Schema Refinement and Normal Forms

Chapter 19

Quiz #2 Next Wednesday

The Evils of Redundancy

- *Redundancy* is at the root of several problems associated with relational schemas:
  - redundant storage, insert/delete/update anomalies
- Integrity constraints, in particular *functional dependencies*, can be used to identify schemas with such problems and to suggest refinements.
- Main refinement technique: *decomposition* (replacing ABCD with, say, AB and BCD, or ACD and ABD).
- Decomposition should be used judiciously:
  - Is there reason to decompose a relation?
  - What problems (if any) does the decomposition cause?

Functional Dependencies (FDs)

- A <u>functional dependency</u> $X \rightarrow Y$ holds over relation R if, for every allowable instance *r* of R:
  - $t_1 \in r,\ \ t_2 \in r,\ \pi_X(t_1) = \pi_X(t_2)$ implies $\pi_Y(t_1) = \pi_Y(t_2)$
  - 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.)
- An FD is a statement about *all* allowable relations.
  - Must be identified based on semantics of application.
  - Given some allowable instance r_1 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 $K \rightarrow R$
  - However, $K \rightarrow R$ does not require K to be *minimal*!

Example: Constraints on Entity Set

- Consider relation obtained from Hourly_Emps:

  Hourly_Emps (*<u>ssn</u>, name, lot, rating, hrly_wages, hrs_worked*)

- *Notation*: We will denote this relation schema by listing the attributes as a single letter: SNLRWH
  - This is really the *set* of attributes {S,N,L,R,W,H}.
  - Sometimes, we will refer to all attributes of a relation by using the relation name. (e.g., Hourly_Emps for SNLRWH)
- Some FDs on Hourly_Emps:
  - *ssn* is the key: $S \rightarrow SNLRWH$
  - *rating* determines *hrly_wages*: $R \rightarrow W$

Example (Contd.)

- Problems due to R → W :
  - *Update anomaly*: Can we change W in just the 1st tuple of SNLRWH?
  - *Insertion anomaly*: What if we want to insert an employee and don't know the hourly wage for his rating?
  - *Deletion anomaly*: If we delete all employees with rating 5, we lose the information about the wage for rating 5!

Will 2 smaller tables be better?

Hourly_Emps

S	N	L	R	W	H
123-22-3666	Attishoo	48	8	10	40
231-31-5368	Smiley	22	8	10	30
131-24-3650	Smethurst	35	5	7	30
434-26-3751	Guldu	35	5	7	32
612-67-4134	Madayan	35	8	10	40

Hourly_Emps2

S	N	L	R	H
123-22-3666	Attishoo	48	8	40
231-31-5368	Smiley	22	8	30
131-24-3650	Smethurst	35	5	30
434-26-3751	Guldu	35	5	32
612-67-4134	Madayan	35	8	40

Wages

R	W
8	10
5	7

Reasoning About FDs

- Given some FDs, we can usually infer additional FDs:
  - *ssn* → *did*, *did* → *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*.
- Armstrong's Axioms (X, Y, Z are sets of attributes):
  - *Reflexivity*: If $X \subseteq Y$, then $Y \rightarrow X$
  - *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*: they will generate only FDs in F^+
  - *complete*: repeated applications will generate all FDs in F^+

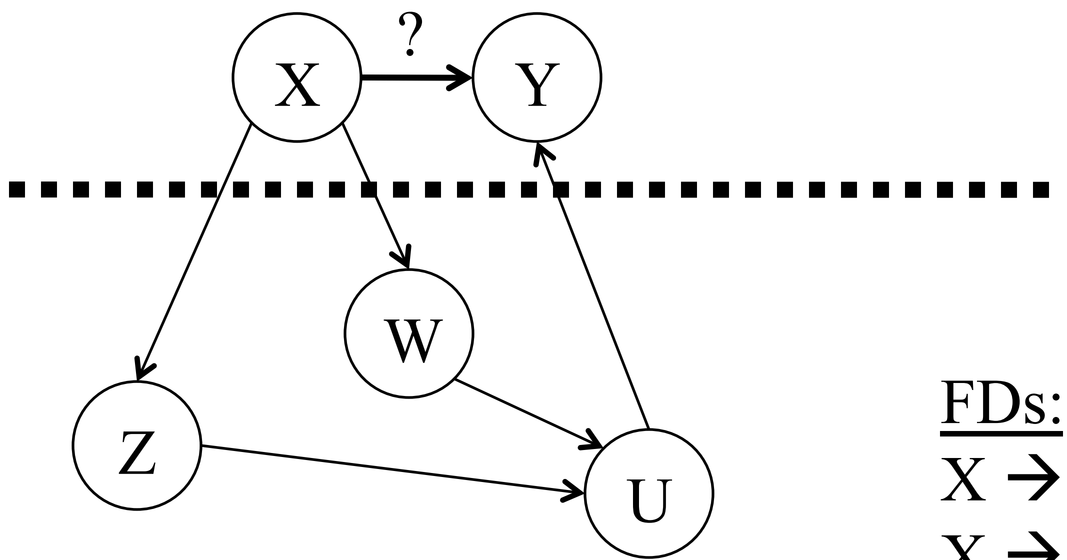
Reasoning About FDs (Contd.)

