SQL:
Recursion, Programming

Introduction to Database Management

CS348 Spring 2021

SQL

- Basic SQL (queries, modifications, and constraints)

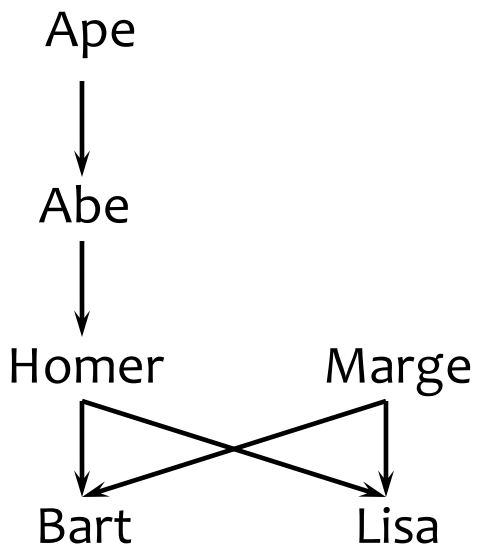
- Intermediate SQL
  - Triggers
  - Views
  - Indexes

- Advanced SQL
  - Recursion
  - Programming

A motivating example

Parent (*parent*, *child*)

parent	*child*
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe



- 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 p2.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 a1.anc, a2.desc
  FROM Ancestor a1, Ancestor a2
  WHERE a1.desc = a2.anc))
SELECT anc
FROM Ancestor
WHERE desc = 'Bart';
```

base case

a1.anc (X) → a1.desc(Z)
a2.anc (Z) → a2.desc (Y)

recursion step

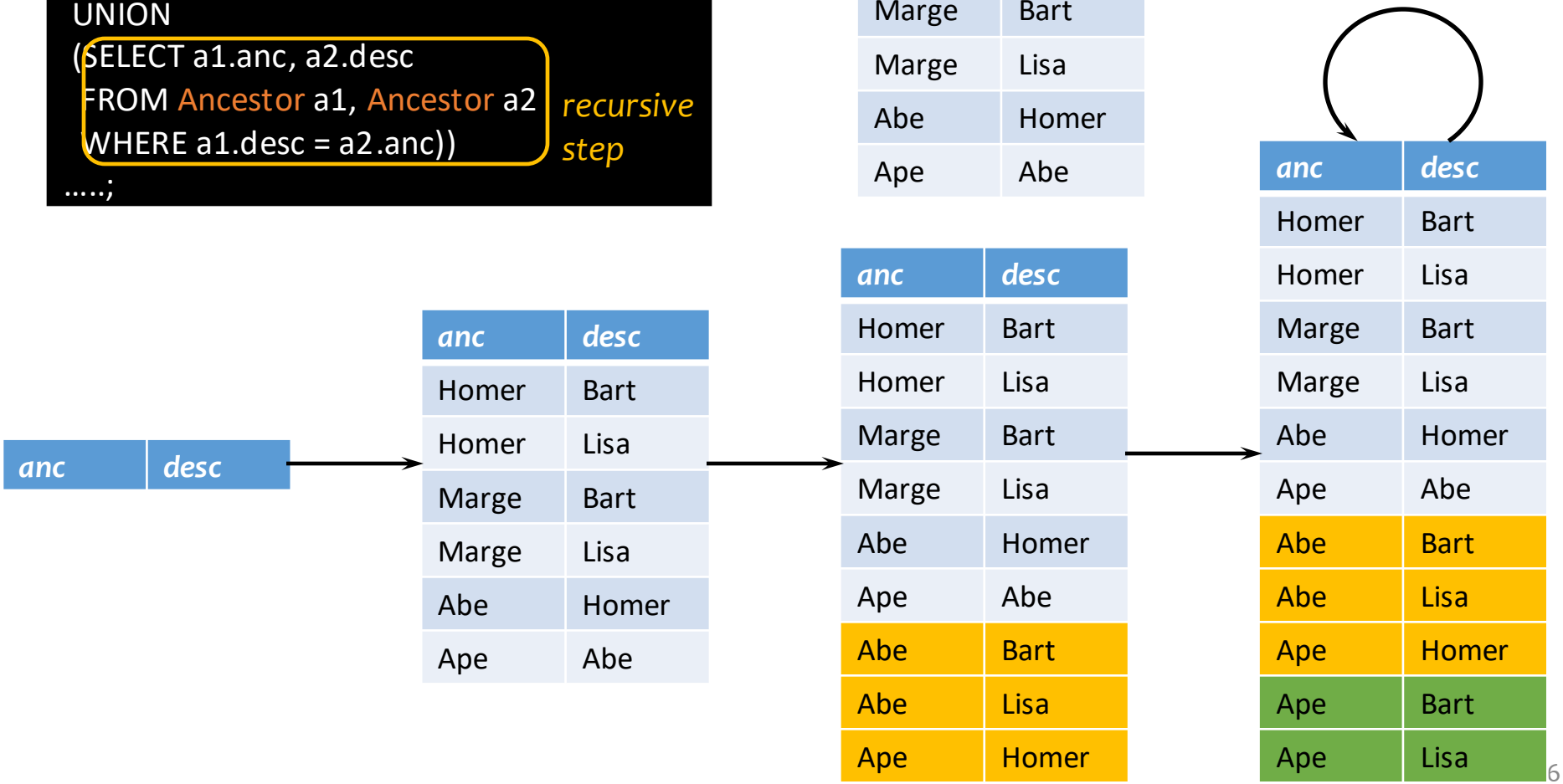
Define a relation recursively

Query using the relation defined in WITH clause

Finding ancestors

