Normalization is a Good Idea

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Steps for a New Application

Requirements
- what are you going to build?

Conceptual Database Design
- pen-and-pencil description

Logical Design
- formal database schema

Schema Refinement:
- fix potential problems, normalization

Normalization

Physical Database Design
- use sample of queries to optimize for speed/storage

App/Security Design
- prevent security problems

Information Retrieval

A Relational Model of Data for Large Shared Data Banks

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Future users of large data banks must be protected from having to know how the data is organized in the machine (the internal representation). A prompting service which supplies such information is not a satisfactory solution. Activities of users at terminals and most application programs should remain unaffected when the internal representation of data is changed and even when some aspects of the external representation are changed. Changes in data representation will often be needed as a result of changes in query, update, and report

Redundancy = Bad

What was our solution?

- Break database into small relations
- Perform good ER modeling and SQL translation
- Kind of ... adhoc

Is there a systematic approach??

Redundancy = Bad

sid	name	address	hobby	cost
1	Eugene	amsterdam	trucks	$$
1	Eugene	amsterdam	cheese	$
2	Bob	40th	paint	$$$
3	Bob	40th	cheese	$
4	Shaq	florida	swimming	$

people have names and addrs

hobbies have costs

people many-to-many with hobbies

What's primary key? sid? sid + hobby?

Update/insert/delete anomalies. Wastes space

Anomalies (Inconsistencies)

Update Anomaly

change one address, need to change all

Insert Anomaly

add person without hobby?

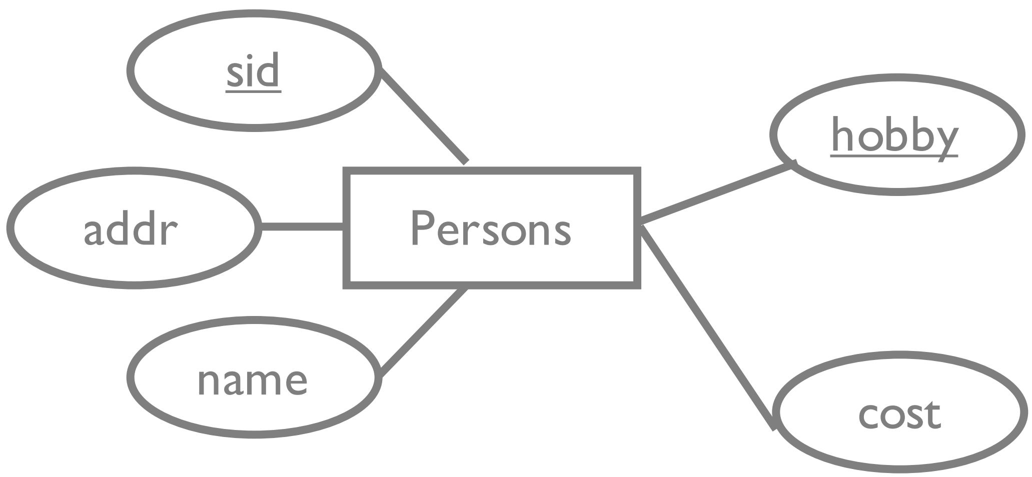
not allowed? dummy hobby?

Delete Anomaly

if delete a hobby. Delete the person?

Theory Can Fix This!

