Schema Refinement and Normal Forms

Chapter 19

PS4 posted, Midterm #2 Postponed until 11/11

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→ Y holds over relation R if, for every allowable instance *r* of R:
  - for all $t_1 \in r$, $t_2 \in r$, $\pi_X(t_1) = \pi_X(t_2)$ implies $\pi_Y(t_1) = \pi_Y(t_2)$
  - i.e., given two tuples in *r*, if the X values match, then the Y values must also match. (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 → R
  - However, K → R does not require K to be *minimal*!

Example: Constraints on Entity Set

- Consider relation obtained from Hourly_Emps:

  Hourly_Emps (*ssn*, *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 → SNLRWH
  - *rating* determines *hrly_wages*: R → 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:
  - *zip* → *state*, *state* → *senator* implies *zip* → *senator*
- 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 → X
  - *Augmentation*: If X → Y, then XZ → YZ for any Z
  - *Transitivity*: If X → Y and Y → Z, then X → 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(*<u>cid</u>,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^+

Algorithm for test if FD is in F^+

- Given X → Y

  closure = X;

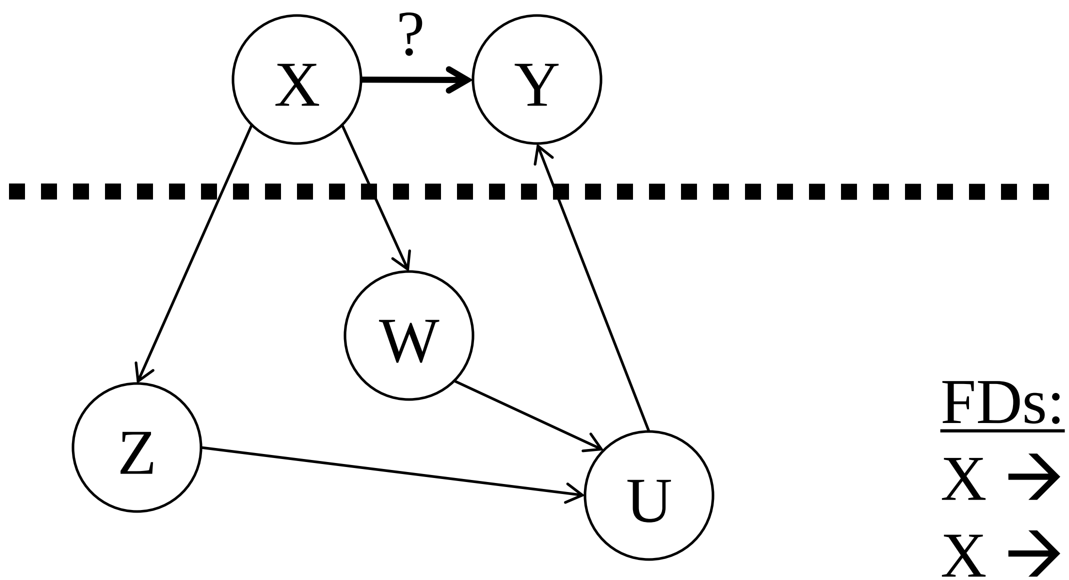
  repeat {

      if there is an FD U→ in F such that U ⊆ closure:

          closure = closure ∪ V

  } until closure does not change
- Consider X → Y as a graph with X and Y as nodes and a directed edge from X to Y.
- Traverse the set of *given* FDs to extend all existing paths
- When the path can be extended no farther determine if there is a path from X→ Y

Example Check



FDs:
X → W
X → Z
WZ → U
U → Y

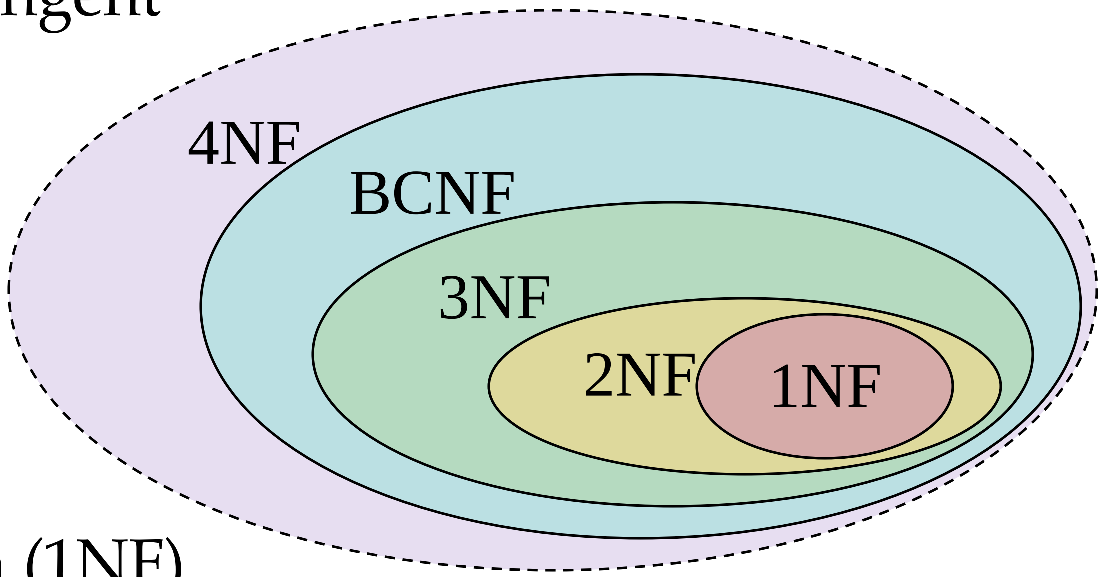
- Does F = {A → B, B → C, C D → E } imply A → E?
  - i.e, is A → E in the closure F^+? Equivalently, is E in A^+?