```
WITH RECURSIVE
Ancestor(anc, desc) AS                    base case
((SELECT parent, child FROM Parent)
 UNION
 (SELECT a1.anc, a2.desc
  FROM Ancestor a1, Ancestor a2           recursive
  WHERE a1.desc = a2.anc))                step
.....;
```

parent	*child*
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe



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?
  - Ans: 0, as f(0)=0 With seed 1: 1, 1/2, 1/4, 1/8, 1/16, … → 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

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

Non-linear v.s. linear recursion

- Non-linear

```
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))  …..;
```

- Linear: a recursive definition can make only one reference to itself

```
WITH RECURSIVE Ancestor2(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: Given $a \rightarrow b \rightarrow c \rightarrow d \rightarrow e$, *i.e.*, a is parent of b, b is parent of c, …., d is parent of e.
    - The linear recursion takes 4 steps to find (a, e) is an ancestor-descendant pair (slide 9, Ancestor2)
    - Question: How about non-linear recursion? (slide 9, Ancestor)

Mutual recursion example

- Table *Natural* (*n*) contains 1, 2, …, 100
- Which numbers are even/odd?
  - An even number plus 1 is an odd number
  - An odd number plus 1 is an even 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
```

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}
- …

Semantics of WITH

- WITH RECURSIVE R_1 AS Q_1,
  ...,
  RECURSIVE R_n AS Q_n
  Q;
  - Q and $Q_1, \ldots, Q_n$ may refer to $R_1, \ldots, R_n$
- Semantics
  1. $R_1 \leftarrow \emptyset, \ldots, R_n \leftarrow \emptyset$
  2. Evaluate $Q_1, \ldots, Q_n$ using the current contents of $R_1, \ldots, R_n$: $R_1^{new} \leftarrow Q_1, \ldots, R_n^{new} \leftarrow Q_n$
  3. If $R_i^{new} \neq R_i$ for some i
     3.1. $R_1 \leftarrow R_1^{new}, \ldots, R_n \leftarrow R_n^{new}$
     3.2. Go to 2.
  4. Compute Q using the current contents of $R_1, \ldots R_n$ and output the result

Starting with non-empty set

```
WITH RECURSIVE
Ancestor(anc, desc) AS                    base case
((SELECT parent, child FROM Parent)
 UNION
 (SELECT a1.anc, a2.desc
  FROM Ancestor a1, Ancestor a2           recursive
  WHERE a1.desc = a2.anc))                step
.....;
```

parent	child
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe

anc	desc
Bogus	Bogus

anc	desc
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe
Bogus	Bogus

anc	desc
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe
Abe	Bart
Abe	Lisa
Ape	Homer
Bogus	Bogus

anc	desc
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe
Abe	Bart
Abe	Lisa
Ape	Homer
Ape	Bart
Ape	Lisa
Bogus	Bogus

Fixed points are not unique

