Normalization

COSC 304 – Introduction to Database Systems

Normalization

Normalization is a technique for producing relations with desirable properties.

Normalization decomposes relations into smaller relations that contain less redundancy. This decomposition requires that no information is lost and reconstruction of the original relations must be possible.

Normalization is a bottom-up design technique for producing relations. It pre-dates ER modeling and was developed by Codd in 1972 and extended by others over the years.

- Normalization can be used after ER modeling or independently.
- Normalization may be especially useful for databases that have already been designed without using formal techniques.

Normalization Motivation

The purpose of normalization is to develop good relational schemas that minimize redundancies and update anomalies.

Redundancy occurs when the same data value is stored more than once in a relation.

- Redundancy wastes space and reduces performance.

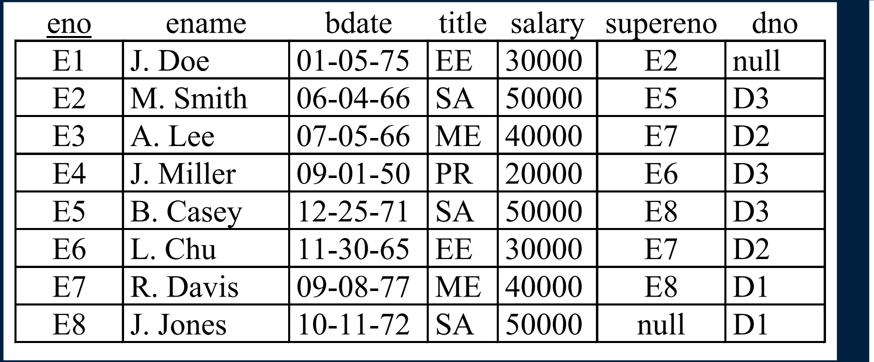
Update anomalies are problems that arise when trying to insert, delete, or update tuples and are often caused by redundancy.

The goal of normalization is to produce a set of relational schemas R_1, R_2, …, R_m from a set of attributes A_1, A_2, … ,A_n.

- Imagine that the attributes are originally all in one big relation R= {A_1, A_2, .., A_n} which we will call the ***Universal Relation***.
- Normalization divides this relation into R_1, R_2, …, R_m.

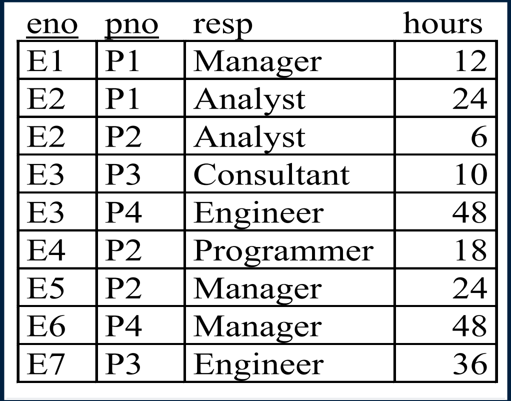
The Power of Normalization
Example Relations

Emp Relation



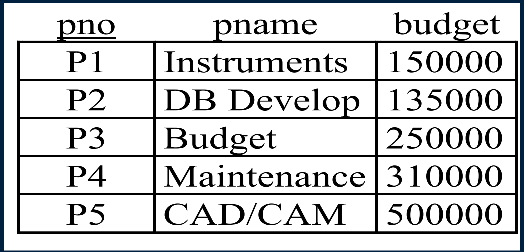
eno	ename	bdate	title	salary	supereno	dno
E1	J. Doe	01-05-75	EE	30000	E2	null
E2	M. Smith	06-04-66	SA	50000	E5	D3
E3	A. Lee	07-05-66	ME	40000	E7	D2
E4	J. Miller	09-01-50	PR	20000	E6	D3
E5	B. Casey	12-25-71	SA	50000	E8	D3
E6	L. Chu	11-30-65	EE	30000	E7	D2
E7	R. Davis	09-08-77	ME	40000	E8	D1
E8	J. Jones	10-11-72	SA	50000	null	D1

WorksOn Relation



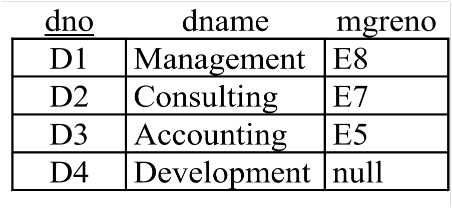
eno	pno	resp	hours
E1	P1	Manager	12
E2	P1	Analyst	24
E2	P2	Analyst	6
E3	P3	Consultant	10
E3	P4	Engineer	48
E4	P2	Programmer	18
E5	P2	Manager	24
E6	P4	Manager	48
E7	P3	Engineer	36

Proj Relation



pno	pname	budget
P1	Instruments	150000
P2	DB Develop	135000
P3	Budget	250000
P4	Maintenance	310000
P5	CAD/CAM	500000

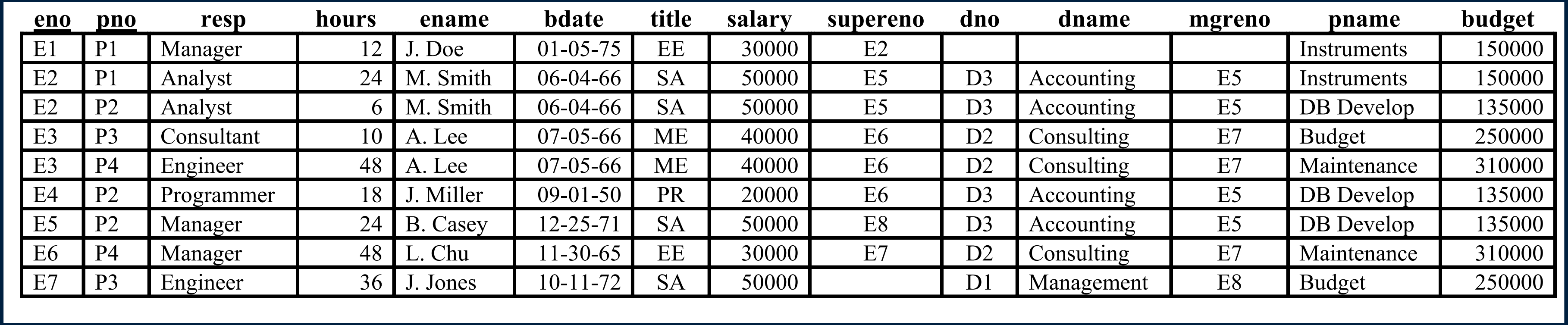
Dept Relation



dno	dname	mgreno
D1	Management	E8
D2	Consulting	E7
D3	Accounting	E5
D4	Development	null

