SQL: Recursion

Introduction to Databases
CompSci 316 Fall 2021
Announcements (Tue., Sep. 28)

• Homework 1 graded
• We are still working on Project Milestone 1 submissions

• Homework 2, Gradiance SQL constraints due today
  • Tomorrow morning:
    • Homework 2 sample solution will be posted on Sakai
    • Old Gradiance exercises will reopen
      • We will take a snapshot of the scores before that

• My office hours today extended to 5pm, but I need to step out 3:30-4pm
• Gradiance SQL recursion assigned
Announcements cont’d

• Thursday: *Midterm*
  • In-class, open-book, open-notes
  • Questions on paper, but you will need a computer to submit—make sure it has enough battery!
  • Sample midterm/solution posted on Sakai
  • **NEW:** it will NOT cover materials discussed today
    • Triggers/views are fair game, but coverage will be light (if any)

• Thursday after fall break
  • Project Milestone 2 due
  • Gradiance SQL Triggers/Views due *(extended)*
  • Gradiance SQL recursion due
WHAT IS IT?

RECURSION

http://xkcdsw.com/1105
A motivating example

• Example: find Bart’s ancestors

• “Ancestor” has a recursive definition
  • $X$ is $Y$’s ancestor if
    • $X$ is $Y$’s parent, or
    • $X$ is $Z$’s ancestor and $Z$ is $Y$’s ancestor
Recursion in SQL

• SQL2 had no recursion
  • You can find Bart’s parents, grandparents, great grandparents, etc.
    
    SELECT p1.parent AS grandparent
    FROM Parent p1, Parent p2
    WHERE p1.child = p2.parent
    AND p1.child = 'Bart';

  • But you cannot find all his ancestors with a single query

• SQL3 introduces recursion
  • WITH clause
  • Implemented in PostgreSQL (common table expressions)
Ancestor query in SQL3

WITH RECURSIVE
Ancestor(anc, desc) AS 
((SELECT parent, child FROM Parent)
UNION
(SELECT al.anc, a2.desc
FROM Ancestor al, Ancestor a2
WHERE al.desc = a2.anc))

SELECT anc
FROM Ancestor
WHERE desc = 'Bart';
Fixed point of a function

• If \( f: D \to D \) is a function from a type \( D \) to itself, a **fixed point** of \( f \) is a value \( x \) such that \( f(x) = x \)

• Example: What is the fixed point of \( f(x) = x/2 \)?
  • 0, because \( f(0) = 0/2 = 0 \)

• To compute a fixed point of \( f \)
  • Start with a “seed”: \( x \leftarrow x_0 \)
  • Compute \( f(x) \)
    • If \( f(x) = x \), stop; \( x \) is fixed point of \( f \)
    • Otherwise, \( x \leftarrow f(x) \); repeat

• Example: compute the fixed point of \( f(x) = x/2 \)
  • With seed 1: 1, 1/2, 1/4, 1/8, 1/16, ... \( \to 0 \)

\( \blacksquare \) Doesn’t always work, but happens to work for us!
Fixed point of a query

• A query $q$ is just a function that maps an input table to an output table, so a **fixed point** of $q$ is a table $T$ such that $q(T) = T$

• To compute fixed point of $q$
  • Start with an empty table: $T \leftarrow \emptyset$
  • Evaluate $q$ over $T$
    • If the result is identical to $T$, stop; $T$ is a fixed point
    • Otherwise, let $T$ be the new result; repeat

$\text{Starting from } \emptyset \text{ produces the unique minimal fixed point (assuming } q \text{ is monotone)}$
Finding ancestors

• WITH RECURSIVE Ancestor(anc, desc) AS
  ((SELECT parent, child FROM Parent)
   UNION
   (SELECT a1.anc, a2.desc
    FROM Ancestor a1, Ancestor a2
    WHERE a1.desc = a2.anc))
• Think of the definition as Ancestor = q(Ancestor)
Intuition behind fixed-point iteration

• Initially, we know nothing about ancestor-descendent relationships

• In the first step, we deduce that parents and children form ancestor-descendent relationships

• In each subsequent steps, we use the facts deduced in previous steps to get more ancestor-descendent relationships

