CS411
Database Systems

05: Relational Schema Design

Why Do We Learn This?

Motivation

- We have designed ER diagram, and translated it into a relational db schema R = set of R1, R2, ...
- Now what?
- We can do the following
  - specify all relevant constraints over R
  - implement R in SQL
  - start using it, making sure the constraints always remain valid
- However, R may not be well-designed, thus causing us a lot of problems

Q: This a good design?

Persons with several phones:

Address	SSN	Phone Number
10 Green	123-321-99	(201) 555-1234
10 Green	123-321-99	(206) 572-4312
431 Purple	909-438-44	(908) 464-0028
431 Purple	909-438-44	(212) 555-4000

Potential Problems

- Redundancy
- Update anomalies
- Deletion anomalies

How do We Obtain a Good Design?

- Start with the original db schema R
- Transform it until we get a good design R*
- Desirable properties for R*
  - must preserve the information of R
  - must have minimal amount of redundancy
  - must be dependency-preserving
    - if R is associated with a set of constraints C, then it should be easy to also check C over R*
  - (must also give good query performance)

OK, But ...

- How do we recognize a good design R*?
- How do we transform R into R*?
- What we need is the “theory” of …

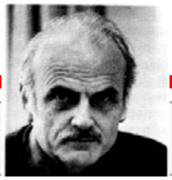
Normal Forms

- DB gurus have developed many normal forms
- Most important ones
  - Boyce-Codd, 3rd, and 4th normal forms
- If R* is in one of these forms, then R* is guaranteed to achieve certain good properties
  - e.g., if R* is in Boyce-Codd NF, it is guaranteed to not have certain types of redundancy
- DB gurus have also developed algorithms to transform R into R* that is in some of these normal forms

Normal Forms (cont.)

- DB gurus have also discussed trade-offs among normal forms
- Thus, all we have to do is
  - learn these forms
  - transform R into R* in one of these forms
  - carefully evaluate the trade-offs
- Many of these normal forms are defined based on various constraints
  - functional dependencies and keys

Behind the Scene: Know whom we should blame?



Normal form	Defined by	Brief definition
First normal form (1NF)	Two versions: E.F. Codd (1970), C.J. Date (2003)[12]	Table faithfully represents a relation and has no "repeating groups"
Second normal form (2NF)	E.F. Codd (1971)[13]	No non-prime attribute in the table is functionally dependent on a part (proper subset) of a candidate key
Third normal form (3NF)	E.F. Codd (1971)[14]; see also Carlo Zaniolo's equivalent but differently-expressed definition (1982)[15]	Every non-prime attribute is non-transitively dependent on every key of the table
Boyce-Codd normal form (BCNF)	Raymond F. Boyce and E.F. Codd (1974)[16]	Every non-trivial functional dependency in the table is a dependency on a superkey
Fourth normal form (4NF)	Ronald Fagin (1977)[17]	Every non-trivial multivalued dependency in the table is a dependency on a superkey
Fifth normal form (5NF)	Ronald Fagin (1979)[18]	Every non-trivial join dependency in the table is implied by the superkeys of the table
Domain/key normal form (DKNF)	Ronald Fagin (1981)[19]	Every constraint on the table is a logical consequence of the table's domain constraints and key constraints
Sixth normal form (6NF)	Chris Date, Hugh Darwen, and Nikos Lorentzos (2002)[20]	Table features no non-trivial join dependencies at all (with reference to generalized join operator)

Our Attack Plan

- Motivation
- Functional dependencies & keys
- Reasoning with FDs and keys
- Desirable properties of schema refinement
- Various normal forms and the trade-offs
  - BCNF, 3rd normal form, 4th normal form, etc.
- Putting all together: how to design DB schema

Functional Dependencies and Keys

Better Designs Exist

Break the relation into two:

SSN	Address
123-321-99	10 Green
909-438-44	431 Purple

SSN	Phone Number
123-321-99	(201) 555-1234
123-321-99	(206) 572-4312
909-438-44	(908) 464-0028
909-438-44	(212) 555-4000

Functional Dependencies

- A form of constraint (hence, part of the schema)
- Finding them is part of the database design
- Used heavily in schema refinement

Definition:

If two tuples agree on the attributes

$A_1, A_2, \ldots A_n$

then they must also agree on the attributes

$B_1, B_2, \ldots B_m$

Formally: $A_1, A_2, \ldots A_n \longrightarrow B_1, B_2, \ldots B_m$

Examples

EmpID	Name	Phone	Position
E0045	Smith	1234	Clerk
E1847	John	9876	Salesrep
E1111	Smith	9876	Salesrep
E9999	Mary	1234	Lawyer

- EmpID $\longrightarrow$ Name, Phone, Position
- Position $\longrightarrow$ Phone
- but Phone $\not\longrightarrow$ Position

In General

- To check if A $\longrightarrow$ B violation:

Erase all other columns

…	A	…	B	
	X1		Y1	
	X2		Y2	
	…		…	

- check if the remaining relation is many-one (called ***functional*** in mathematics)

Example

EmpID	Name	Phone	Position
E0045	Smith	1234 ←	Clerk
E1847	John	9876 ←	Salesrep
E1111	Smith	9876 ←	Salesrep
E9999	Mary	1234 ←	lawyer

More examples:

Product: name $\rightarrow$ price, manufacturer

Person: ssn $\rightarrow$ name, age

Company: name $\rightarrow$ stock price, president

Q: From this, can you conclude phone → SSN?

SSN	Phone Number
123-321-99	(201) 555-1234
123-321-99	(206) 572-4312
909-438-44	(908) 464-0028
909-438-44	(212) 555-4000

Relation Keys

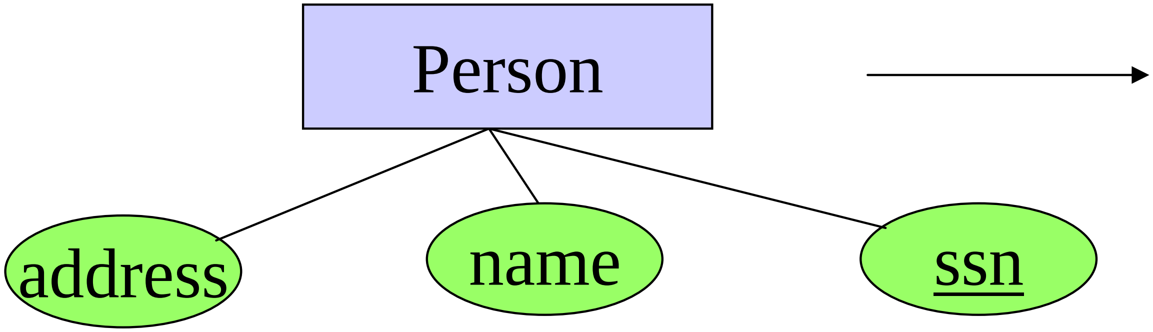
- After defining FDs, we can now define keys
- Key of a relation R is a set of attributes that
  - functionally determines all attributes of R
  - none of its subsets determines all attributes of R
- Superkey
  - a set of attributes that contains a key
- We will need to know the keys of the relations in a DB schema, so that we can refine the schema

Finding the Keys of a Relation

Given a relation constructed from an E/R diagram, what is its key?

Rules:

1. If the relation comes from an entity set,
   the key of the relation is the set of attributes which is the key of the entity set.

