

Datalog

Logical Rules
Recursion
SQL-99 Recursion

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Logic As a Query Language

- ◆ If-then logical rules have been used in many systems.
 - ◆ Most important today: EII (Enterprise Information Integration).
- ◆ Nonrecursive rules are equivalent to the core relational algebra.
- ◆ Recursive rules extend relational algebra --- have been used to add recursion to SQL-99.

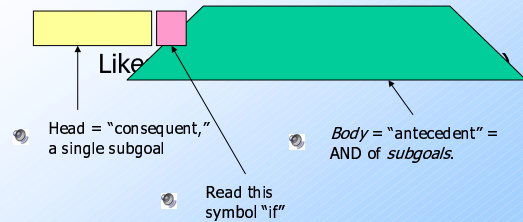
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A Logical Rule

- ◆ Our first example of a rule uses the relations `Frequents(drinker,bar)`, `Likes(drinker,beer)`, and `Sells(bar,beer,price)`.
- ◆ The rule is a query asking for "happy" drinkers --- those that frequent a bar that serves a beer that they like.

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Anatomy of a Rule



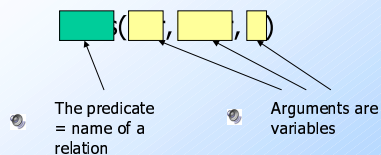
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Subgoals Are Atoms

- ◆ An *atom* is a *predicate*, or relation name with variables or constants as arguments.
- ◆ The head is an atom; the body is the AND of one or more atoms.
- ◆ Convention: Predicates begin with a capital, variables begin with lower-case.

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Example: Atom



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Interpreting Rules

- ◆ A variable appearing in the head is called *distinguished*; otherwise it is *nondistinguished*.
- ◆ Rule meaning: The head is true of the distinguished variables if there exist values of the nondistinguished variables that make all subgoals of the body true.

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Example: Interpretation

Happy(d) \leftarrow Frequent(d, b, p) AND
Likes(d, b, p) AND Sells(b, p)

◆ Distinguished variable

◆ Nondistinguished variables

◆ Interpretation: drinker d is happy if there exist a bar, a beer, and a price p such that d frequents the bar, likes the beer, and the bar sells the beer at price p .

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Arithmetic Subgoals

- ◆ In addition to relations as predicates, a predicate for a subgoal of the body can be an arithmetic comparison.
 - ◆ We write such subgoals in the usual way, e.g.: $x < y$.

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Example: Arithmetic

- ◆ A beer is "cheap" if there are at least two bars that sell it for under \$2.
Cheap(beer) \leftarrow Sells(bar1,beer,p1) AND
Sells(bar2,beer,p2) AND $p1 < 2.00$
AND $p2 < 2.00$ AND bar1 \neq bar2

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Negated Subgoals

- ◆ We may put NOT in front of a subgoal, to negate its meaning.
 - ◆ Example: Think of Arc(a,b) as arcs in a graph.
 - ◆ S(x,y) says the graph is not transitive from x to y ; i.e., there is a path of length 2 from x to y , but no arc from x to y .
- S(x,y) \leftarrow Arc(x,z) AND Arc(z,y)
AND NOT Arc(x,y)

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Safe Rules

- ◆ A rule is *safe* if:
 1. Each distinguished variable,
 2. Each variable in an arithmetic subgoal,
 3. Each variable in a negated subgoal, also appears in a nonnegated, relational subgoal.
- ◆ We allow only safe rules.

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Example: Unsafe Rules

- ◆ Each of the following is unsafe and not allowed:
 1. $S(x) \leftarrow R(y)$
 2. $S(x) \leftarrow R(x) \text{ AND NOT } R(y)$
 3. $S(x) \leftarrow R(y) \text{ AND } x < y$
- ◆ In each case, an infinity of x 's can satisfy the rule, even if R is a finite relation.

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Algorithms for Applying Rules

- ◆ Two approaches:
 1. *Variable-based*: Consider all possible assignments to the variables of the body. If the assignment makes the body true, add that tuple for the head to the result.
 2. *Tuple-based*: Consider all assignments of tuples from the non-negated, relational subgoals. If the body becomes true, add the head's tuple to the result.