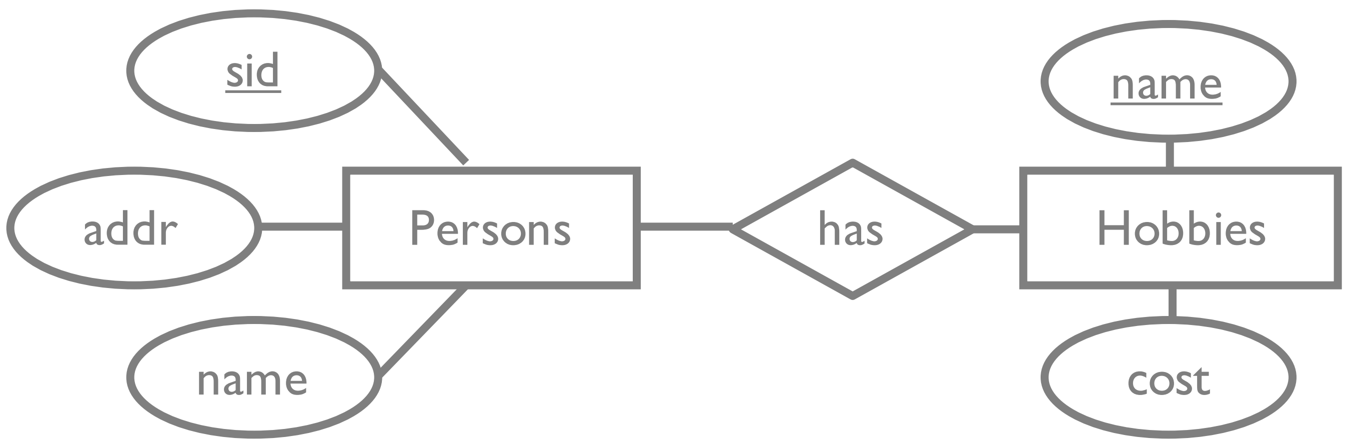
A Possible Approach



`data(sid, addr, name, hobby, cost)`

A Possible Approach

ER diagram was a heuristic



We have decomposed example table into:

```
person(sid, addr, name)
hobby(name, cost)
personhobby(hobbyname, sid)
```

WHY is this a good decomposition??

A Possible Approach

What if decompose into:

```
person(sid, name, addr, cost)
personhobby(sid, hobbyname)
```

sid	name	addr	cost
1	Eugene	amsterdam	$$
1	Eugene	amsterdam	$
2	Bob	40th	$$$
3	Bob	40th	$
4	Shaq	florida	$

sid	hobby
1	trucks
1	cheese
2	paint
3	cheese
4	swimming

but… which cost goes with which hobby?

lost information: *lossy decomposition*

Decomposition

Replace schema R with 2+ smaller schemas that

1. each contain subset of attrs in R
2. together include all attrs in R

ABCD replaced with AB, BCD or AB, BC, CD

Not free – may introduce problems!

1. lossy-join: not able to recover R from smaller relations
2. non-dependency-preserving: constraints on R cannot be enforced y only looking at an individual decomposed relation
3. performance: additional joins, may affect performance

Can we systematically
decompose our relation to

prevent
decomposition
problems

&

remove
redundancy?

Functional Dependencies (FD)

sid	name	address	hobby	cost
1	Eugene	amsterdam	trucks	$$
1	Eugene	amsterdam	cheese	$
2	Bob	40th	paint	$$$
3	Bob	40th	cheese	$
4	Shaq	florida	swimming	$

sid sufficient to identify name and addr, but not hobby

e.g., exists a function f(sid) → name, addr

sid → name, addr is a functional dependency

"sid determines name, addr"

"name, addr are functionally dependent on sid"

"if 2 records have the same sid, their name and addr are the same"

Functional Dependencies (FD)

$$X \rightarrow Y$$

holds on R

if $t_1.X = t_2.X$ then $t_1.Y = t_2.Y$

where X,Y are subsets of attrs in R

Examples of FDs in person-hobbies table

sid, hobby $\rightarrow$ name, address cost

hobby $\rightarrow$ cost

sid $\rightarrow$ name, address

Fun Facts

Functional Dependency is an integrity constraint

- statement about all instances of relation
- Generalizes key constraints
  - if K is candidate key of R, then K → R

Given FDs, simple definition of redundancy

- when left side of FD is not table key

Where do FDs come from?