- Couple of additional rules (that follow from AA):
  - *Union*: If X → Y and X → Z, then X → YZ
  - *Decomposition*: If X → YZ, then X → Y and X → Z
- Example: Contracts(*cid,sid,jid,did,pid,qty,value*), and:
  - C is the key: C → CSJDPQV
  - Projects purchase each part using single contract: JP → C
  - Dept purchase at most one part from a supplier: SD → P
- JP → C, C → CSJDPQV imply JP → CSJDPQV
- SD → P implies SDJ → JP
- SDJ → JP, JP →CSJDPQV imply SDJ → CSJDPQV

Reasoning About FDs (Contd.)

- Computing the closure of a set of FDs can be expensive. (Size of closure is exponential in # attrs!)
- Typically, we just want to check if a given FD $X \rightarrow Y$ is in the closure of a set of FDs F. An efficient check:
  - Compute *attribute closure* of X (denoted X^+) wrt F:
    - Set of all attributes A such that $X \rightarrow A$ is in F^+
    - There is a linear time algorithm to compute this.
  - Check if Y is in X^+

Example Check



<u>FDs:</u>

$X \rightarrow W$

$X \rightarrow Z$

$WZ \rightarrow U$

$U \rightarrow Y$

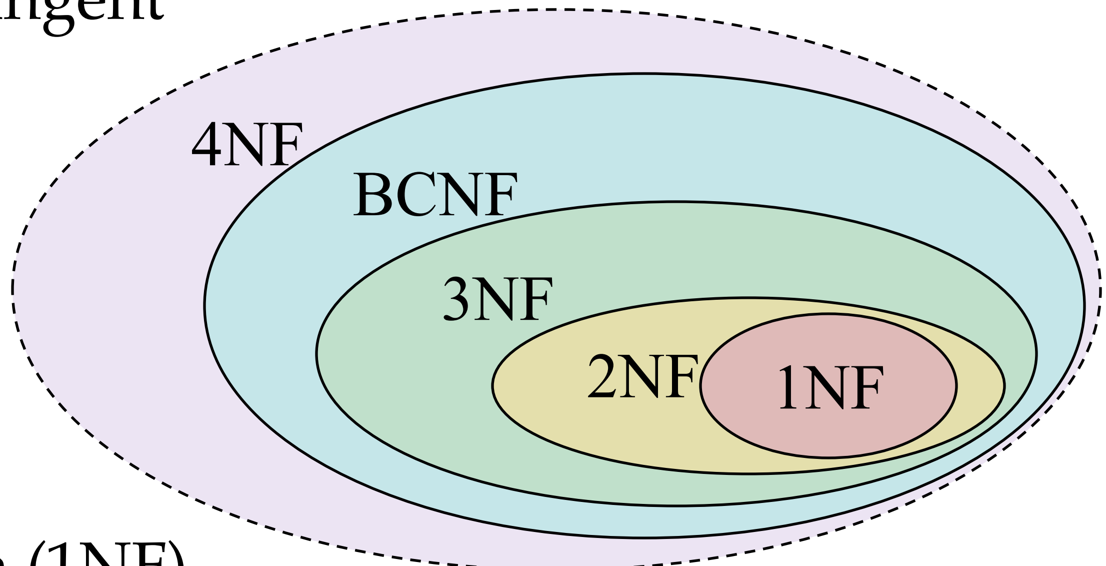
- Does $F = \{A \rightarrow B,\ B \rightarrow C,\ C\,D \rightarrow E\}$ imply $A \rightarrow E$?
  - i.e, is $A \rightarrow E$ in the closure F^+? Equivalently, is E in A^+?

Normal Forms

- To eliminate redundancy and potential update anomalies, one can identify generic templates called "normal forms"
- If a relation is in a certain *normal form* (BCNF, 3NF etc.), it is known that certain kinds of problems are avoided/minimized. This can be used to help us decide whether decomposing the relation will help.
- Role of FDs in detecting redundancy:
  - Consider a relation R with 3 attributes, ABC.
    - No FDs hold: There is no redundancy here.
    - Given A → B: Several tuples could have the same A value, and if so, they'll all have the same B value!