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* (Boyce-Codd Normal Form (BCNF), third normal form (3NF) etc.), it is known that certain kinds of redundancy 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

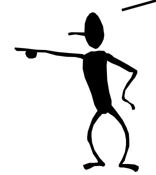
- An increasingly stringent hierarchy of "Normal Forms"
- Each outer form trivially satisfies the requirements of inner forms



- 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 → 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.



Includes silly FDs like:
(city, state) → state

- 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 → A, FL → P

- Not in BCNF

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

  An attempt to allow a person to have multiple emails.
  Functional Dependencies: FL → A, FL → P

Third Normal Form (3NF)

- Reln R with FDs *F* is in 3NF if, for all X → A in F^+
  - A ∈ 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).

3NF Examples

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

  Person(First, Last, Addr, Phone)

  Functional Dependencies:

  FLA → P, P → A

- Not in 3NF or BCNF

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

  Functional Dependencies:

  FLA → P, P → A, FL → 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: SBD→SBDC, 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 $\rightarrow$ SNLRWH and R $\rightarrow$ W
  - Second FD violates 3NF
    (R is not a key, W is not part of a key)
  - Redundancy: W values repeatedly associated with R values.
  - Easiest fix; 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
- Given SNLRWH tuples, we just store the projections 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 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 ∩ Y → X, or
  - X ∩ Y → 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 → 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

⋈

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 ∩ Y → X, or
  - X ∩ Y → 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 → V holds over R.

ABC ⇒ AB, AC

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

A	B
1	2
4	5
7	2

⋈

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 $\rightarrow$ C and SD $\rightarrow$ P.
  - BCNF decomposition: CSJDQV and SDP
  - Problem: Checking JP $\rightarrow$ 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 on slide 21)*
- *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 $\rightarrow$ V in F^+ (*closure of F*) such that U, V are in X.

Dependency Preserving Decomposition

- Decomposition of R into X and Y is *dependency preserving* if $(F_X \cup F_Y)^+ = F^+$
  - 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 → B, B → C, C → A, decomposed into AB and BC.
  - Is this dependency preserving? Is C → A preserved?????
- Dependency preserving *does not imply* lossless join:
  - ABC, A → 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 process violations can 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 <u>JP</u>C 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 → Y is not preserved, add relation XY.
  - Problem is that XY may violate 3NF! e.g., consider the addition of CJP to "preserve" JP → C. What if we also have J → C ?
- Refinement: Instead of the given set of FDs F, use a *minimal cover for F*.

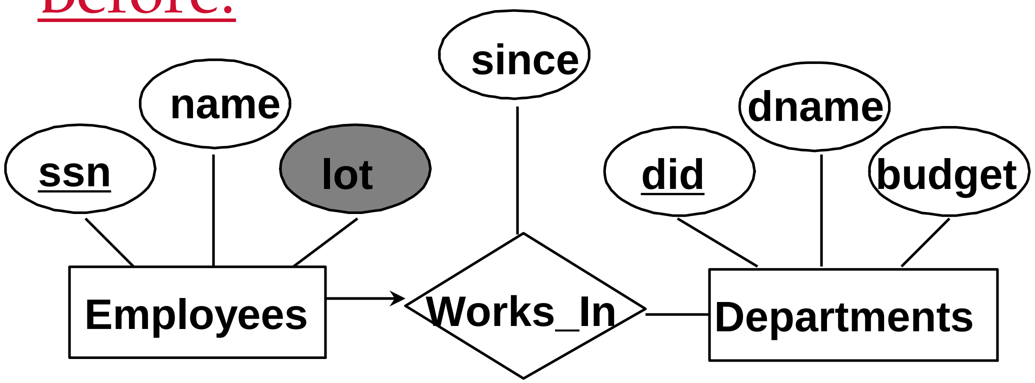
Minimal Cover for a Set of FDs

- 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 a 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!!!

Refining an Entities and Relations

- 1st diagram translated:
  EmpWorksIn(<u>S</u>,N,L,D,C)
  Dept(<u>D</u>,M,B)
  - Lots associated with workers.
- Suppose all workers in a dept are assigned the same lot: D → L
- And Employees start their new lot at a given date: SL→C
- Redundancy is fixed by:
  Emp(<u>S</u>,N)
  WorksIn(<u>S</u>,<u>L</u>,<u>D</u>,C) (note 3NF)
  Dept(<u>D</u>,M,B)
- Enforcement of FD: D → L is supported by
  DeptLot(<u>D</u>,<u>L</u>)

Before:



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.