```
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))
…..;
```

parent	*child*
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe

anc	*desc*
Homer	Bart
Homer	Lisa
Marge	Bart
Marge	Lisa
Abe	Homer
Ape	Abe
Abe	Bart
Abe	Lisa
Ape	Homer
Ape	Bart
Ape	Lisa
Bogus	Bogus

Note how the bogus tuple reinforces itself!

Lecture 2

- If q is monotone, then starting from $\emptyset$ produces the unique minimal fixed point
  - All these fixed points must contain this fixed point

  → the unique minimal fixed point is the "natural" answer

Mixing negation with recursion

- If q is non-monotone
  - The fixed-point iteration may never converge
  - There could be multiple minimal fixed points

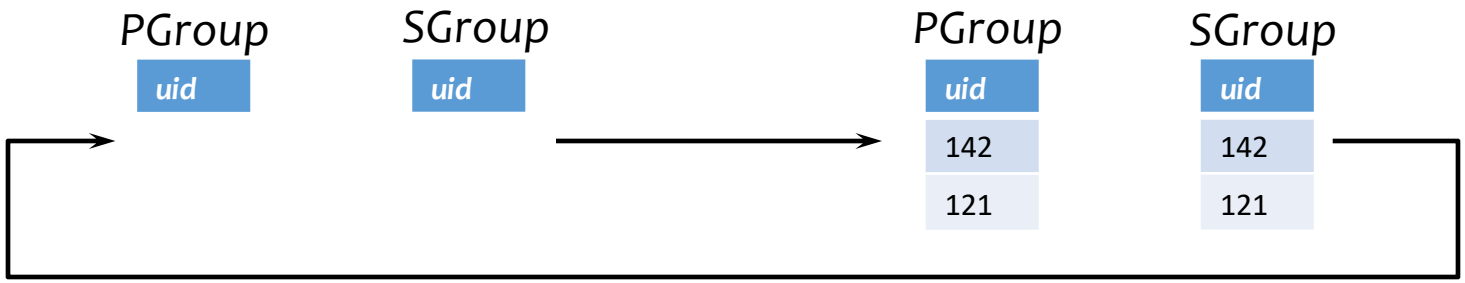
- Example: popular users (pop $\geq$ 0.8) join either SGroup or PGroup
  - Those not in SGroup should be in PGroup
  - Those not in GGroup should be in SGroup

```
WITH RECURSIVE PGroup(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM SGroup)),
 RECURSIVE SGroup(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM PGroup))
```

Fixed-point iter may not converge

```
WITH RECURSIVE PGroup(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM SGroup)),
 RECURSIVE SGroup(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM PGroup))
```

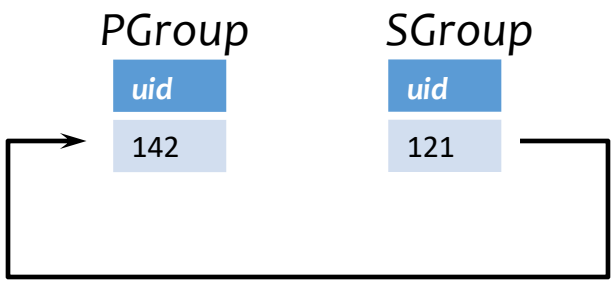
uid	*name*	*age*	*pop*
142	Bart	10	0.9
121	Allison	8	0.85

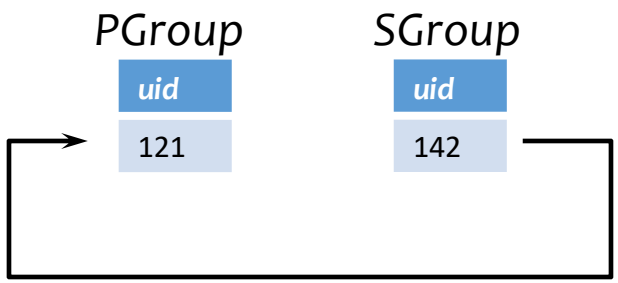


Multiple minimal fixed points