The Power of Normalization
Universal Relation

A Universal Relation with all attributes:



<u>eno</u>	<u>pno</u>	resp	hours	ename	bdate	title	salary	supereno	dno	dname	mgreno	pname	budget
E1	P1	Manager	12	J. Doe	01-05-75	EE	30000	E2				Instruments	150000
E2	P1	Analyst	24	M. Smith	06-04-66	SA	50000	E5	D3	Accounting	E5	Instruments	150000
E2	P2	Analyst	6	M. Smith	06-04-66	SA	50000	E5	D3	Accounting	E5	DB Develop	135000
E3	P3	Consultant	10	A. Lee	07-05-66	ME	40000	E6	D2	Consulting	E7	Budget	250000
E3	P4	Engineer	48	A. Lee	07-05-66	ME	40000	E6	D2	Consulting	E7	Maintenance	310000
E4	P2	Programmer	18	J. Miller	09-01-50	PR	20000	E6	D3	Accounting	E5	DB Develop	135000
E5	P2	Manager	24	B. Casey	12-25-71	SA	50000	E8	D3	Accounting	E5	DB Develop	135000
E6	P4	Manager	48	L. Chu	11-30-65	EE	30000	E7	D2	Consulting	E7	Maintenance	310000
E7	P3	Engineer	36	J. Jones	10-11-72	SA	50000		D1	Management	E8	Budget	250000

U(<u>eno</u>, <u>pno</u>, resp, hours, ename, bdate, title, salary, supereno, dno, dname, mgreno, pname, budget)

What are some of the problems with the Universal Relation?

Normalization will allow us to get back to the starting relations.

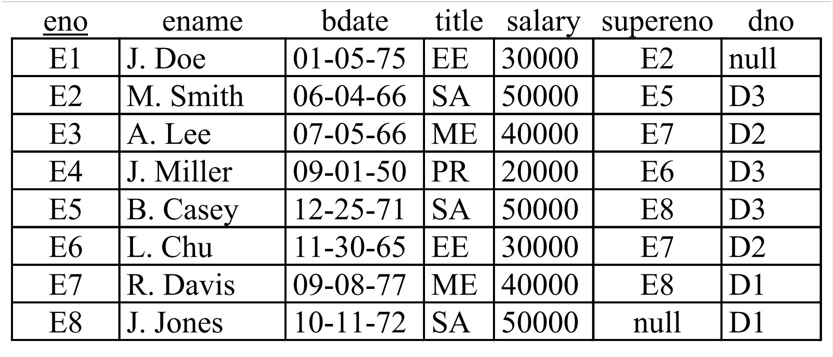
Update Anomalies

There are three major types of update anomalies:

- ***Insertion Anomalies*** - Insertion of a tuple into the relation either requires insertion of redundant information or cannot be performed without setting key values to `NULL`.
- ***Deletion Anomalies*** - Deletion of a tuple may lose information that is still required to be stored.
- ***Modification Anomalies*** - Changing an attribute of a tuple may require changing multiple attribute values in other tuples.

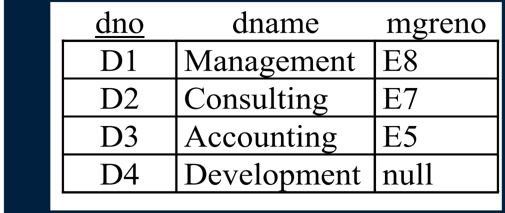
Example Relation Instances

Emp Relation



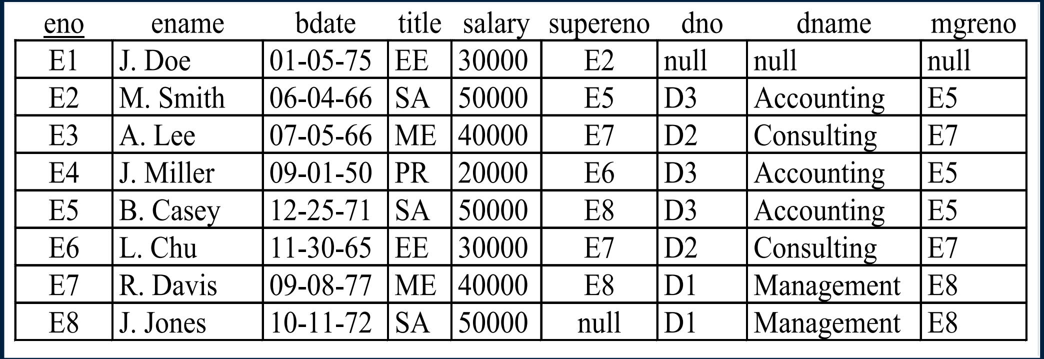
eno	ename	bdate	title	salary	supereno	dno
E1	J. Doe	01-05-75	EE	30000	E2	null
E2	M. Smith	06-04-66	SA	50000	E5	D3
E3	A. Lee	07-05-66	ME	40000	E7	D2
E4	J. Miller	09-01-50	PR	20000	E6	D3
E5	B. Casey	12-25-71	SA	50000	E8	D3
E6	L. Chu	11-30-65	EE	30000	E7	D2
E7	R. Davis	09-08-77	ME	40000	E8	D1
E8	J. Jones	10-11-72	SA	50000	null	D1