• We stop when no new facts can be proven
Linear recursion

- With linear recursion, a recursive definition can make only one reference to itself

- Non-linear
  - `WITH RECURSIVE Ancestor(anc, desc) AS
    ((SELECT parent, child FROM Parent)
     UNION
     (SELECT al.anc, a2.desc
      FROM Ancestor al, Ancestor a2
      WHERE al.desc = a2.anc))`

- Linear
  - `WITH RECURSIVE Ancestor(anc, desc) AS
    ((SELECT parent, child FROM Parent)
     UNION
     (SELECT anc, child
      FROM Ancestor, Parent
      WHERE desc = parent))`
Linear vs. non-linear recursion

• Linear recursion is easier to implement
  • For linear recursion, just keep joining newly generated Ancestor rows with Parent
  • For non-linear recursion, need to join newly generated Ancestor rows with all existing Ancestor rows

• Non-linear recursion may take fewer steps to converge, but perform more work
  • Example: $a \rightarrow b \rightarrow c \rightarrow d \rightarrow e$
  • Linear recursion takes 4 steps
  • Non-linear recursion takes 3 steps
    • More work: e.g., $a \rightarrow d$ has two different derivations
http://xkcdsw.com/3080
Mutual recursion example

• Table Natural \( (n) \) contains 1, 2, \ldots, 100

• Which numbers are even/odd?
  • An odd number plus 1 is an even number
  • An even number plus 1 is an odd number
  • 1 is an odd number

WITH RECURSIVE Even\( (n) \) AS
  (SELECT n FROM Natural
   WHERE n = ANY(SELECT n+1 FROM Odd)),

RECURSIVE Odd\( (n) \) AS
  ((SELECT n FROM Natural WHERE n = 1)
   UNION
   (SELECT n FROM Natural
    WHERE n = ANY(SELECT n+1 FROM Even)))
Semantics of WITH

WITH RECURSIVE $R_1$ AS $Q_1$, …,
RECURSIVE $R_n$ AS $Q_n$

$Q$;

• $Q$ and $Q_1$, …, $Q_n$ may refer to $R_1$, …, $R_n$

• Semantics

1. $R_1 \leftarrow \emptyset$, …, $R_n \leftarrow \emptyset$
2. Evaluate $Q_1$, …, $Q_n$ using the current contents of $R_1$, …, $R_n$:
   $R_1^{new} \leftarrow Q_1$, …, $R_n^{new} \leftarrow Q_n$
3. If $R_i^{new} \neq R_i$ for some $i$
   3.1. $R_1 \leftarrow R_1^{new}$, …, $R_n \leftarrow R_n^{new}$
   3.2. Go to 2.
4. Compute $Q$ using the current contents of $R_1$, …, $R_n$
and output the result
Computing mutual recursion

WITH RECURSIVE Even(n) AS
    (SELECT n FROM Natural
     WHERE n = ANY(SELECT n+1 FROM Odd)),

RECURSIVE Odd(n) AS
    ((SELECT n FROM Natural WHERE n = 1)
     UNION
     (SELECT n FROM Natural
      WHERE n = ANY(SELECT n+1 FROM Even)))

• Even = ∅, Odd = ∅
• Even = ∅, Odd = {1}
• Even = {2}, Odd = {1}
• Even = {2}, Odd = {1, 3}
• Even = {2, 4}, Odd = {1, 3}
• Even = {2, 4}, Odd = {1, 3, 5}
• ...

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Fixed points are not unique

• But if $q$ is monotone, then all these fixed points must contain the fixed point we computed from fixed-point iteration starting with $\emptyset$
  • Thus the unique **minimal** fixed point is the “natural” answer

WITH RECURSIVE
Ancestor(anc, desc) AS
((SELECT parent, child FROM Parent)
 UNION
 (SELECT al.anc, a2.desc FROM Ancestor al, Ancestor a2
 WHERE al.desc = a2.anc))