```
WITH RECURSIVE PGroup(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM SGroup)),
 RECURSIVE SGroup(uid) AS
    (SELECT uid FROM User WHERE pop >= 0.8
     AND uid NOT IN (SELECT uid FROM PGroup))
```

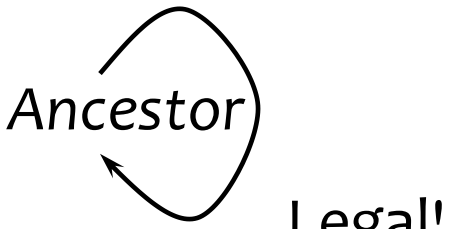
uid	*name*	*age*	*pop*
142	Bart	10	0.9
121	Allison	8	0.85



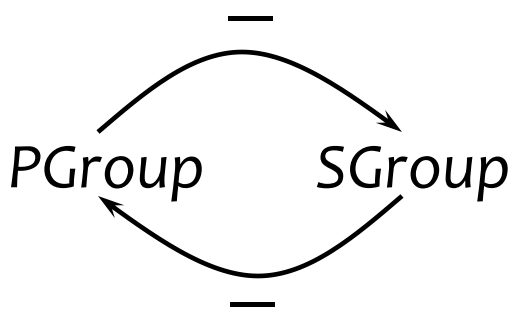


Legal mix of negation and recursion

- Construct a dependency graph
  - One node for each table defined in 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 stratified negation
- Bad mix: a cycle with at least one edge labeled "—"



Legal!



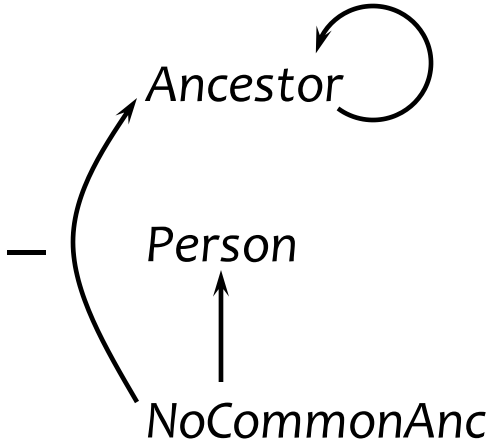
Illegal!

Stratified negation example

- Find pairs of persons with no common ancestors

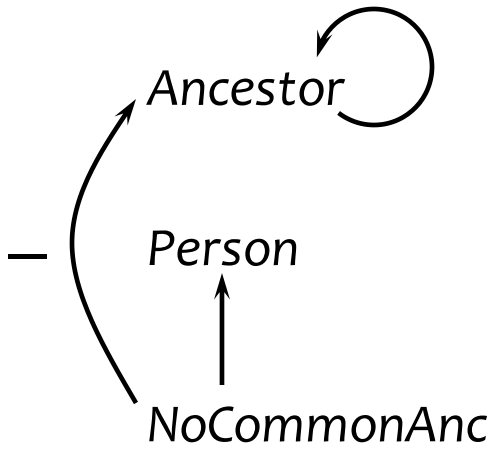
```
WITH RECURSIVE Ancestor(anc, desc) AS
    ((SELECT parent, child FROM Parent) UNION
     (SELECT a1.anc, a2.desc
      FROM Ancestor a1, Ancestor a2
      WHERE a1.desc = a2.anc)),
RECURSIVE  Person(person) AS
    ((SELECT parent FROM Parent) UNION
     (SELECT child FROM Parent)),
RECURSIVE NoCommonAnc(person1, 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
  - *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

SQL features covered so far

- Basic SQL (queries, modifications, and constraints)
- Intermediate SQL(triggers, views, indexes)

- Recursion
  - SQL3 WITH recursive queries
  - Solution to a recursive query (with no negation)
  - Mixing negation and recursion is tricky

- Programming

Motivation

- Pros and cons of SQL
  - Very high-level, possible to optimize
  - Not intended for general-purpose computation
- Solutions
  - Augment SQL with constructs from general-purpose programming languages
    - E.g.: SQL/PSM
  - Use SQL together with general-purpose programming languages: many possibilities
    - Through an API, e.g., Python psycopg2
    - Embedded SQL, e.g., in C
    - Automatic object-relational mapping, e.g.: Python SQLAlchemy
    - Extending programming languages with SQL-like constructs, e.g.: LINQ