- thinking really hard aka application semantics
- can't stare at database to derive (like ICs)

Fun Facts

- Functional Dependency is an integrity constraint
  - statement about all instances of relation
  - Generalizes key constraints
    - if K is candidate key of R, then K → R

Functional Dependency Discovery: An Experimental Evaluation of Seven Algorithms

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Normal Forms

Two different criterias for decomposing a relation

Boyce Codd Normal Form (BCNF)

No redundancy, may lose dependencies

Third Normal Form (3NF)

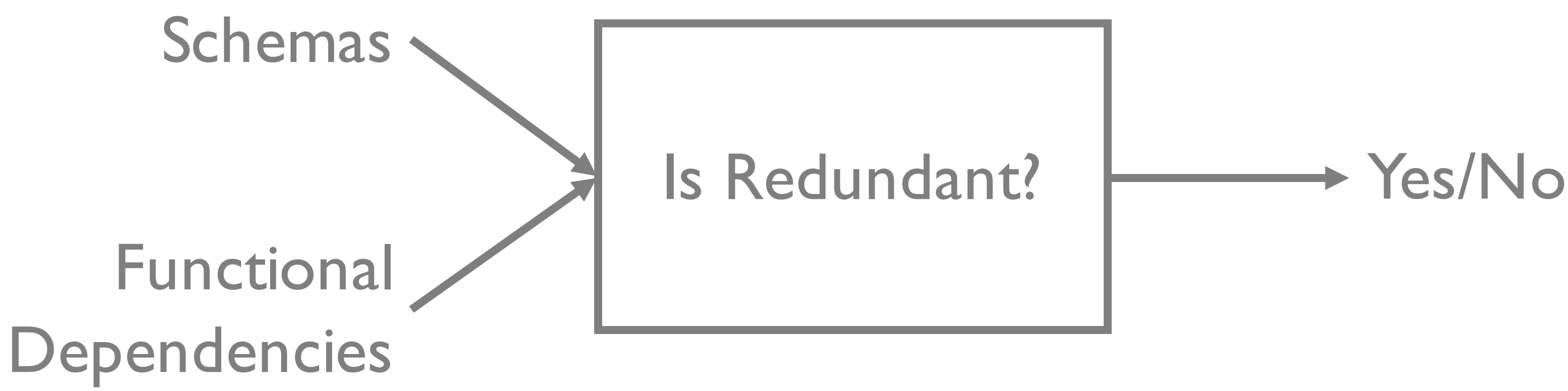
May have redundancy, no decomposition problems

Redundancy depends on FDs

consider R(ABC)

no FDs: no redundancy

if A→B: tuples with same A value means B is duplicated!



BCNF

Relation R in BCNF has *no redundancy* wrt FDs

(only FDs are key constraints)

```
F: set of functional dependencies over relation R

for (X→Y) in F
    Y is in X or
    X is a superkey of R
```

Is this in BCNF?

sid → name

sid	hobby	name
x	y_1	z
x	y_2	?

BCNF

Relation R in BCNF has *no redundancy* wrt FDs

(only FDs are key constraints)

```
F: set of functional dependencies over relation R

for (X→Y) in F
   Y is in X or
   X is a superkey of R
```

Functional Dependencies

SH → NAC (sid, hobby → name, addr, cost)
H → C
S → NA

What's in BCNF?

SHNAC	NO
SNA, SHC	NO
SNA, HC, SH	YES

BCNF

Relation R in BCNF has *no redundancy* wrt FDs

(only FDs are key constraints)

```
F: set of functional dependencies over relation R

for (X→Y) in F
   Y is in X or
   X is a superkey of R
```

Remember that F is *all* possible FDs valid over R!

Given A→B, B→C, then A→C is in F and should be checked

This gets us into closure of FDs, which we discuss soon.

BCNF

Suppose we have

Client, Office → Account

Account → Office

What's in BCNF?

R(Account, Client, Office)

R(Account, Office)   R(Client, Account)

Where did CO→A go? *Lost a Functional Dependency*

Can we preserve FDs *and* remove most redundancy?