Dept Relation



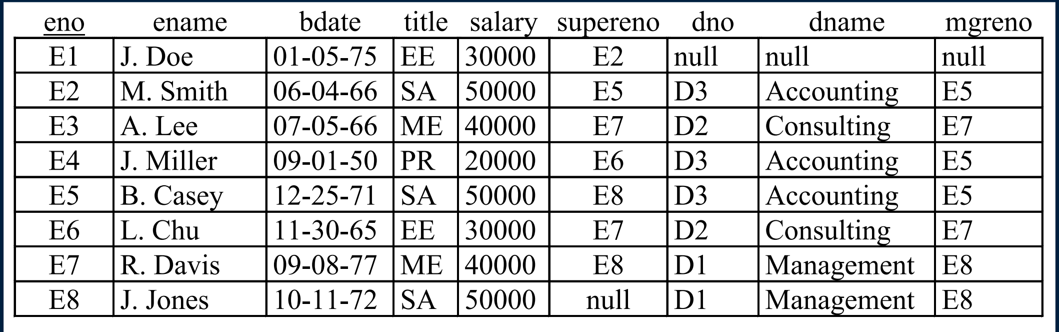
dno	dname	mgreno
D1	Management	E8
D2	Consulting	E7
D3	Accounting	E5
D4	Development	null

EmpDept Relation



eno	ename	bdate	title	salary	supereno	dno	dname	mgreno
E1	J. Doe	01-05-75	EE	30000	E2	null	null	null
E2	M. Smith	06-04-66	SA	50000	E5	D3	Accounting	E5
E3	A. Lee	07-05-66	ME	40000	E7	D2	Consulting	E7
E4	J. Miller	09-01-50	PR	20000	E6	D3	Accounting	E5
E5	B. Casey	12-25-71	SA	50000	E8	D3	Accounting	E5
E6	L. Chu	11-30-65	EE	30000	E7	D2	Consulting	E7
E7	R. Davis	09-08-77	ME	40000	E8	D1	Management	E8
E8	J. Jones	10-11-72	SA	50000	null	D1	Management	E8

Insertion Anomaly Example

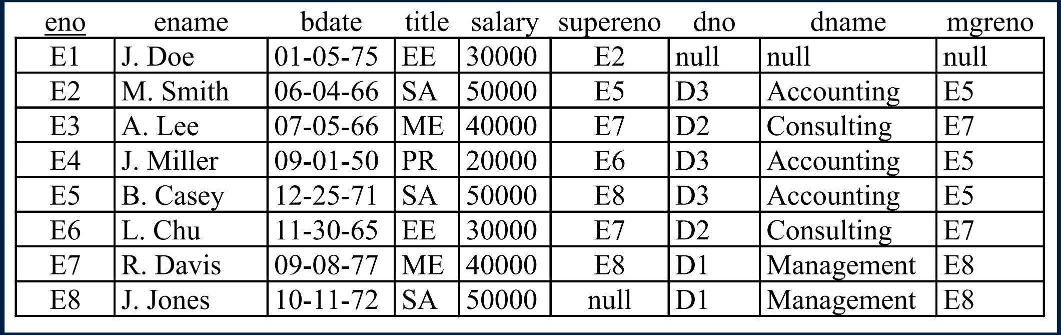


eno	ename	bdate	title	salary	supereno	dno	dname	mgreno
E1	J. Doe	01-05-75	EE	30000	E2	null	null	null
E2	M. Smith	06-04-66	SA	50000	E5	D3	Accounting	E5
E3	A. Lee	07-05-66	ME	40000	E7	D2	Consulting	E7
E4	J. Miller	09-01-50	PR	20000	E6	D3	Accounting	E5
E5	B. Casey	12-25-71	SA	50000	E8	D3	Accounting	E5
E6	L. Chu	11-30-65	EE	30000	E7	D2	Consulting	E7
E7	R. Davis	09-08-77	ME	40000	E8	D1	Management	E8
E8	J. Jones	10-11-72	SA	50000	null	D1	Management	E8

Consider these two types of insertion anomalies:

- 1) Insert a new employee E9 working in department D2.
  - You have to redundantly insert the department name and manager when adding this record.
- 2) Insert a department D4 that has no current employees.
  - This insertion is not possible without creating a dummy employee id and record because `eno` is the primary key of the relation.

Deletion Anomaly Example

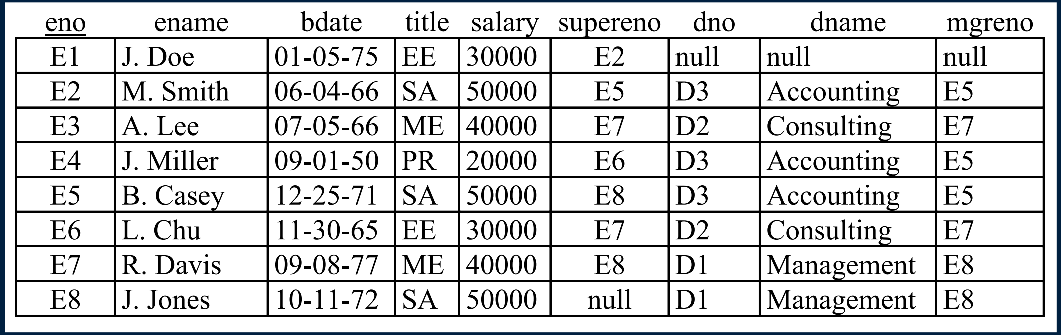


eno	ename	bdate	title	salary	supereno	dno	dname	mgreno
E1	J. Doe	01-05-75	EE	30000	E2	null	null	null
E2	M. Smith	06-04-66	SA	50000	E5	D3	Accounting	E5
E3	A. Lee	07-05-66	ME	40000	E7	D2	Consulting	E7
E4	J. Miller	09-01-50	PR	20000	E6	D3	Accounting	E5
E5	B. Casey	12-25-71	SA	50000	E8	D3	Accounting	E5
E6	L. Chu	11-30-65	EE	30000	E7	D2	Consulting	E7
E7	R. Davis	09-08-77	ME	40000	E8	D1	Management	E8
E8	J. Jones	10-11-72	SA	50000	null	D1	Management	E8

Consider this deletion anomaly:

- Delete employees E3 and E6 from the database.
- Deleting those two employees removes them from the database, and we now have lost information about department D2!