An "impedance mismatch"

- SQL operates on a set of records at a time
- Typical low-level general-purpose programming languages operate on one record at a time

☞Solution: cursor

- Open (a result table), Get next, Close

☞Found in virtually every database language/API

- With slightly different syntaxes

Augmenting SQL: SQL/PSM

- PSM = Persistent Stored Modules
- CREATE PROCEDURE *proc_name*(*param_decls*)
  local_decls
  proc_body;
- CREATE FUNCTION *func_name*(*param_decls*)
  RETURNS *return_type*
  local_decls
  func_body;
- CALL *proc_name*(*params*);
- Inside procedure body:
  SET *variable* = CALL *func_name*(*params*);

SQL/PSM example

```
CREATE FUNCTION SetMaxPop(IN newMaxPop FLOAT)
RETURNS INT
-- Enforce newMaxPop; return # rows modified.
BEGIN
DECLARE rowsUpdated INT DEFAULT 0;
DECLARE thisPop FLOAT;
        -- A cursor to range over all users:
DECLARE userCursor CURSOR FOR
   SELECT pop FROM User
FOR UPDATE;
        -- Set a flag upon "not found" exception:
DECLARE noMoreRows INT DEFAULT 0;
DECLARE CONTINUE HANDLER FOR NOT FOUND
   SET noMoreRows = 1;
        … (see next slide) …
        RETURN rowsUpdated;
END
```

Declare local variables

SQL/PSM example continued

```
-- Fetch the first result row:
OPEN userCursor;
FETCH FROM userCursor INTO thisPop;
-- Loop over all result rows:
WHILE noMoreRows <> 1 DO
   IF thisPop > newMaxPop THEN
      -- Enforce newMaxPop:
      UPDATE User SET pop = newMaxPop
      WHERE CURRENT OF userCursor;
      -- Update count:
      SET rowsUpdated = rowsUpdated + 1;
   END IF;
   -- Fetch the next result row:
   FETCH FROM userCursor INTO thisPop;
END WHILE;
CLOSE userCursor;
```

Function body

Other SQL/PSM features

- Assignment using scalar query results
  - SELECT INTO
- Other loop constructs
  - FOR, REPEAT UNTIL, LOOP
- Flow control
  - GOTO
- Exceptions
  - SIGNAL, RESIGNAL

…

- For more PostgreSQL-specific information, look for "PL/pgSQL" in PostgreSQL documentation
  - https://www.postgresql.org/docs/9.6/plpgsql.html

Working with SQL through an API

- E.g.: Python psycopg2, JDBC, ODBC (C/C++/VB)
  - All based on the SQL/CLI (Call-Level Interface) standard

- The application program sends SQL commands to the DBMS at runtime

- Responses/results are converted to objects in the application program

Example API: Python psycopg2

```
import psycopg2
conn = psycopg2.connect(dbname='beers')
cur = conn.cursor()
# list all drinkers:
cur.execute('SELECT * FROM Drinker')
for drinker, address in cur:
    print(drinker + ' lives at ' + address)
# print menu for bars whose name contains "a":
cur.execute('SELECT * FROM Serves WHERE bar LIKE %s', ('%a%',))
for bar, beer, price in cur:
    print('{} serves {} at ${:,.2f}'.format(bar, beer, price))
cur.close()
conn.close()
```

You can iterate over cur one tuple at a time

Placeholder for query parameter

Tuple of parameter values, one for each %s

More psycopg2 examples

```
# “commit” each change immediately—need to set this option just once at the start of the session
conn.set_session(autocommit=True)
# ...
bar = input('Enter the bar to update: ').strip()
beer = input('Enter the beer to update: ').strip()
price = float(input('Enter the new price: '))
try:
    cur.execute('‘’
            UPDATE Serves
            SET price = %s
            WHERE bar = %s AND beer = %s''', (price, bar, beer))
    if cur.rowcount != 1:
        print('{} row(s) updated: correct bar/beer?'\
            .format(cur.rowcount))
except Exception as e:
    print(e)
```

Perform passing, semantic analysis, optimization, compilation, and finally execution