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Example: Variable-Based --- 1

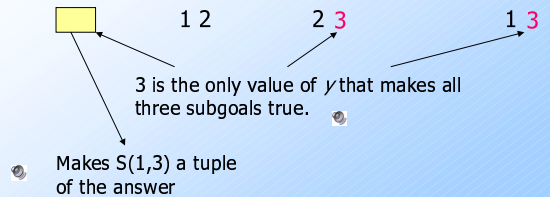
$S(x,y) \leftarrow \text{Arc}(x,z) \text{ AND } \text{Arc}(z,y) \text{ AND NOT } \text{Arc}(x,y)$

- ◆ $\text{Arc}(1,2)$ and $\text{Arc}(2,3)$ are the only tuples in the Arc relation.
- ◆ Only assignments to make the first subgoal $\text{Arc}(x,z)$ true are:
 1. $x = 1; z = 2$
 2. $x = 2; z = 3$

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Example: Variable-Based; $x=1, z=2$

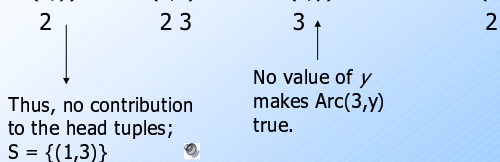
$S(x,y) \leftarrow \text{Arc}(x,z) \text{ AND } \text{Arc}(z,y) \text{ AND NOT } \text{Arc}(x,y)$



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Example: Variable-Based; $x=2, z=3$

$S(x,y) \leftarrow \text{Arc}(x,z) \text{ AND } \text{Arc}(z,y) \text{ AND NOT } \text{Arc}(x,y)$



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Tuple-Based Assignment

- ◆ Start with the non-negated, relational subgoals only.
- ◆ Consider all assignments of tuples to these subgoals.
 - ◆ Choose tuples only from the corresponding relations.
- ◆ If the assigned tuples give a consistent value to all variables and make the other subgoals true, add the head tuple to the result.

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Example: Tuple-Based

$S(x,y) \leftarrow \text{Arc}(x,z) \text{ AND } \text{Arc}(z,y) \text{ AND NOT } \text{Arc}(x,y)$
 $\text{Arc}(1,2), \text{Arc}(2,3)$

- ◆ Four possible assignments to first two subgoals:

Arc(x,z)	Arc(z,y)
(1,2)	(1,2)
(2,3)	(1,2)
(2,3)	(2,3)

Only assignment with consistent z-value. Since it also makes NOT Arc(x,y) true, add S(1,3) to result.

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Datalog Programs

- ◆ A *Datalog program* is a collection of rules.
- ◆ In a program, predicates can be either
 1. EDB = *Extensional Database* = stored table.
 2. IDB = *Intensional Database* = relation defined by rules.
- ◆ Never both! No EDB in heads.

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Evaluating Datalog Programs

- ◆ As long as there is no recursion, we can pick an order to evaluate the IDB predicates, so that all the predicates in the body of its rules have already been evaluated.
- ◆ If an IDB predicate has more than one rule, each rule contributes tuples to its relation.

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Example: Datalog Program

- ◆ Using EDB $\text{Sells}(\text{bar}, \text{beer}, \text{price})$ and $\text{Beers}(\text{name}, \text{manf})$, find the manufacturers of beers Joe doesn't sell.

$\text{JoeSells}(b) \leftarrow \text{Sells}(\text{'Joe's Bar'}, b, p)$
 $\text{Answer}(m) \leftarrow \text{Beers}(b,m)$
 AND NOT $\text{JoeSells}(b)$

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Expressive Power of Datalog

- ◆ Without recursion, Datalog can express all and only the queries of core relational algebra.
 - ◆ The same as SQL select-from-where, without aggregation and grouping.
- ◆ But with recursion, Datalog can express more than these languages.
- ◆ Yet still not Turing-complete.