Modification Anomaly Example



eno	ename	bdate	title	salary	supereno	dno	dname	mgreno
E1	J. Doe	01-05-75	EE	30000	E2	null	null	null
E2	M. Smith	06-04-66	SA	50000	E5	D3	Accounting	E5
E3	A. Lee	07-05-66	ME	40000	E7	D2	Consulting	E7
E4	J. Miller	09-01-50	PR	20000	E6	D3	Accounting	E5
E5	B. Casey	12-25-71	SA	50000	E8	D3	Accounting	E5
E6	L. Chu	11-30-65	EE	30000	E7	D2	Consulting	E7
E7	R. Davis	09-08-77	ME	40000	E8	D1	Management	E8
E8	J. Jones	10-11-72	SA	50000	null	D1	Management	E8

Consider these modification anomalies:

- 1) Change the name of department D3 to Embezzling.
  - You must update the department name in 3 different records.
- 2) Change the manager of D1 to E4.
  - You must update the `mgreno` field in 2 different records.

Desirable Relational Schema Properties

Relational schemas that are well-designed have several important properties:

- 1) The most basic property is that relations consists of attributes that are logically related.
  - The attributes in a relation should belong to only one entity or relationship.
- 2) ***Lossless-join property*** ensures that the information decomposed across many relations can be reconstructed using natural joins.
- 3) ***Dependency preservation property*** ensures that constraints on the original relation can be maintained by enforcing constraints on the normalized relations.

Normalization Question

Question: How many of the following statements are ***true***?

1) Normalization is a bottom up process.

2) Anomalies with updates often are indicators of a bad design.

3) The lossless-join property means that it is possible to reconstruct the original relation after normalization using joins.

4) The dependency preservation property means that constraints should be preserved before and after normalization.

A) 0 **B)** 1 **C)** 2 **D)** 3 **E)** 4

Functional Dependencies

Functional dependencies represent constraints on the values of attributes in a relation and are used in normalization.

A ***functional dependency*** (abbreviated ***FD***) is a statement about the relationship between attributes in a relation. We say a set of attributes *X* functionally determines an attribute *Y* if given the values of *X* we always know the only possible value of *Y*.

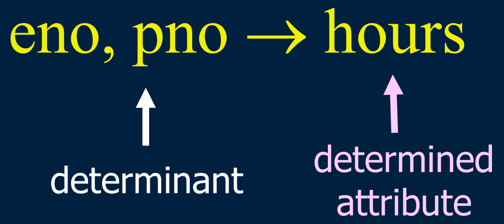
- Notation: $X \rightarrow Y$
- *X* functionally determines *Y*
- *Y* is functionally dependent on *X*

Example:

- eno → ename
- eno, pno → hours

Notation for Functional Dependencies

A functional dependency has a left-side called the ***determinant*** which is a set of attributes, and one attribute on the right-side.



$$\text{eno, pno} \rightarrow \text{hours}$$

determinant

determined attribute

Strictly speaking, there is always only one attribute on the RHS, but we can combine several functional dependencies into one:

$$\text{eno, pno} \rightarrow \text{hours}$$
$$\text{eno, pno} \rightarrow \text{resp}$$

$$\text{eno, pno} \rightarrow \text{hours, resp}$$

Remember that this is really short-hand for two functional dependencies.

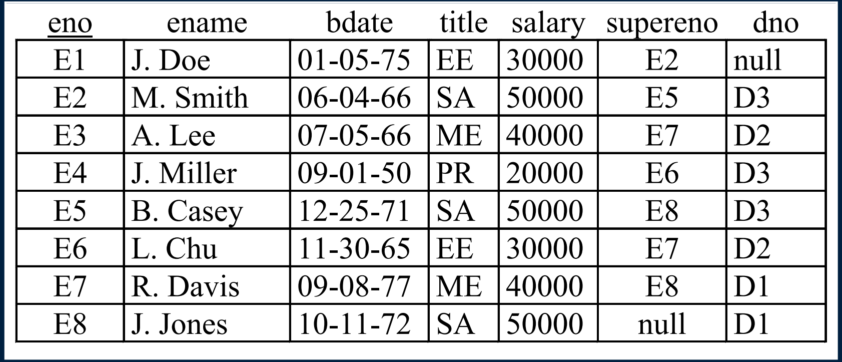
The Semantics of Functional Dependencies

Functional dependencies are a property of the ***domain*** being modeled **NOT** of the data instances currently in the database.

- This means that similar to keys you cannot tell if one attribute is functionally dependent on another by looking at the data.

Example:

Emp Relation



eno	ename	bdate	title	salary	supereno	dno
E1	J. Doe	01-05-75	EE	30000	E2	null
E2	M. Smith	06-04-66	SA	50000	E5	D3
E3	A. Lee	07-05-66	ME	40000	E7	D2
E4	J. Miller	09-01-50	PR	20000	E6	D3
E5	B. Casey	12-25-71	SA	50000	E8	D3
E6	L. Chu	11-30-65	EE	30000	E7	D2
E7	R. Davis	09-08-77	ME	40000	E8	D1
E8	J. Jones	10-11-72	SA	50000	null	D1

- List the functional dependencies of the attributes in this relation.