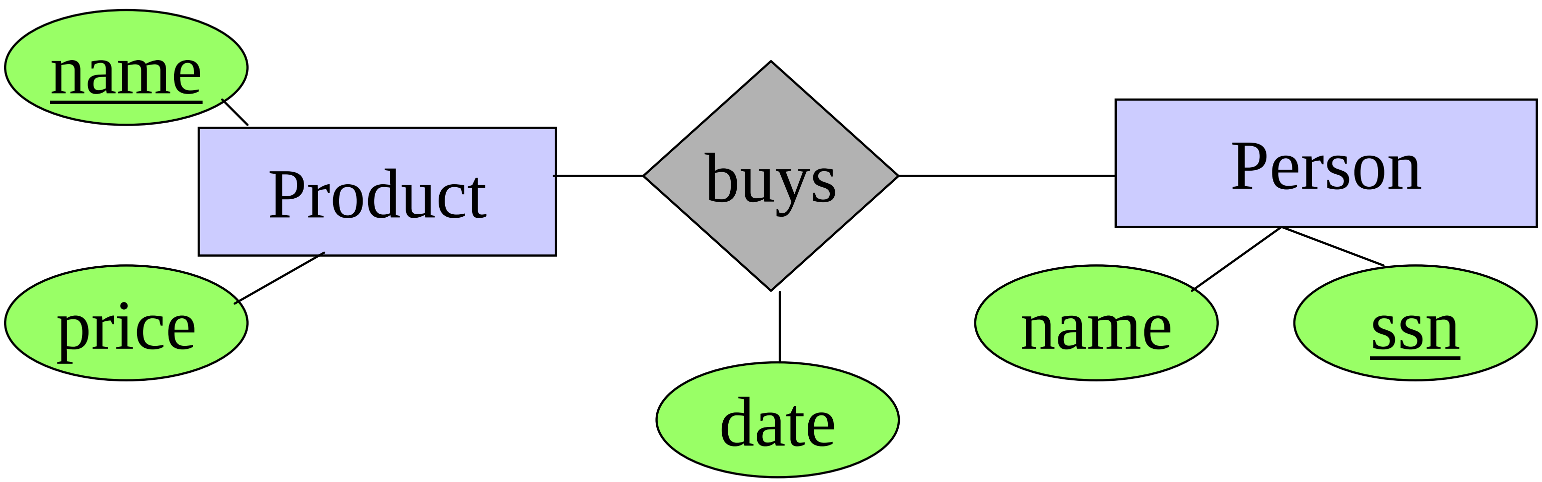


Person(address, name, ssn**)**

Finding the Keys

Rules:

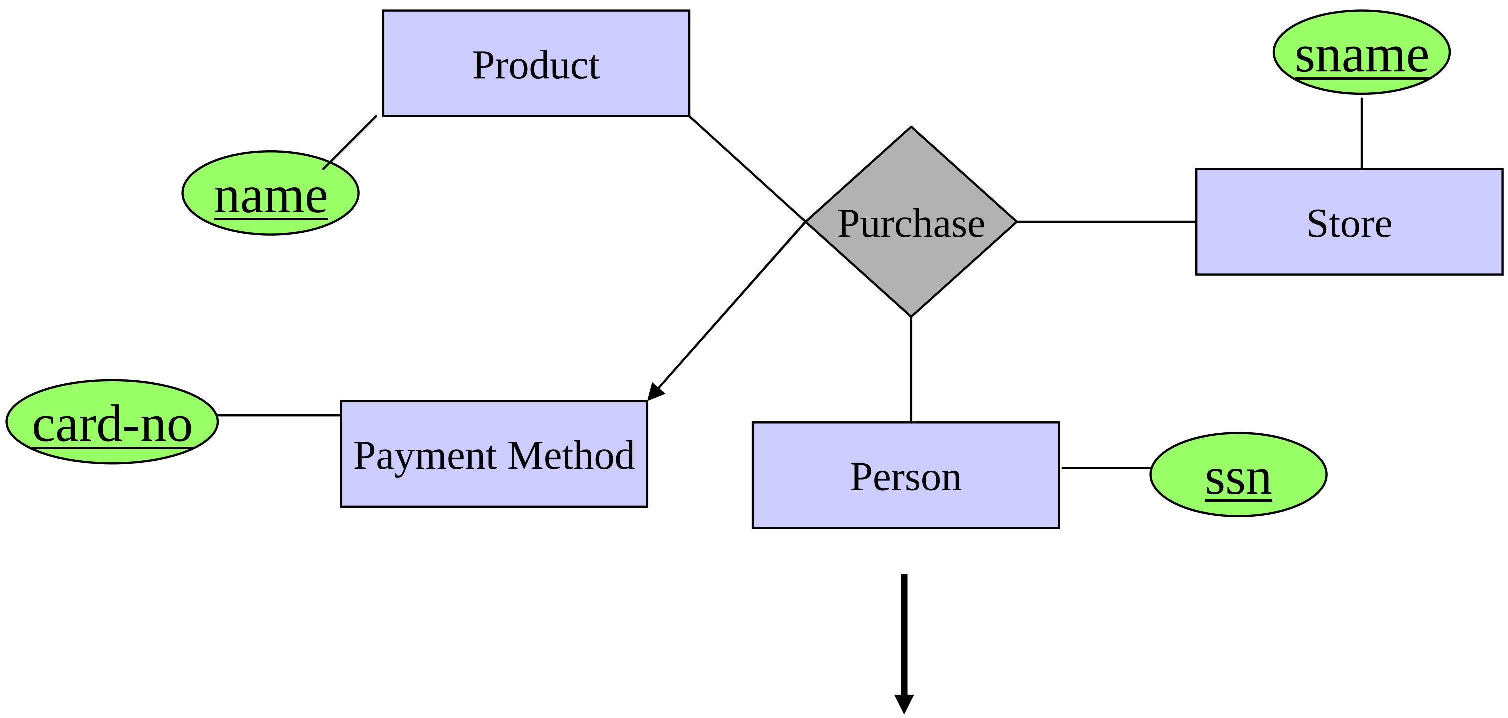
2. If the relation comes from a many-many relationship,
   the key of the relation include the set of all attribute keys in the relations corresponding to the entity sets
   (and additional attributes if necessary)



