↠ *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
…	…

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
- Other normal forms
  - 3NF: More relaxed than BCNF; will not remove redundancy if doing so makes FDs harder to enforce
  - 2NF: Slightly more relaxed than 3NF
  - 1NF: All column values must be atomic