<table>
<thead>
<tr>
<th>anc</th>
<th>desc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homer</td>
<td>Bart</td>
</tr>
<tr>
<td>Homer</td>
<td>Lisa</td>
</tr>
<tr>
<td>Marge</td>
<td>Bart</td>
</tr>
<tr>
<td>Marge</td>
<td>Lisa</td>
</tr>
<tr>
<td>Abe</td>
<td>Homer</td>
</tr>
<tr>
<td>Abe</td>
<td>Abe</td>
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<td>Ape</td>
<td>Homer</td>
</tr>
<tr>
<td>Ape</td>
<td>Lisa</td>
</tr>
<tr>
<td>Bogus</td>
<td>Bogus</td>
</tr>
</tbody>
</table>

Note how the bogus tuple reinforces itself!
Mixing negation with recursion

• If $q$ is non-monotone
  • The fixed-point iteration may flip-flop and never converge
  • There could be multiple minimal fixed points—we wouldn’t know which one to pick as answer!

• Example: popular users ($\text{pop} \geq 0.8$) join either Jessica’s Circle or Tommy’s
  • Those not in Jessica’s Circle should be in Tom’s
  • Those not in Tom’s Circle should be in Jessica’s
  • WITH RECURSIVE TommyCircle(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM JessicaCircle))
  RECURSIVE JessicaCircle(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM TommyCircle))
Fixed-point iter may not converge

WITH RECURSIVE TommyCircle(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM JessicaCircle)),
RECURSIVE JessicaCircle(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM TommyCircle))

<table>
<thead>
<tr>
<th>uid</th>
<th>name</th>
<th>age</th>
<th>pop</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>Bart</td>
<td>10</td>
<td>0.9</td>
</tr>
<tr>
<td>121</td>
<td>Allison</td>
<td>8</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Multiple minimal fixed points

WITH RECURSIVE TommyCircle(uid) AS
  (SELECT uid FROM User WHERE pop >= 0.8
   AND uid NOT IN (SELECT uid FROM JessicaCircle)),
RECURSIVE JessicaCircle(uid) AS
  (SELECT uid FROM User WHERE pop >= 0.8
   AND uid NOT IN (SELECT uid FROM TommyCircle))

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**TommyCircle** and **JessicaCircle**
Legal mix of negation and recursion

• Construct a dependency graph
  • One node for each table defined in \textit{WITH}
  • A directed edge $R \rightarrow S$ if $R$ is defined in terms of $S$
  • Label the directed edge “$-$” if the query defining $R$ is not monotone with respect to $S$

• Legal SQL3 recursion: no cycle with a “$-$” edge
  • Called \textit{stratified negation}

• Bad mix: a cycle with at least one edge labeled “$-$”

Stratified negation example

• Find pairs of persons with no common ancestors

WITH RECURSIVE Ancestor(anc, desc) AS
  ((SELECT parent, child FROM Parent) UNION
   (SELECT a1.anc, a2.desc
    FROM Ancestor a1, Ancestor a2
    WHERE a1.desc = a2.anc)),

Person(person) AS
  ((SELECT parent FROM Parent) UNION
   (SELECT child FROM Parent)),

NoCommonAnc(person1, person2) AS
  ((SELECT p1.person, p2.person
    FROM Person p1, Person p2
    WHERE p1.person <> p2.person)
   EXCEPT
   (SELECT a1.desc, a2.desc
    FROM Ancestor a1, Ancestor a2
    WHERE a1.anc = a2.anc))

SELECT * FROM NoCommonAnc;
Evaluating stratified negation

• The **stratum** of a node $R$ is the maximum number of “$-$” edges on any path from $R$ in the dependency graph
  - Ancestor: stratum 0
  - Person: stratum 0
  - NoCommonAnc: stratum 1

• Evaluation strategy
  - Compute tables lowest-stratum first
  - For each stratum, use fixed-point iteration on all nodes in that stratum
    - Stratum 0: Ancestor and Person
    - Stratum 1: NoCommonAnc

☞ Intuitively, there is no negation within each stratum
Summary

• SQL3 WITH recursive queries
• Solution to a recursive query (with no negation): unique minimal fixed point
• Computing unique minimal fixed point: fixed-point iteration starting from $\emptyset$
• Mixing negation and recursion is tricky
  • Illegal mix: fixed-point iteration may not converge; there may be multiple minimal fixed points
  • Legal mix: stratified negation (compute by fixed-point iteration stratum by stratum)