buys(<u>name, ssn</u>, date)

Finding the Keys

But: if there is an arrow from the relationship to E, then
we don’t need the key of E as part of the relation key.



Purchase(name , sname, ssn, card-no)

Finding the Keys

More specific rules:

- Many-one, one-many, one-one relationships
- Multi-way relationships
- Weak entity sets

(Try to find them yourself)

Reasoning with FDs

1) closure of FD sets
2) closure of attribute sets

Closure of FD sets

- Given a relation schema R & a set S of FDs
  - is the FD f logically implied by S?
- Example
  - R = {A,B,C,G,H,I}
  - S = A ➔B, A ➔C, CG ➔ H, CG ➔ I, B ➔ H
  - would A ➔ H be logically implied?
  - yes (you can prove this, using the definition of FD)
- Closure of S: S+ = all FDs logically implied by S
- How to compute S+?
  - we can use Armstrong's axioms

Armstrong's Axioms

- Reflexivity rule
  - A1A2...An ➔ a subset of A1A2...An
- Augmentation rule
  - A1A2...An ➔ B1B2...Bm, then
    A1A2...An C1C2..Ck ➔ B1B2...Bm C1C2...Ck
- Transitivity rule
  - A1A2...An ➔ B1B2...Bm and
    B1B2...Bm ➔ C1C2...Ck, then
    A1A2...An ➔ C1C2...Ck

Inferring S+ using Armstrong's Axioms

- S+ = S
- Loop
  - foreach f in S, apply reflexivity and augment. rules
  - add the new FDs to S+
  - foreach pair of FDs in S, apply the transitivity rule
  - add the new FD to S+
- Until S+ does not change any further

Additional Rules

- Union rule
  - $X \rightarrow Y$ and $X \rightarrow Z$, then $X \rightarrow YZ$
  - (X, Y, Z are sets of attributes)
- Decomposition rule
  - $X \rightarrow YZ$, then $X \rightarrow Y$ and $X \rightarrow Z$
- Pseudo-transitivity rule
  - $X \rightarrow Y$ and $YZ \rightarrow U$, then $XZ \rightarrow U$
- These rules can be inferred from Armstrong's axioms

Closure of a Set of Attributes

Given a set of attributes {$\boldsymbol{A1, \ldots, An}$} and a set of dependencies S.
Problem: find all attributes B such that:

any relation which satisfies S also satisfies:

$A1, \ldots, An \rightarrow B$

The **closure** of $\{A1, \ldots, An\}$, denoted $\{A1, \ldots, An\}^+$,
is the set of all such attributes B

We will discuss the motivations for attribute closures soon

Algorithm to Compute Closure

Start with X={A1, …, An}.

Repeat until X doesn't change **do**:

if $B_1, B_2, \ldots B_n \longrightarrow C$ is in S, **and**

$B_1, B_2, \ldots B_n$ are all in X, **and**

C is not in X

then

add C to X.