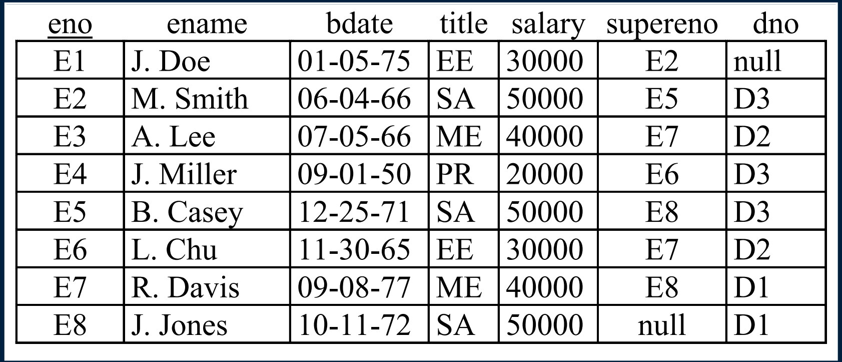
The Semantics of Functional Dependencies (2)

Functional dependencies are directional.

eno → ename does not mean that ename → eno

Example:

Emp Relation



eno	ename	bdate	title	salary	supereno	dno
E1	J. Doe	01-05-75	EE	30000	E2	null
E2	M. Smith	06-04-66	SA	50000	E5	D3
E3	A. Lee	07-05-66	ME	40000	E7	D2
E4	J. Miller	09-01-50	PR	20000	E6	D3
E5	B. Casey	12-25-71	SA	50000	E8	D3
E6	L. Chu	11-30-65	EE	30000	E7	D2
E7	R. Davis	09-08-77	ME	40000	E8	D1
E8	J. Jones	10-11-72	SA	50000	null	D1

- Given an employee name there may be multiple values for `eno` if we have employees in the database with the same name.
- Thus knowing `ename` does not uniquely tell us the value of `eno`.

Trivial Functional Dependencies

A functional dependency is ***trivial*** if the attributes on its left-hand side are a superset of the attributes on its right-hand side.

Examples:

$$\text{eno} \rightarrow \text{eno}$$

$$\text{eno, ename} \rightarrow \text{eno}$$

$$\text{eno, pno, hours} \rightarrow \text{eno, hours}$$

Trivial functional dependencies are not interesting because they do not tell us anything.

- Trivial FDs basically say "If you know the values of these attributes, then you uniquely know the values of any subset of those attributes.

We are only interested in ***nontrivial*** FDs.

Functional Dependencies and Keys

Functional dependencies can be used to determine the candidate and primary keys of a relation.

- For example, if an attribute functionally determines all other attributes in the relation, that attribute can be a key:

$$\text{eno} \rightarrow \text{eno, ename, bdate, title, supereno, dno}$$

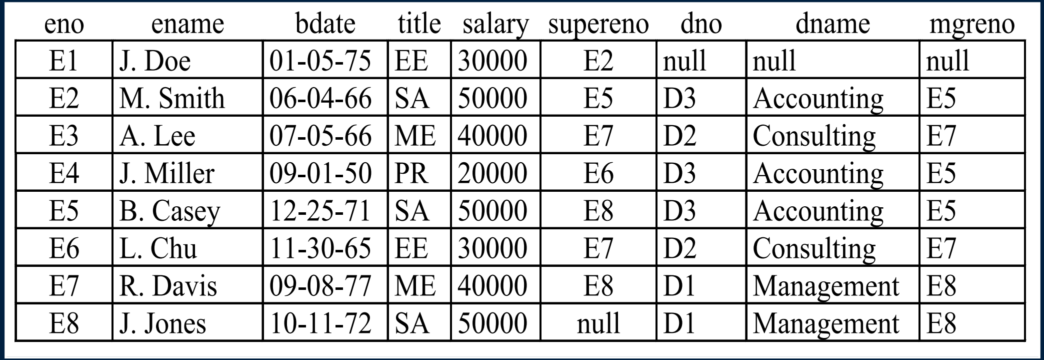
- `eno` is a candidate key for the `Employee` relation.

Alternate definition of keys:

- A set of attributes *K* is a ***superkey*** for a relation *R* if the set of attributes *K* functionally determines all attributes in *R*.
- A set of attributes *K* is a ***candidate key*** for a relation *R* if *K* is a *minimal* superkey of *R*.

Functional Dependencies and Keys (2)

EmpDept Relation



eno	ename	bdate	title	salary	supereno	dno	dname	mgreno
E1	J. Doe	01-05-75	EE	30000	E2	null	null	null
E2	M. Smith	06-04-66	SA	50000	E5	D3	Accounting	E5
E3	A. Lee	07-05-66	ME	40000	E7	D2	Consulting	E7
E4	J. Miller	09-01-50	PR	20000	E6	D3	Accounting	E5
E5	B. Casey	12-25-71	SA	50000	E8	D3	Accounting	E5
E6	L. Chu	11-30-65	EE	30000	E7	D2	Consulting	E7
E7	R. Davis	09-08-77	ME	40000	E8	D1	Management	E8
E8	J. Jones	10-11-72	SA	50000	null	D1	Management	E8

eno → eno, ename, bdate, title, salary, supereno, dno

dno → dname, mgreno

Question: List the candidate key(s) of this relation.

Functional Dependency Rules

Functional dependencies follow rules (Armstrong's Axioms 1974) with the most important being ***transitivity***.

Transitive Rule: If $A \rightarrow B$ and $B \rightarrow C$ then $A \rightarrow C$

Functional Dependency Question

Question: How many of the following statements are ***true***?

1) Functional dependencies are not directional.

2) A trivial functional dependency has its right side as a subset of (or the same as) its left side.

3) A candidate key is a minimal set of attributes that functionally determines all attributes in a relation.

4) Functional dependencies can be determined by examining the data in a relation.

A) 0 **B)** 1 **C)** 2 **D)** 3 **E)** 4

Computing the Attribute Closure

Given any set of attributes *X* and a set of functional dependencies *F*, we can compute the set of all attributes X^+ that can be functionally determined using *F*.

This is called the ***closure of X under F***.

Note that X is a superkey of R if X^+ is all attributes of R.