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Recursive Example

- ◆ EDB: $\text{Par}(c,p) = p$ is a parent of c .
- ◆ Generalized cousins: people with common ancestors one or more generations back:
 - $\text{Sib}(x,y) \leftarrow \text{Par}(x,p) \text{ AND } \text{Par}(y,p) \text{ AND } x \neq y$
 - $\text{Cousin}(x,y) \leftarrow \text{Sib}(x,y)$
 - $\text{Cousin}(x,y) \leftarrow \text{Par}(x,xp) \text{ AND } \text{Par}(y,yp)$
 AND $\text{Cousin}(xp,yp)$

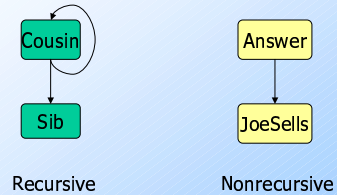
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Definition of Recursion

- ◆ Form a *dependency graph* whose nodes = IDB predicates.
- ◆ Arc $X \rightarrow Y$ if and only if there is a rule with X in the head and Y in the body.
- ◆ Cycle = recursion; no cycle = no recursion.

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Example: Dependency Graphs



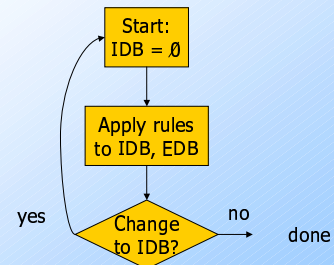
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Evaluating Recursive Rules

- ◆ The following works when there is no negation:
 1. Start by assuming all IDB relations are empty.
 2. Repeatedly evaluate the rules using the EDB and the previous IDB, to get a new IDB.
 3. End when no change to IDB.

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The "Naïve" Evaluation Algorithm



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Example: Evaluation of Cousin

- ◆ We'll proceed in rounds to infer Sib facts (red) and Cousin facts (green).
- ◆ Remember the rules:

$Sib(x,y) \leftarrow Par(x,p) \text{ AND } Par(y,p) \text{ AND } x \neq y$
 $Cousin(x,y) \leftarrow Sib(x,y)$
 $Cousin(x,y) \leftarrow Par(x,xp) \text{ AND } Par(y,yp) \text{ AND } Cousin(xp,yp)$

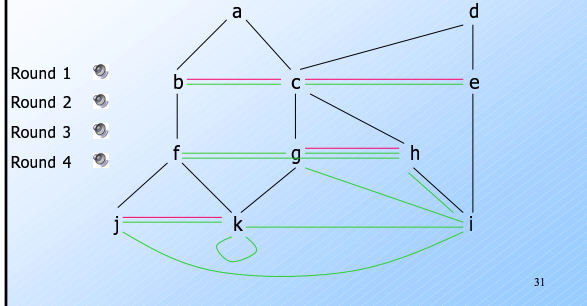
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Seminaive Evaluation

- ◆ Since the EDB never changes, on each round we only get new IDB tuples if we use at least one IDB tuple that was obtained on the previous round.
- ◆ Saves work; lets us avoid rediscovering *most* known facts.
 - ◆ A fact could still be derived in a second way.

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Par Data: Parent Above Child



Recursion Plus Negation

- ◆ "Naïve" evaluation doesn't work when there are negated subgoals.
- ◆ In fact, negation wrapped in a recursion makes no sense in general.
- ◆ Even when recursion and negation are separate, we can have ambiguity about the correct IDB relations.

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Stratified Negation

- ◆ Stratification is a constraint usually placed on Datalog with recursion and negation.
- ◆ It rules out negation wrapped inside recursion.
- ◆ Gives the sensible IDB relations when negation and recursion are separate.

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Problematic Recursive Negation

$P(x) \leftarrow Q(x) \text{ AND NOT } P(x)$
EDB: $Q(1), Q(2)$

Initial: $P = \{ \}$
Round 1: $P = \{(1), (2)\}$
Round 2: $P = \{ \}$
Round 3: $P = \{(1), (2)\}, \text{ etc., etc. ...}$

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Strata

- ◆ Intuitively, the *stratum* of an IDB predicate P is the maximum number of negations that can be applied to an IDB predicate used in evaluating P .
- ◆ Stratified negation = "finite strata."
- ◆ Notice in $P(x) \leftarrow Q(x) \text{ AND NOT } P(x)$, we can negate P an infinite number of times deriving $P(x)$.