3rd Normal Form (3NF)

Relax BCNF (e.g., BCNF $\subseteq$ 3NF)

```
F: set of functional dependencies over relation R

for (X→Y) in F
    Y is in X or
    X is a superkey of R or
```

3rd Normal Form (3NF)

Relax BCNF (e.g., BCNF⊆3NF)

```
F: set of functional dependencies over relation R

for (X→Y) in F
    Y is in X or
    X is a superkey of R or
    Y is part of a key in R
```

Is new condition trivial? NO! key is minimal

Nice properties

lossless join ^ dependency preserving decomposition to 3NF always possible

3^{rd} Normal Form (3NF)

Relax BCNF (e.g., BCNF ⊆ 3NF)

```
F: set of functional dependencies over relation R

for (X→Y) in F
   Y is in X or
   X is a superkey of R or
   Y is part of a key in R
```

FDs

CO → A

A → O

(AO), (CA) splits up key in CO→A

COA is in 3NF!

3rd Normal Form (3NF)

Relax BCNF (e.g., BCNF ⊆ 3NF)

```
F: set of functional dependencies over relation R

for (X→Y) in F
    Y is in X or
    X is a superkey of R or
    Y is part of a key in R
```

Schema: SBDC

SBD→C, S→C — Not in 3NF

SBD→C, S→C, C→S — In 3NF (Hint: CBD is a key)

In both cases, SC is stored redundantly

We’re going to need some theory

Closure of FDs

- armstrong’s axioms

Minimal FD Set

Principled Decomposition

BCNF & 3NF

Closure of FDs

If I know

Name → Bday and Bday → age

Then it implies

Name → age

f' is implied by set F if f' is true when F is true

F^+ closure of F is all FDs implied by F

Can we construct this closure automatically? YES

Closure of FDs

Inference rules called Armstrong's Axioms

Reflexivity	if $Y \subseteq X$ then $X \rightarrow Y$
Augmentation	if $X \rightarrow Y$ then $XZ \rightarrow YZ$ for any Z
Transitivity	if $X \rightarrow Y$ & $Y \rightarrow Z$ then $X \rightarrow Z$

These are sound and complete rules

sound	doesn't produce FDs not in the closure
complete	doesn't miss any FDs in the closure

Closure of FDs

Can we compute the closure?   YES. slowly

expensive. exponential in # attributes

Can we *check* if X → Y is in the closure of F?

X^+ = *attribute closure* of X (expand X using axioms)

check if Y is implied in the attribute closure

Closure of FDs

F = {A→B, B→C, CB→E}

Is A→E in the closure?

A → B	given
A → AB	augmentation A
A → BB	apply A→B (transitivity)
A → BC	apply B→C (transitivity)
A → E	apply BC→E (transitivity)

We're going to need some theory

Closure of FDs

- armstrong's axioms

Minimal FD Set

Principled Decomposition

BCNF & 3NF

Minimum Cover of FDs

Closures let us compare sets of FDs meaningfully

F1 = {A → B, A → C, A → BC}

F2 = {A → B, A → C}

F1 equivalent to F2

If there's a closure (a maximally expanded FD), there's a *minimal* FD. Let's find it

Minimum Cover of FDs

1. Turn FDs into *standard form*

   decompose each FD so single attr on the right side

2. Minimize left side of each FD

   for each FD, check if can delete left attr w/out changing closure

   given $ABC \rightarrow D, B \rightarrow C$ can reduce to $AB \rightarrow D, B \rightarrow C$

3. Delete redundant FDs

   check each remaining FD and see if it can be deleted

   e.g., in closure of the other FDs

2 must happen before 3!