Computing the Attribute Closure

The algorithm is as follows:

- Given a set of attributes *X*.
- Let $X^+ = X$
- Repeat
  - Find a FD in *F* whose left side is a subset of X^+.
  - Add the right side of *F* to X^+.
- Until (X^+ does not change)

After the algorithm completes you have a set of attributes X^+ that can be functionally determined from *X*. This allows you to produce FDs of the form:

- $X \rightarrow A$ where *A* is in X^+

Computing Attribute Closure Example

$R\ (A,B,C,D,E,G)$

$F = \{A \rightarrow B,C \quad , \quad C \rightarrow D \quad , \quad D \rightarrow G\}$

Compute $\{A\}^+$:

- $\{A\}^+ = \{A\}$ (initial step)
- $\{A\}^+ = \{A,B,C\}$ (by using FD $A \rightarrow B,C$)
- $\{A\}^+ = \{A,B,C,D\}$ (by using FD $C \rightarrow D$)
- $\{A\}^+ = \{A,B,C,D,G\}$ (by using FD $D \rightarrow G$)

Similarly we can compute $\{C\}^+$, $\{E,G\}^+$, and $\{\mathrm{A},E\}^+$:

- $\{C\}^+ = \{C,D,G\}$
- $\{E,G\}^+ = \{E,G\}$
- $\{A,E\}^+ = \{A,B,C,D,\mathrm{E},G\}$ **Since this is all attributes of R, {A,E} is a key for R.**

Function Dependency Closure Question

Question: Given the following, is D in {A, B}$^{+}$?

```
R = (A,B,C,D)
F = { A,B → C ; C → D ; D → A }
```

A) yes

B) no

Function Dependency Key Question

Question: Given the following FDs, how many keys of R?

$$R = (A,B,C,D)$$

$$F = \{\ A,B \rightarrow C\ ;\ C \rightarrow D\ ;\ D \rightarrow A\ \}$$

A) 0

B) 1

C) 2

D) 3

E) 4

Normal Forms

A relation is in a ***normal form*** if it satisfies certain properties:

- 1NF - First Normal Form: All attribute values are atomic (no arrays or tuples).
- 2NF - Second Normal Form: All non-key attributes full FD on a candidate key.
- 3NF - Third Normal Form: All attributes are FD by a candidate key or are part of a candidate key. (no transitive dependencies)
- BCNF - Boyce-Codd Normal Form: All attributes are only FD by a candidate key.
- 4NF - Fourth Normal Form: No multi-value dependencies exist.
- 5NF - Fifth Normal Form: No join dependencies exist.

Each of these normal forms are stricter than the next.

- For example, 3NF is better than 2NF because it removes more redundancy/anomalies from the schema than 2NF.

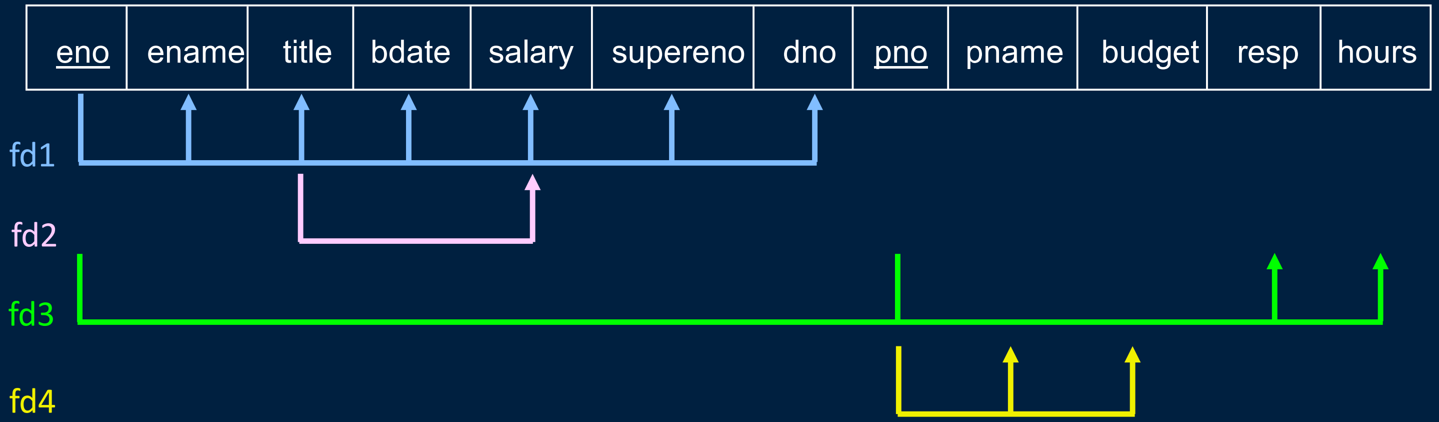
Conversion to BCNF

Algorithm for converting to BCNF given relation *R* with FDs *F*:

- Look among the given FDs for a BCNF violation $X \rightarrow Y$.
- Compute X^+.
  - X^+ is all the attributes that can be determined from X (called the closure of X).
  - Note that X^+ cannot be the set of all attributes or else X is a superkey.
- Replace R by relations with schemas:
  - $R_1 = X^+$
  - $R_2 = (R - X^+) \cup X$
- Project the FDs *F* onto the two new relations by:
  - Computing the closure of *F* and then using only the FDs whose attributes are all in R_1 or R_2.

BCNF Normalization Example

EmpProj relation:



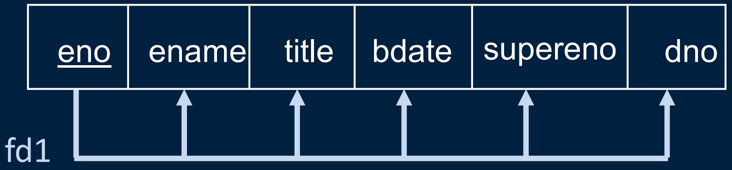
Key is `eno, pno`.

Left-hand side of fd1, fd2, and fd4 are not superkeys.

Compute the closure of each one and separate into own relations.