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Stratum Graph

- ◆ To formalize strata use the *stratum graph*:
 - ◆ Nodes = IDB predicates.
 - ◆ Arc $A \rightarrow B$ if predicate A depends on B .
 - ◆ Label this arc "-" if the B subgoal is negated.

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Stratified Negation Definition

- ◆ The *stratum* of a node (predicate) is the maximum number of $-$ arcs on a path leading from that node.
- ◆ A Datalog program is *stratified* if all its IDB predicates have finite strata.

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Example

$P(x) \leftarrow Q(x) \text{ AND NOT } P(x)$



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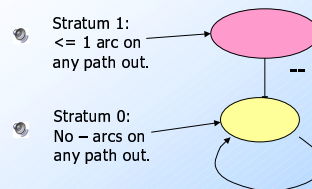
Another Example

- ◆ EDB = Source(x), Target(x), Arc(x,y).
- ◆ Rules for "targets not reached from any source":

$\text{Reach}(x) \leftarrow \text{Source}(x)$
 $\text{Reach}(x) \leftarrow \text{Reach}(y) \text{ AND Arc}(y,x)$
 $\text{NoReach}(x) \leftarrow \text{Target}(x)$
 $\text{AND NOT Reach}(x)$

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The Stratum Graph



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Models

- ◆ A *model* is a choice of IDB relations that, with the given EDB relations makes all rules true regardless of what values are substituted for the variables.
 - ◆ Remember: a rule is true whenever its body is false.
 - ◆ But if the body is true, then the head must be true as well.

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Minimal Models

- ◆ When there is no negation, a Datalog program has a unique minimal model (one that does not contain any other model).
- ◆ But with negation, there can be several minimal models.
- ◆ The stratified model is the one that "makes sense."

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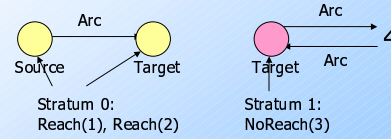
The Stratified Model

- ◆ When the Datalog program is stratified, we can evaluate IDB predicates lowest-stratum-first.
- ◆ Once evaluated, treat it as EDB for higher strata.

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Example: Multiple Models --- 1

```
Reach(x) <- Source(x)
Reach(x) <- Reach(y) AND Arc(y,x)
NoReach(x) <- Target(x) AND NOT Reach(x)
```



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Example: Multiple Models --- 2

```
Reach(x) <- Source(x)
Reach(x) <- Reach(y) AND Arc(y,x)
NoReach(x) <- Target(x) AND NOT Reach(x)
```



Another model! Reach(1), Reach(2),
Reach(3), Reach(4); NoReach is empty.

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SQL-99 Recursion

- ◆ Datalog recursion has inspired the addition of recursion to the SQL-99 standard.
- ◆ Trickier, because SQL allows grouping-and-aggregation, which behaves like negation and requires a more complex notion of stratification.

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Form of SQL Recursive Queries

WITH
 <stuff that looks like Datalog rules>
 <an SQL query about EDB, IDB>

Rule =
 [RECURSIVE] <name>(<arguments>)
 AS <query>

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Example: SQL Recursion --- 1

- ◆ Find Sally's cousins, using SQL like the recursive Datalog example.
- ◆ Par(child,parent) is the EDB.

WITH Sib(x,y) AS

Like Sib(x,y) <-
 Par(x,p) AND
 Par(y,p) AND
 x <> y



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Example: SQL Recursion --- 2

WITH ...
 RECURSIVE Cousin(x,y) AS
 [Green Box]
 UNION
 [Yellow Box]

Reflects Cousin(x,y) <- Sib(x,y)

Reflects Cousin(x,y) <- Par(x,yp) AND Par(y,yp) AND Cousin(xp,yp)

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Example: SQL Recursion --- 3

◆ With those definitions, we can add the query, which is about the "temporary view" Cousin(x,y):

```
SELECT y
FROM Cousin
WHERE x = 'Sally';
```

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Plan to Explain Legal SQL Recursion

1. Define "monotonicity," a generalization of "stratified."
2. Generalize stratum graph to apply to SQL.
3. Define proper SQL recursions in terms of the stratum graph.