Normal Form Hierarchy

- An increasingly stringent hierarchy of "Normal Forms"
- Each outer form trivially satisfies the requirements of inner forms



- The 1st normal form (1NF) is part of the definition of the relational model. Relations must be sets (unique) and all attributes atomic (not multiple fields or variable length records).
- The 2nd normal form (2NF) requires schemas not have any FD, $X \rightarrow Y$, where X as a strict subset of the schema's key.

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.
- In other words, R is in BCNF if the only non-trivial FDs that hold over R are key constraints.
- BCNF considers all domain keys, not just the primary one
- BCNF schemas do not contain redundant information that arise from FDs

BCNF Examples

- In BCNF

  Person(First, Last, Address, Phone)

  Functional Dependencies: FL $\rightarrow$ A, FL $\rightarrow$ P

- Not in BCNF

  Person(First, Last, Address, Phone, Hobby)

  Functional Dependencies: FL $\rightarrow$ A, FL $\rightarrow$ P

Third Normal Form (3NF)

- Reln R with FDs *F* is in 3NF if, for all X $\rightarrow$ A in F^+
  - A $\in$ X (called a *trivial* FD), or
  - X contains a key for R, or
  - A is part of some key for R.
- *Minimality* of a key is crucial in third condition above!
- If R is in BCNF, it is trivially in 3NF.
- If R is in 3NF, some redundancy is possible. It is a compromise, used when BCNF not achievable (e.g., no "good" decomp, or performance considerations).
  - *Lossless-join, dependency-preserving decomposition of R into a collection of 3NF relations always possible.*

3NF Examples

- Phonebook where friends have multiple addresses
- In 3NF, not in BCNF

  Person(First, Last, Addr, Phone)

  Functional Dependencies:

  FLA $\rightarrow$ P, P $\rightarrow$ A

- Not in 3NF or BCNF

  Person(First, Last, Addr, Phone, Mobile)

  Functional Dependencies:

  FLA $\rightarrow$ P, P $\rightarrow$ A, FL $\rightarrow$ M

What Does 3NF Achieve?

- If 3NF is violated by X → A, one of the following holds:
  - X is a proper subset of some key K (partial dependency)
    - We store (X, A) pairs redundantly.
  - X is not a proper subset of any key (transitive dependency).
    - There is a chain of FDs K → X → A, which means that we cannot associate an X value with a K value unless we also associate an A value with an X value.
- But, even if relation is in 3NF, problems can arise.

Lingering 3NF Redundancies

- Revisiting an old Schema

  Reserves(Sailor, Boat, Date, CreditCardNo)

  FDs: C→S

- In 3NF, but database likely stores many redundant copies of the (C, S) tuple
- Thus, 3NF is indeed a compromise relative to BCNF.

Decomposition of a Relation Scheme

- Suppose that relation R contains attributes *A1 … An*. A *decomposition* of R consists of replacing R by two or more relations such that:
  - Each new relation scheme contains a subset of the attributes of R (and no attributes that do not appear in R), and
  - Every attribute of R appears as an attribute of one of the new relations.
- Intuitively, decomposing R means we will store instances of the relation schemes produced by the decomposition, instead of instances of R.
- E.g., Can decompose SNLRWH into SNLRH and RW.

Example Decomposition

- Decompositions should be used only when needed.
  - SNLRWH has FDs S → SNLRWH and R → W
  - Second FD causes violation of 3NF; W values repeatedly associated with R values. Easiest way to fix this is to create a relation RW to store these associations, and to remove W from the main schema:
    - i.e., we decompose SNLRWH into SNLRH and RW
- The information to be stored consists of SNLRWH tuples. If we just store the projections of these tuples onto SNLRH and RW, are there any potential problems that we should be aware of?

Problems with Decompositions

- There are three potential problems to consider:
  - Problem 1) Some queries become more expensive.
    - e.g., How much did sailor Joe earn? (salary = W*H)
  - Problem 2) Given instances of the decomposed relations, we may not be able to reconstruct the corresponding original relation!
    - Fortunately, not in the SNLRWH example.
  - Problem 3) Checking some dependencies may require joining the instances of the decomposed relations.
    - Fortunately, not in the SNLRWH example.
- *Tradeoff*: Must consider these issues vs. redundancy.