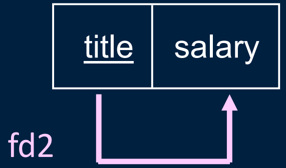
BCNF Normalization Example (2)

Emp



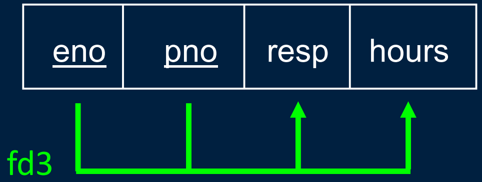
eno	ename	title	bdate	supereno	dno

Pay



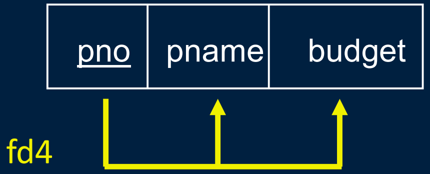
title	salary

WorksOn relation:



eno	pno	resp	hours

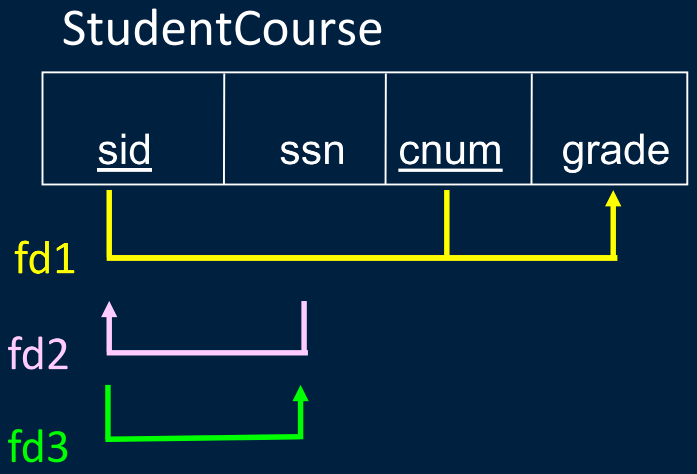
Proj relation:



pno	pname	budget

Normalization to BCNF Question

Given this schema normalize into BCNF.



StudentCourse

sid	ssn	cnum	grade

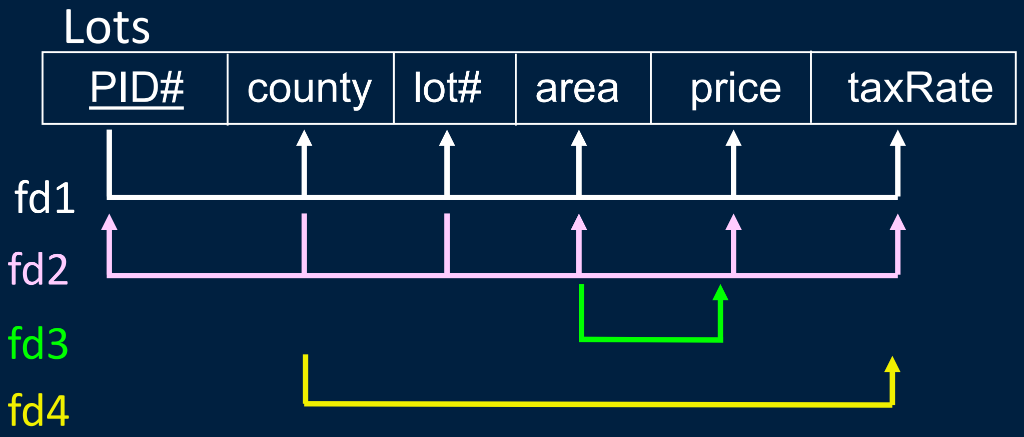
fd1

fd2

fd3

Normalization Question

Given this database schema normalize into BCNF.



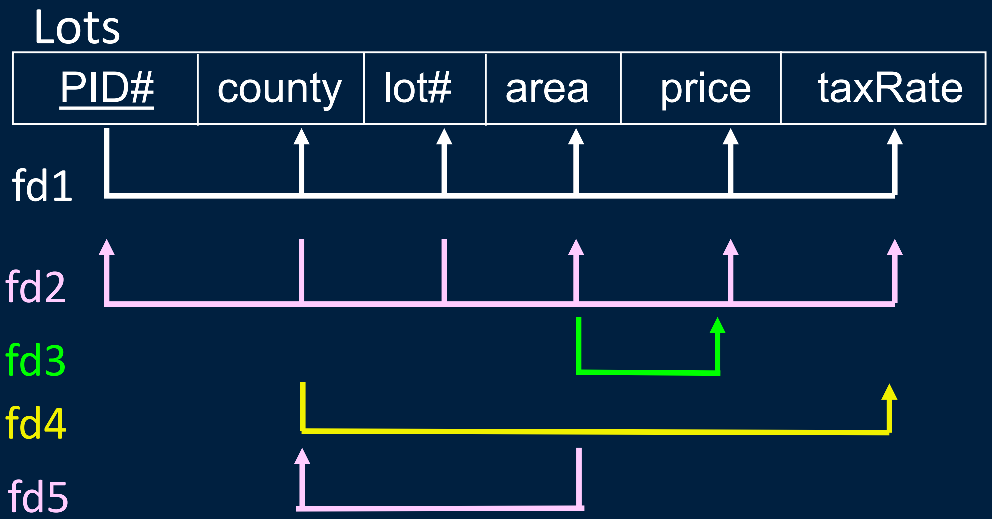
Lots

PID#	county	lot#	area	price	taxRate

- Description:
    - Lots (parcels of land) are identified within each county.
    - Each lot can be uniquely identified either by the Property ID# or by the County name and the Lot#. Property id's are unique but lot#'s are unique only with the county.
    - The tax rate is constant within each county.
    - The price is based on the area of the land.

Normalization Question 2

Given this database schema normalize into BCNF.



Lots

PID#	county	lot#	area	price	taxRate

fd1

fd2

fd3

fd4

fd5

- New FD5 says that the size of the parcel of land determines what county it is in.
- What normal form does fd5 violate?