Minimum Cover of FDs

A→B, ABC→E, EF→G, ACF→EG

Standard form

A→B, ABC→E, EF→G, ACF→E, ACF→G

Minimize left side

A→B, AC→E, EF→G, ACF→E, ACF→G

reason: AC→E + A→B implies ABC→E

Delete Redundant FDs

A→B, AC→E, EF→G, ~~ACF→E, ACF→G~~

reason: ACF→E implied by AC→E, EF→G

We're going to need some theory

Closure of FDs

- armstrong's axioms

Minimal FD Set

Principled Decomposition

BCNF & 3NF

Decomposition

Eventually want to decompose R into $R_1 \ldots R_n$ wrt F

We've seen issues with decomposition.

Lost Joins: Can't recover R from $R_1 \ldots R_n$

Lost dependencies

Principled way of avoiding these?

Lossless Join Decomposition

Let's say relation R is decomposed into relations X, Y

Join the decomposed tables to get *exactly the* original

$\pi_X(R) \bowtie \pi_Y(R) = R$

Lossless wrt F if and only if F^+ contains

$X \cap Y \rightarrow X$ or $Y \cap X \rightarrow Y$

intersection of X, Y is a key for one of them

Lossless Join Decomposition

Lossless wrt F if and only if F^+ contains

$X \cap Y \rightarrow X$ or $Y \cap X \rightarrow Y$

intersection of X, Y is a key for one of them

FDs: $A \rightarrow C, A \rightarrow B$

A	B	C
1	2	1
5	3	4
9	2	6

→

A	B
1	2
5	3
9	2

B	C
2	1
3	4
2	6

→

A	B	C
1	2	1
5	3	4
9	2	6
1	2	6
9	2	1

Lossy! $AB \cap BC = B$ doesn't determine anything

Lossless Join Decomposition

Lossless wrt F if and only if F^+ contains

$X \cap Y \rightarrow X$ or $Y \cap X \rightarrow Y$

intersection of X, Y is a key for one of them

FDs: $A \rightarrow C, A \rightarrow B$

A	B	C
1	2	1
5	3	4
9	2	6

A	B
1	2
5	3
9	2

A	C
1	1
5	4
9	6

A	B	C
1	2	1
5	3	4
9	2	6

OK

Dependency-preserving Decomposition

F_R = Projection of F onto R

Subset of F that are "valid" for R

FDs $X \rightarrow Y$ in F^+ s.t. X and Y attrs are in R

If R decompose to X, Y.

FDs that hold on X, Y equivalent to all FDs on R

$(F_X \cup F_Y)^+ = F^+$

Consider ABCD, C is key, $AB \rightarrow C$, $D \rightarrow A$

BCNF decomposition: BCD, DA

$AB \rightarrow C$ doesn't apply to either table!

We're going to need some theory

Closure of FDs

- armstrong's axioms

Minimal FD Set

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BCNF & 3NF

BCNF

```
while BCNF is violated
    R with FDs F_R
    if an FD X→y violates BCNF
        turn R into R-y & Xy
```

y is single attr

ABCDE key A, BC→A, D→B, C→D

DB, ACDE using D→B

ACDE is in BCNF

A is key

C determines A

Seems like we lost BC→A?

BCNF Decomp in Normal Terms

BCNF is based on checking *all* FDs (in F^+) for a given relation.

Simple procedure:

1. For each attribute or combination of attributes in R. Call it *attrs*
2. Does the closure of *attrs* contain all attributes in R?
3. If yes: continue. Else: decompose
4. Recall that *attrs*→*attrs* is trivially true.