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Monotonicity

- ◆ If relation P is a function of relation Q (and perhaps other relations), we say P is *monotone* in Q if inserting tuples into Q cannot cause any tuple to be deleted from P .
- ◆ Examples:
- ◆ $P = Q \text{ UNION } R$.
 - ◆ $P = \text{SELECT}_{a=10}(Q)$.

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Example: Nonmonotonicity

◆ If Sells(bar,beer,price) is our usual relation, then the result of the query:

```
SELECT AVG(price)
FROM Sells
WHERE bar = 'Joe's Bar';
```

is not monotone in Sells.

◆ Inserting a Joe's-Bar tuple into Sells usually changes the average price and thus deletes the old average price.

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SQL Stratum Graph --- 2

- ◆ Nodes =
1. IDB relations declared in WITH clause.
 2. Subqueries in the body of the "rules."
 - ◆ Includes subqueries at any level of nesting.

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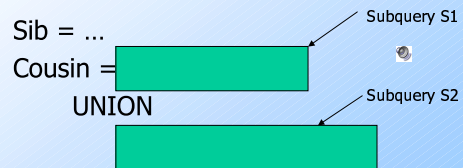
SQL Stratum Graph --- 2

- ◆ Arcs $P \rightarrow Q$:
 1. P is a rule head and Q is a relation in the FROM list (not of a subquery).
 2. P is a rule head and Q is an immediate subquery of that rule.
 3. P is a subquery, and Q is a relation in its FROM or an immediate subquery (like 1 and 2).
- ◆ Put “-” on an arc if P is not monotone in Q .
- ◆ Stratified SQL = finite #'s of -'s on paths.

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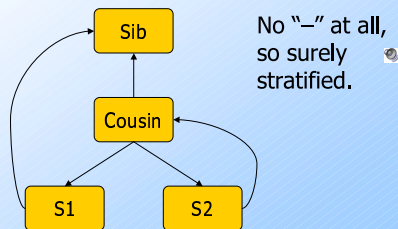
Example: Stratum Graph

- ◆ In our Cousin example, the structure of the rules was:



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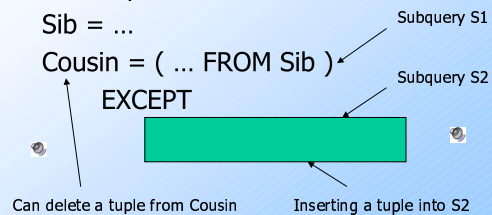
The Graph



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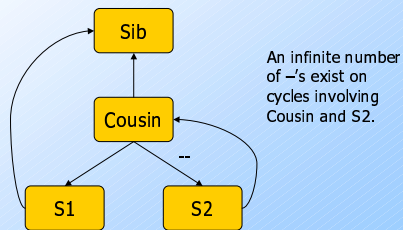
Nonmonotone Example

- ◆ Change the UNION in the Cousin example to EXCEPT:



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The Graph



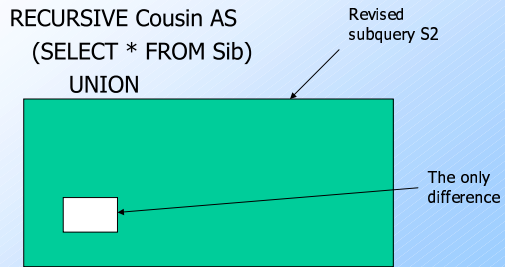
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NOT Doesn't Mean Nonmonotone

- ◆ Not every NOT means the query is nonmonotone.
 - ◆ We need to consider each case separately.
- ◆ Example: Negating a condition in a WHERE clause just changes the selection condition.
 - ◆ But all selections are monotone.

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Example: Revised Cousin



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S2 Still Monotone in Cousin

- ◆ Intuitively, adding a tuple to Cousin cannot delete from S2.
- ◆ All former tuples in Cousin can still work with Par tuples to form S2 tuples.
- ◆ In addition, the new Cousin tuple might even join with Par tuples to add to S2.

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