Example

$AB \longrightarrow C$

$AD \longrightarrow E$

$B \longrightarrow D$

$AF \longrightarrow B$

Closure of {A,B}: X = {A, B, C, D, E}

Closure of {A, F}: X = {A, F, B, D, C, E}

Usage for Attribute Closure

- Test if X is a superkey
  - compute X+, and check if X+ contains all attrs of R

- Check if X ➔ Y holds
  - by checking if Y is contained in X+

Desirable Properties of Schema Refinement

1) minimize redundancy
2) avoid info loss
3) preserve dependency
4) ensure good query performance

Normal Forms

First Normal Form = all attributes are atomic

Second Normal Form (2NF) = old and obsolete

Boyce Codd Normal Form (BCNF)

Third Normal Form (3NF)

Fourth Normal Form (4NF)

Others...

Boyce-Codd Normal Form

A simple condition for removing anomalies from relations:

A relation R is in BCNF if and only if:

$$A_1, A_2, \ldots A_n \longrightarrow B$$

Whenever there is a nontrivial FD for R , it is the case that $\{ A_1, A_2, \ldots A_n \}$ is a super-key for R.

In English (though a bit vague):

Whenever a set of attributes of *R* is determining another attribute, it should determine ***<u>all</u>*** attributes of *R*.

Example

Name	SSN	Phone Number
Fred	123-321-99	(201) 555-1234
Fred	123-321-99	(206) 572-4312
Joe	909-438-44	(908) 464-0028
Joe	909-438-44	(212) 555-4000

What are the dependencies?

SSN $\rightarrow$ Name

What are the keys?

Is it in BCNF?

Decompose it into BCNF

SSN	Name
123-321-99	Fred
909-438-44	Joe

SSN $\rightarrow$ Name

SSN	Phone Number
123-321-99	(201) 555-1234
123-321-99	(206) 572-4312
909-438-44	(908) 464-0028
909-438-44	(212) 555-4000

What About This?

Name	Price	Category
Gizmo	$19.99	gadgets
OneClick	$24.99	camera

Name $\longrightarrow$ Price, Category

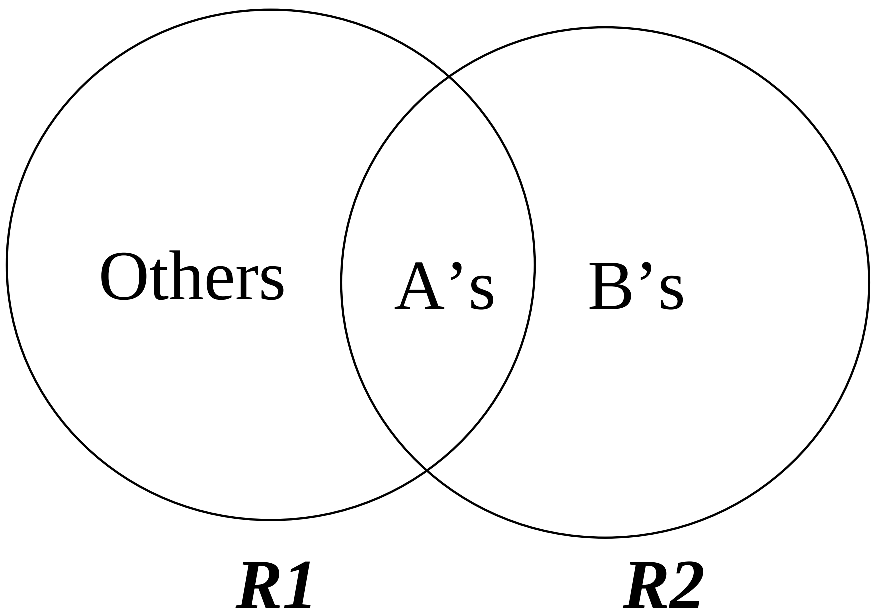
BCNF Decomposition

Find a dependency that violates the BCNF condition:

$$A_1, A_2, \ldots A_n \longrightarrow B_1, B_2, \ldots B_m$$

Heuristics: choose B_1, B_2, … B_m "as large as possible"

Decompose:



Continue until there are no BCNF violations left.