More psycopg2 examples

```
....
while true:
# Input bar, beer, price…
    cur.execute('''
            UPDATE Serves
            SET price = %s
            WHERE bar = %s AND beer = %s''', (price, bar, beer))
    ....
    # Check result…
```

Perform passing, semantic analysis, optimization, compilation, and finally execution

Execute many times

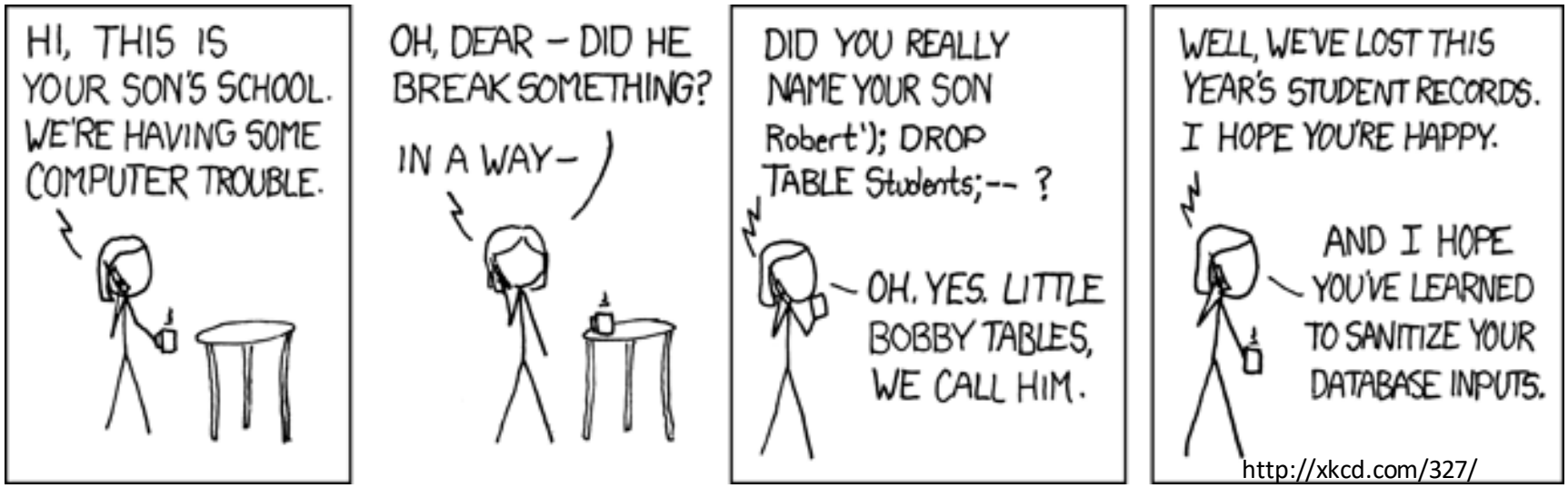
Can we reduce this overhead?

Prepared statements: example

```
cur.execute('''              # Prepare once (in SQL).
        PREPARE update_price AS      # Name the prepared plan,
        UPDATE Serves
        SET price = $1               # and note the $1, $2, … notation for
        WHERE bar = $2 AND beer = $3''') # parameter placeholders.
while true:
# Input bar, beer, price…
    cur.execute('
        EXECUTE update_price(%s, %s, %s)',\ # Execute many times.
            (price, bar, beer))….
    # Check result…
```

Prepare only once

“Exploits of a mom”



- The school probably had something like:

```
cur.execute("SELECT * FROM Students " + \
        "WHERE (name = '" + name + "')")
```

where name is a string input by user

- Called an SQL injection attack

Guarding against SQL injection

- Escape certain characters in a user input string, to ensure that it remains a single string
  - E.g., ', which would terminate a string in SQL, must be replaced by '' (two single quotes in a row) within the input string

- Luckily, most API's provide ways to "sanitize" input automatically (if you use them properly)
  - E.g., pass parameter values in psycopg2 through %s's

Augmenting SQL vs. API

- Pros of augmenting SQL:
  - More processing features for DBMS
  - More application logic can be pushed closer to data

- Cons of augmenting SQL:
  - SQL is already too big
  - Complicate optimization and make it impossible to guarantee safety