A) none **B)** 1NF **C)** 2NF **D)** 3NF **E)** BCNF

Normalization to BCNF Question

Given this schema normalize into BCNF:

- R (courseNum, secNum, offeringDept, creditHours, courseLevel, instructorSSN, semester, year, daysHours, roomNum, numStudents)
- courseNum → offeringDept,creditHours, courseLevel
- courseNum, secNum, semester, year → daysHours, roomNum, numStudents, instructorSSN
- roomNum, daysHours, semester, year → instructorSSN, courseNum, secNum

How many relations in your final result?

A) 1 **B)** 2 **C)** 3 **D)** 4 **E)** 5

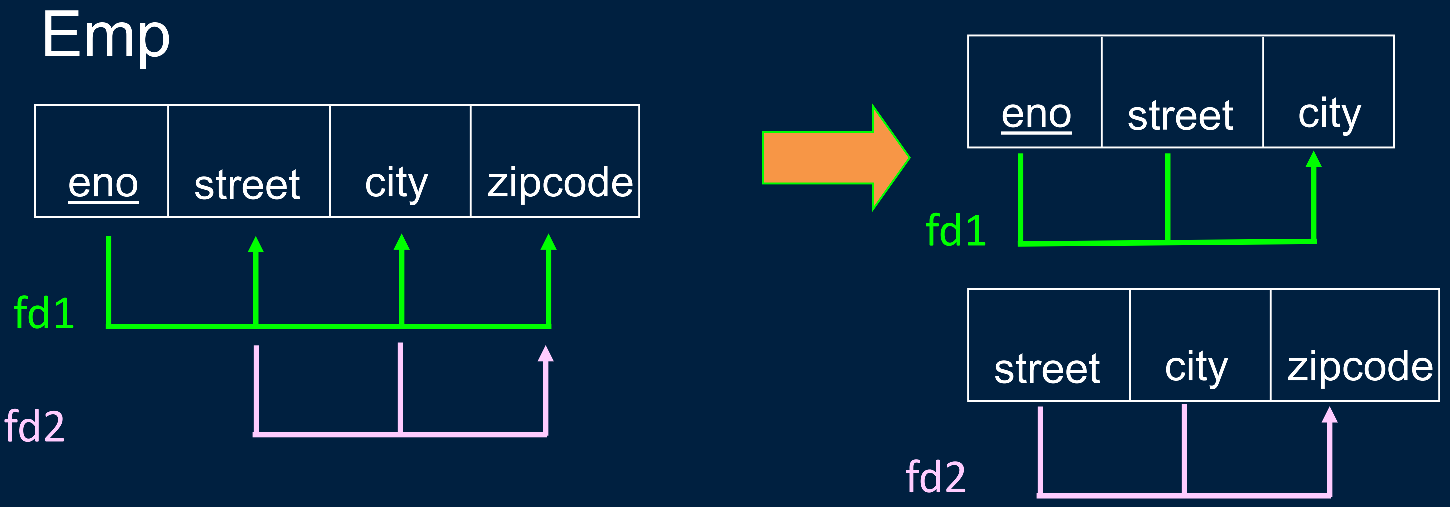
Normal Forms in Practice

Normal forms are used to prevent anomalies and redundancy. However, just because successive normal forms are better in reducing redundancy that does not mean they always have to be used.

For example, query execution time may increase because of normalization as more joins become necessary to answer queries.

Normal Forms in Practice Example

For example, `street` and `city` uniquely determine a `zipcode`.



Emp

eno	street	city	zipcode

fd1

fd2

eno	street	city

fd1

street	city	zipcode

fd2

In this case, reducing redundancy is not as important as the fact that a join is necessary every time the `zipcode` is needed.

- When a `zipcode` does change, it is easy to scan the entire `Emp` relation and update it accordingly.

Normal Forms and ER Modeling

Normalization and ER modeling are two independent concepts.

You can use ER modeling to produce an initial relational schema and then use normalization to remove any remaining redundancies.

- If you are a good ER modeler, it is rare that much normalization will be required.

In theory, you can use normalization by itself. This would involve identifying all attributes, giving them unique names, discovering all FDs and MVDs, then applying the normalization algorithms.

- Since this is a lot harder than ER modeling, most people do not do it.

Normal Forms in Practice Summary

In summary, normalization is typically used in two ways:

- To improve on relational schemas after ER design.
- To improve on existing relational schemas that are poorly designed and contain redundancy and potential for anomalies.

In practice, most designers make sure their schemas are in 3NF or BCNF because this removes most anomalies and redundancies. If multi-valued dependencies exist, they should definitely be removed to go to 4NF.

There is always a tradeoff in normalization. Normalization reduces redundancy but fragments the relations which makes it more expensive to query. Some redundancy may help performance.

- This is the classic time versus space tradeoff!

Conclusion

Normalization produces relations with desirable properties and reduces redundancy and update anomalies.

Normal forms indicate when relations satisfy certain properties.

- 1NF - All attributes are atomic.
- 2NF - All attributes are fully functionally dependent on a key.
- 3NF - There are no transitive dependencies in the relation.
- 4NF - There are no multi-valued dependencies in the relation.
- 5NF - The relation has no join dependency.

In practice, normalization is used to improve schemas produced after ER design and existing relational schemas.

- Full normalization is not always beneficial as it may increase query time.

Objectives

- Explain the process of normalization and why it is beneficial.
- Describe the concept of the Universal Relation.
- What are the motivations for normalization?
- What are the 3 types of update anomalies? Be able to give examples.
- Describe the lossless-join property and dependency preservation property.
- Define and explain the concept of a functional dependency.
- What is a trivial FD?
- Describe the relationship between FDs and keys.
- Define normal forms (1NF, 2NF, 3NF, BCNF).
- Normalize into BCNF.
- Explain normalization in terms of the time versus space tradeoff.
- Explain the relationship between normalization and ER modeling.

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