Example Decomposition

Person:

Name	SSN	Age	EyeColor	PhoneNumber

Functional dependencies:

SSN $\longrightarrow$ Name, Age, Eye Color

BNCF: Person1(SSN, Name, Age, EyeColor),
Person2(SSN, PhoneNumber)

What if we also had an attribute Draft-worthy, and the FD:

Age $\longrightarrow$ Draft-worthy

BCNF Decomposition: The Algorithm

- Input: relation R, set S of FDs over R

1) Compute S+
2) Compute keys for R (from ER or from S+)
3) Use S+ and keys to check if R is in BCNF, if not:
   a) pick a violation FD f: A ➔ B
   b) expand B as much as possible, by computing A+
   c) create R1 = A union B, R2 = A union (others in R)
   d) compute all FDs over R1, using R and S+, then compute keys for R1. Repeat similarly for R2
   e) Repeat Step 3 for R1 and R2
4) Stop when all relations are BCNF, or are two-attributes

Q: Is BCNF unique?

Q: Does BCNF always exist?

Properties of BCNF

- BCNF removes certain types of redundancy
  - those caused by adding many-many or one-many relations
- For examples of redundancy that it cannot remove, see "multivalued redundancy"
- BCNF avoids information loss

Lossless Decompositions

A decomposition is *lossless* if we can recover:

R(A,B,C)

$\downarrow$ Decompose

{ R1(A,B) , R2(A,C) }

$\downarrow$ Recover

R'(A,B,C) = R(A,B,C)

R' is in general larger than R. Must ensure R' = R

Decomposition Based on BCNF is Necessarily Lossless

R(A, B, C), $A \rightarrow C$

BCNF: R1(A,B), R2(A,C)

Some tuple (a,b,c) in R (a,b',c') also in R
decomposes into (a,b) in R1 (a,b') also in R1
and (a,c) in R2 (a,c') also in R2

Recover tuples in R: (a,b,c), (a,b,c'), (a,b',c), (a,b',c') also in R ?

Can (a,b,c') be a bogus tuple? What about (a,b',c') ?

However,

- BCNF is not always dependency preserving
- In fact, some times we cannot find a BCNF decomposition that is dependency preserving
- Can handle this situation using 3NF
- See next few slides for example

Behind the Scene: The Great Debate of ‘75

- The network/COBOL camp:
  - DBTG (Database Task Group, under CODASYL), 1971
  - closely aligned with COBOL
  - DBTG Report would standardize network model
  - Bachman (for network model) got Turing award in 1973
- The relational camp:
  - Codd’s paper in 1970
  - resistance even within IBM
  - First implementations, 1973: System R (IBM), INGRES (Berkeley)
  - System R at IBM San Jose Lab
- The “Great Debate” in 1975 SIGMOD conf.
- Codd got Turing award in 1981

Behind the Scene: Arguments Against the Other Side?

- COBOL/CODASYL → Relational
  - too mathematical (to understand)

- Relational → COBOL/CODASYL
  - too complicated (to program)

Normal Forms

First Normal Form = all attributes are atomic

Second Normal Form (2NF) = old and obsolete

Boyce Codd Normal Form (BCNF)

Third Normal Form (3NF)

Fourth Normal Form (4NF)

Others...

3NF: A Problem with BCNF

Unit	Company	Product

FD's: Unit $\rightarrow$ Company; Company, Product $\rightarrow$ Unit

So, there is a BCNF violation, and we decompose.

Unit	Company

Unit $\rightarrow$ Company

Unit	Product

No FDs

So What's the Problem?

Unit	Company
Galaga99	UI
Bingo	UI

Unit	Product
Galaga99	databases
Bingo	databases

No problem so far. All *local* FD's are satisfied.

Let's put all the data back into a single table again:

Unit	Company	Product
Galaga99	UI	databases
Bingo	UI	databases

Violates the dependency: company, product -> unit!

Preserving FDs

- What if, when a relation is decomposed, the X of an $X \rightarrow Y$ ends up only in one of the new relations and the Y ends up only in another?
- Such a decomposition is not “dependency-preserving.”
- Goal: Always have FD-preserving decompositions

Solution: 3rd Normal Form (3NF)

A simple condition for removing anomalies from relations:

A relation R is in 3rd normal form if :

Whenever there is a nontrivial dependency $A_1, A_2, ..., A_n \rightarrow B$ for R , then $\{A_1, A_2, ..., A_n\}$ is a super-key for R,
or B is part of a key.