A brief look at other approaches

- "Embed" SQL in a general-purpose programming language
  - E.g.: embedded SQL
- Support database features through an object-oriented programming language
  - E.g., object-relational mappers (ORM) like Python SQLAlchemy
- Extend a general-purpose programming language with SQL-like constructs
  - E.g.: LINQ (Language Integrated Query for .NET)

Embedding SQL in a language

Example in C

```
EXEC SQL BEGIN DECLARE SECTION;
int thisUid; float thisPop;
EXEC SQL END DECLARE SECTION;
EXEC SQL DECLARE ABCMember CURSOR FOR
   SELECT uid, pop FROM User
   WHERE uid IN (SELECT uid FROM Member WHERE gid = 'abc')
   FOR UPDATE;
EXEC SQL OPEN ABCMember;
EXEC SQL WHENEVER NOT FOUND DO break;
while (1) {
   EXEC SQL FETCH ABCMember INTO :thisUid, :thisPop;
   printf("uid %d: current pop is %f\n", thisUid, thisPop);
                  printf("Enter new popularity: ");
   scanf("%f", &thisPop);
   EXEC SQL UPDATE User SET pop = :thisPop
      WHERE CURRENT OF ABCMember;
}
EXEC SQL CLOSE ABCMember;
```

Declare variables to be "shared" between the application and DBMS

Embedded SQL v.s. API

- Pros of embedded SQL:
  - Be processed by a preprocessor prior to compilation → may catch SQL-related errors at preprocessing time
  - API: SQL statements are interpreted at runtime

- Cons of embedded SQL:
  - New host language code → complicate debugging

A brief look at other approaches

- "Embed" SQL in a general-purpose programming language
  - E.g.: embedded SQL
- Support database features through an object-oriented programming language
  - E.g., object-relational mappers (ORM) like Python SQLAlchemy
- Extend a general-purpose programming language with SQL-like constructs
  - E.g.: LINQ (Language Integrated Query for .NET)

Object-relational mapping

- Example: Python SQLAlchemy

```
class User(Base):
  __tablename__ = 'users'
  id = Column(Integer, primary_key=True)
  name = Column(String)
  password = Column(String)
```

```
class Address(Base):
  __tablename__ = 'addresses'
  id = Column(Integer, primary_key=True)
  email_address = Column(String, nullable=False)
  user_id = Column(Integer, ForeignKey('users.id'))
```

```
Address.user = relationship("User", back_populates="addresses")
User.addresses = relationship("Address", order_by=Address.id, back_populates="user")
```

```
jack = User(name='jack', password='gjffdd')
jack.addresses = [Address(email_address='jack@google.com'),
                  Address(email_address='j25@yahoo.com')]
session.add(jack)
session.commit()
```

```
session.query(User).join(Address).filter(Address.email_address=='jack@google.com').all()
```

- Automatic data mapping and query translation
- But syntax may vary for different host languages
- Very convenient for simple structures/queries, but quickly get complicated and less intuitive for more complex situations

A brief look at other approaches

- "Embed" SQL in a general-purpose programming language
  - E.g.: embedded SQL
- Support database features through an object-oriented programming language
  - By automatically storing objects in tables and translating methods to SQL
  - E.g., object-relational mappers (ORM) like Python SQLAlchemy
- Extend a general-purpose programming language with SQL-like constructs
  - E.g.: LINQ (Language Integrated Query for .NET)

Deeper language integration

- Example: LINQ (Language Integrated Query) for Microsoft .NET languages (e.g., C#)

```
int someValue = 5;
var results = from c in someCollection
              let x = someValue * 2
              where c.SomeProperty < x
              select new {c.SomeProperty, c.OtherProperty};
foreach (var result in results) {
  Console.WriteLine(result);
}
```

- Again, automatic data mapping and query translation
- Much cleaner syntax, but it still may vary for different host languages

Summary

- Basic SQL (queries, modifications, and constraints)
- Intermediate SQL(triggers, views, indexes)
- Recursion
- Programming
  - Augment SQL, e.g., SQL/PSM
  - Through an API, e.g., Python psycopg2, JDBC
  - Embedded SQL, e.g., in C
  - Automatic object-relational mapping, e.g.: Python SQLAlchemy
  - Extending programming languages with SQL-like constructs, e.g.: LINQ