Lossless Join Decompositions

- Decomposition of R into X and Y is *lossless-join* w.r.t. a set of FDs F if, for every instance *r* that satisfies F:
  - $\pi_X(r) \bowtie \pi_Y(r) = r$
- It is always true that $r \subseteq \pi_X(r) \bowtie \pi_Y(r)$
  - In general, the other direction does not hold! If equal, the decomposition is lossless-join.
- Definition extended to decomposition into 3 or more relations in a straightforward way.
- *It is essential that all decompositions used to eliminate redundancy be lossless! (Avoids Problem 2)*

More on Lossless Join

- The decomposition of R into X and Y is lossless-join wrt F if and only if the closure of F contains:
  - $X \cap Y \rightarrow X$, or
  - $X \cap Y \rightarrow Y$

  (in other words the attributes common to X and Y must contain a key for either X or Y)
- In particular, the decomposition of R into UV and R - V is lossless-join if $U \rightarrow V$ holds over R.

ABC ⇒ AB, BC

A	B	C
1	2	3
4	5	6
7	2	8

A	B
1	2
4	5
7	2

$\bowtie$

B	C
2	3
5	6
2	8

A	B	C
1	2	3
4	5	6
7	2	8
1	2	8
7	2	3

Not lossless

More on Lossless Join

- The decomposition of R into X and Y is lossless-join wrt F if and only if the closure of F contains:
  - $X \cap Y \rightarrow X$, or
  - $X \cap Y \rightarrow Y$

  (in other words the attributes common to X and Y must contain a key for either X or Y)
- In particular, the decomposition of R into UV and R - V is lossless-join if $U \rightarrow V$ holds over R.

$ABC \Rightarrow AB, AC$

A	B	C
1	2	3
4	5	6
7	2	8

A	B
1	2
4	5
7	2

$\bowtie$

A	C
1	3
4	6
7	8

A	B	C
1	2	3
4	5	6
7	2	8

Lossless

Dependency Preserving Decomposition

Contracts(*Cid,Sid,Jid,Did,Pid,Qty,Value*)

- Consider CSJDPQV, C is key, JP → C and SD → P.
  - BCNF decomposition: CSJDQV and SDP
  - Problem: Checking JP → C requires a join!
- Dependency preserving decomposition (Intuitive):
  - If R is decomposed into X, Y and Z, and we enforce the FDs that hold on X, on Y and on Z, then all FDs that were given to hold on R must also hold. *(Avoids Problem 3)*
- *Projection of set of FDs F*: If R is decomposed into X, ... projection of F onto X (denoted F_X) is the set of FDs U → V in F^+ (*closure of F*) such that U, V are in X.

Dependency Preserving Decomposition

- Decomposition of R into X Y is *dependency preserving* if $(F_X \text{ union } F_Y)^+ = F^+$
  - i.e., if we consider only dependencies in the closure F^+ that can be checked in X without considering Y, and in Y without considering X, these imply all dependencies in F^+.
- MUST consider F^+, (not just F), in this definition:
  - ABC, $A \rightarrow B$, $B \rightarrow C$, $C \rightarrow A$, decomposed into AB and BC.
  - Is this dependency preserving? Is $C \rightarrow A$ preserved?????
- Dependency preserving *does not imply* lossless join:
  - ABC, $A \rightarrow B$, decomposed into AB and BC.
- And vice-versa!

Decomposition into BCNF

- Consider relation R with FDs F.

  If X → Y violates BCNF,

  decompose R into R - Y and XY.

  - Repeated applications of this rule gives relations in BCNF; lossless join decomposition, and is guaranteed to terminate.

- Example: CSJDPQV, SD → P, J → S (new),

  (ignoring JP → C for now)

  - To deal with SD → P, decompose into SDP, CSJDQV.
  - To deal with J → S, decompose CSJDQV into JS and CJDQV

- The order in which we "deal with" violations could lead to a different set of relations!

BCNF and Dependency Preservation

- In general, there may not be a dependency preserving decomposition into BCNF.
  - e.g., CSZ, CS → Z, Z → C
  - Can't decompose while preserving 1st FD; not in BCNF.
- Similarly, decomposition of CSJDQV into SDP, JS and CJDQV is not dependency preserving (w.r.t. the FDs: JP → C, SD → P and J → S).
  - However, it is a lossless join decomposition.
  - In this case, adding CJP to the collection of relations gives us a dependency preserving decomposition.
    - JPC tuples stored only for checking FD! (*Adds Redundancy!*)

Decomposition into 3NF

- Obviously, the algorithm for lossless join decomp into BCNF can be used to obtain a lossless join decomp into 3NF (typically, it can stop earlier).
- To ensure dependency preservation, one idea:
  - If $X \rightarrow Y$ is not preserved, add relation XY.
  - Problem is that XY may violate 3NF! e.g., consider the addition of CJP to "preserve" $JP \rightarrow C$. What if we also have $J \rightarrow C$?
- Refinement: Instead of the given set of FDs F, use a *minimal cover for F*.