3NF (General Definition)

- A relation is in Third Normal Form (3NF) if whenever $X \rightarrow A$ holds, either X is a superkey, or A is a prime attribute.

Informally: everything depends on the key or is in a key.

- Despite the thorny technical definitions that lead up to it, 3NF is intuitive and not hard to achieve. ***Aim for it in all designs unless you have strong reasons otherwise.***

3NF vs. BCNF

- R is in BCNF if whenever $X \rightarrow A$ holds, then X is a superkey.
- Slightly stronger than 3NF.
- Example: R(A,B,C) with $\{A,B\} \rightarrow C$, $C \rightarrow A$
  - 3NF but not BCNF

Guideline: Aim for BCNF and settle for 3NF

Decomposing R into 3NF

- The algorithm is complicated
- 1. Get a “minimal cover” of FDs
- 2. Find a lossless-join decomposition of R (which might miss dependencies)
- 3. Add additional relations to the decomposition to cover any missing FDs of the cover
- Result will be lossless, will be dependency-preserving 3NF; might not be BCNF

- This way equivalent to textbook, but easier to follow.
- → *Example 3.27 in textbook.*

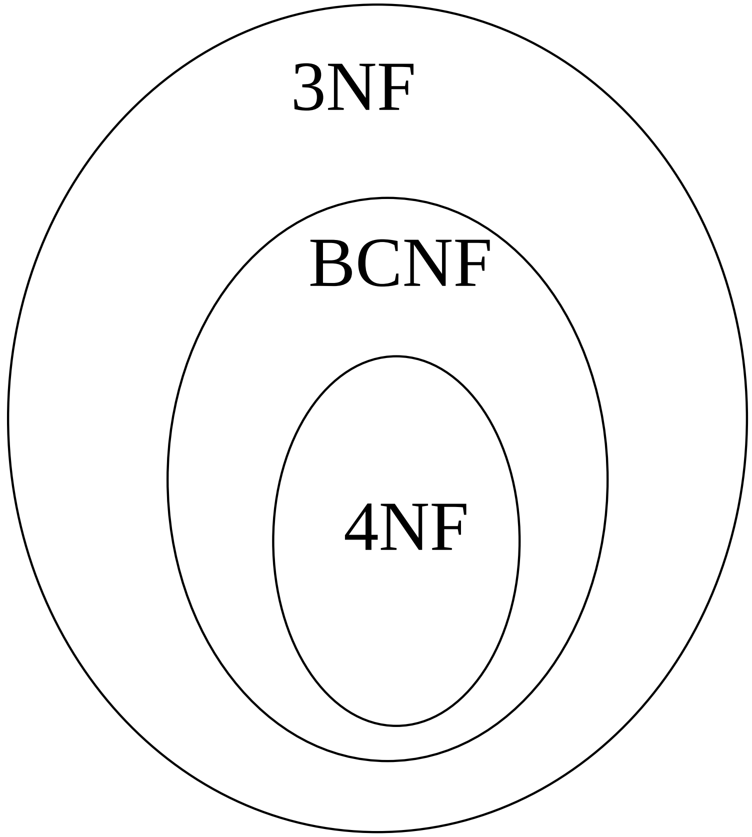
Fact of life...

Finding a decomposition which is both lossless and dependency-preserving is not always possible.

Multi-valued Dependencies and 4NF

we will not cover this.

Confused by Normal Forms ?



In practice: (1) 3NF is enough, (2) don't overdo it !

Normalization Summary

- 1NF: usually part of the woodwork
- 2NF: usually skipped
- 3NF: a biggie
  - always aim for this
- BCNF and 4NF: tradeoffs start here
  - in re: d-preserving and losslessness
- 5NF: You can say you've heard of it...

Caveat

- Normalization is not the be-all and end-all of DB design
- Example: suppose attributes A and B are always used together, but normalization theory says they should be in different tables.
  - decomposition might produce unacceptable performance loss (extra disk reads)
- Plus -- there are constraints other than FDs and MVDs

Current Trends

- Object DBs and Object-Relational DB’s
  - may permit complex attributes
  - 1st normal form unnecessary
- Data Warehouses
  - huge historical databases, seldom or never updated after creation
  - joins expensive or impractical
  - argues against normalization
- Everyday relational DBs
  - aim for BCNF, settle for 3NF