Given A→B, B→C, and relation ABCD

Consider A:	it determines B, and C, but not D
Decompose using A→B:	AB, ACD
Consider A for ACD:	it determines C, but not D
Decompose using A→C:	AB, AC, AD

3NF

F^{min} = minimal cover of F

Run BCNF using F^{min}

for $X \rightarrow Y$ in F^{min} not in projection onto $R_1 \ldots R_N$

    create relation XY

ABCDE   key A, $BC \rightarrow A$, $D \rightarrow B$, $C \rightarrow D$

Expand $A \rightarrow BCDE$

3NF

F^{min} = minimal cover of F

Run BCNF using F^{min}

for $X \rightarrow Y$ in F^{min} not in projection onto $R_1 \ldots R_N$

    create relation XY

ABCDE $A \rightarrow B$, $A \rightarrow C$, $A \rightarrow D$, $A \rightarrow E$,
$BC \rightarrow A$, $D \rightarrow B$, $C \rightarrow D$

Due to $C \rightarrow D$ and $D \rightarrow B$, we know that $C \rightarrow B$

3NF

F^{min} = minimal cover of F

Run BCNF using F^{min}

for $X \rightarrow Y$ in F^{min} not in projection onto $R_1 \ldots R_N$

create relation XY

ABCDE $A \rightarrow B$, $A \rightarrow C$, $A \rightarrow D$, $A \rightarrow E$,

$C \rightarrow A$, $D \rightarrow B$, $C \rightarrow D$

$C \rightarrow A$ and $A \rightarrow D$ implies $C \rightarrow D$

3NF

F^{min} = minimal cover of F

Run BCNF using F^{min}

for $X \rightarrow Y$ in F^{min} not in projection onto $R_1 \ldots R_N$

    create relation XY

ABCDE $A \rightarrow B$, $A \rightarrow C$, $A \rightarrow D$, $A \rightarrow E$,
$C \rightarrow A$, $D \rightarrow B$

$A \rightarrow D$ and $D \rightarrow B$ implies $A \rightarrow B$

3NF

F^{min} = minimal cover of F

Run BCNF using F^{min}

for $X \rightarrow Y$ in F^{min} not in projection onto $R_1 \ldots R_N$

  create relation XY

ABCDE $A \rightarrow C$, $A \rightarrow D$, $A \rightarrow E$,
$C \rightarrow A$, $D \rightarrow B$

3NF

F^{min} = minimal cover of F

Run BCNF using F^{min}

for $X \rightarrow Y$ in F^{min} not in projection onto $R_1 \ldots R_N$

    create relation XY

ABCDE $A \rightarrow C$, $A \rightarrow D$, $A \rightarrow E$,

    $C \rightarrow A$, $D \rightarrow B$

DB, ACDE

consider D, only implies B

consider A, determines ACDE

consider C, determines ACDE

3NF

Note that F has another minimal cover:

ABCDE $A \rightarrow C$, $C \rightarrow D$, $A \rightarrow E$, $C \rightarrow A$, $D \rightarrow B$

DB, ACDE using $D \rightarrow B$

Summary

Normal Forms: BCNF and 3NF

FD closures: Armstrong's axioms

Proper Decomposition

Summary

Accidental redundancy is really really bad

Adding lots of joins can hurt performance

Can be at odds with each other

Normalization good starting point, relax as needed

People usually think in terms of entities and keys, usually ends up reasonable

What you should know

- Purpose of normalization
  - Anomalies
  - Decomposition problems
  - Functional dependencies & axioms
- 3NF & BCNF
  - properties
  - algorithm

Exercises

w4111.github.io/fd

Functional Dependency Problem Generator

We have generated 99 random functional dependency problems for you to have practice with. You can press ← or → on the keyboard to go to the previous or next problem.

Click to Toggle Answer | ← | Go to random question | →

Problem 0 out of 100

Info

Relation	ABCDEFGH
Functional Deps	FD -> HE FE -> DB C -> FED GB -> E
Is BCNF?	
Is 3NF?	

Minimal FDs

List the minimal closure for the functional dependencies

Decomposition

BCNF using FDs

List the BCNF decomposition using the provided functional dependencies:

BCNF using Minimal Cover

List the BCNF decomposition using the minimal closure of the functional deps (this is just to give you more decomposition exercises):

3NF

List the 3NF decomposition:

Designed for Normalization lectures in Columbia's W4111