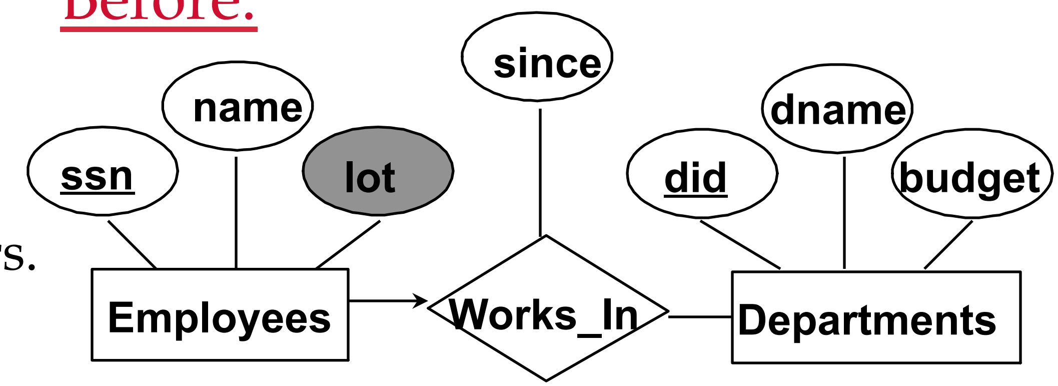
Minimal Cover for a Set of FDs

- Properties of a *Minimal cover*, G, for a set of FDs F:
  - Closure of F = closure of G.
  - Right hand side of each FD in G is a single attribute.
  - If we modify G by deleting an FD or by deleting attributes from an FD in G, the closure changes.
- Intuitively, every FD in G is needed, and is "*as small as possible*" in order to get the same closure as F.
- e.g., A → B, ABCD → E, EF → GH, ACDF → EG has the following minimal cover:
  - A → B, ACD → E, EF → G and EF → H
- M.C. → Lossless-Join, Dep. Pres. Decomp!!! (in book)

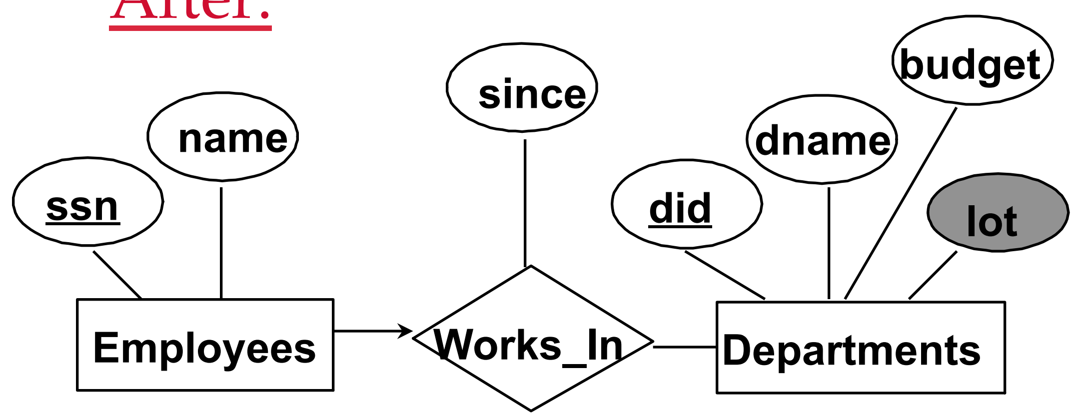
Refining an ER Diagram

- 1st diagram translated:
  Workers(S,N,L,D,S)
  Departments(D,M,B)
  - Lots associated with workers.
- Suppose all workers in a dept are assigned the same lot: D → L
- Redundancy; fixed by:
  Workers2(S,N,D,S)
  Dept_Lots(D,L)
- Can fine-tune this:
  Workers2(S,N,D,S)
  Departments(D,M,B,L)

Before:



After:



Summary of Schema Refinement

- If a relation is in BCNF, it is free of redundancies that can be detected using FDs. Thus, trying to ensure that all relations are in BCNF is a good heuristic.
- If a relation is not in BCNF, we can try to decompose it into a collection of BCNF relations.
  - Must consider whether all FDs are preserved. If a lossless-join, dependency preserving decomposition into BCNF is not possible (or unsuitable, given typical queries), should consider decomposition into 3NF.
  - Decompositions should be carried out and/or re-examined while keeping *performance requirements* in mind.