Compiling PL/SQL Away

CIDR 2020

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How is Everyone Enjoying Their PL/SQL?

From time to time I seek comfort in the success stories that tell how users benefit from the technology we've created ...

PL/SQL: Computation Close to the Data (↓ Robot Walk)

```
CREATE FUNCTION walk(origin coord, win int, loose int, steps int) RETURNS int AS
$$
DECLARE
 reward   int   = 0;
 location coord = origin;
 movement text  = '';
 roll     float;
BEGIN
 -- move robot repeatedly
 FOR step IN 1..steps LOOP
  -- where does the Markov policy send the robot from here?
  movement = (SELECT p.action
              FROM   policy AS p
              WHERE  location = p.loc);
  -- compute new location of robot,
  -- robot may randomly stray from policy's direction
  roll = random();
  location =
    (SELECT move.loc
     FROM   (SELECT a.there AS loc,
                    COALESCE(SUM(a.prob) OVER lt, 0.0) AS lo,
                             SUM(a.prob) OVER leq      AS hi
             FROM   actions AS a
             WHERE  location = a.here AND movement = a.action
             WINDOW leq AS (ORDER BY a.there),
                    lt  AS (leq ROWS UNBOUNDED PRECEDING
                                EXCLUDE CURRENT ROW)
            ) AS move(loc, lo, hi)
     WHERE  roll BETWEEN move.lo AND move.hi);
  -- robot collects reward (or penalty) at new location
  reward = reward + (SELECT c.reward
                     FROM   cells AS c
                     WHERE  location = c.loc);
  -- bail out if we win or loose early
  IF reward >= win OR reward <= loose THEN
    RETURN step * sign(reward);
  END IF;
 END LOOP;
 -- draw: robot performed all steps without winning or losing
 RETURN 0;
END;
$$ LANGUAGE PLPGSQL;
```

PL/SQL: ½ Imperative PL + ½ SQL (↓ N-Body Simulation)

```
CREATE FUNCTION force(b body, theta float) RETURNS point AS
$$
 DECLARE
 force      point := point(0,0);
 G CONSTANT float := 6.67e-11;
 Q          barneshut[];
 node       barneshut;
 children   barneshut[];
 dist       float;
 dir        point;
 grav       point;
BEGIN
 -- enter Barnes-Hut tree at the root
 node = (SELECT t
         FROM   barneshut AS t
         WHERE  t.node = 0);
 Q = array[node];
 -- iterate while there are Barnes-Hut nodes to consider
 WHILE cardinality(Q) > 0 LOOP
  node = Q[1];
  Q    = Q[2:];
  dist = node.center->b.pos;
  dir  = node.center - b.pos;
  grav = point(0,0);
  -- bodies separated by walls do not affect each other
  IF NOT EXISTS (SELECT 1
                 FROM   walls AS w
                 WHERE  (b.pos <= b.pos ## w.wall) <>
                        (node.center <= node.center ## w.wall)) THEN
   grav = (G * b.mass * node.mass / dist^2) * dir;
  END IF;
  -- Barnes-Hut optimization: approximate effect of distant bodies
  IF (node.node IS NULL) OR (width(node.bbox) / dist < theta) THEN
   force = force + grav;
  ELSE
   -- inspect area at higher resolution: descend into subtrees
   children = (SELECT array_agg(t)
               FROM   barneshut AS t
               WHERE  t.parent = node.node);
   Q = Q || children;
  END IF;
 END LOOP;
 -- return aggregated force on body
 RETURN force;
END;
$$ LANGUAGE PLPGSQL STABLE STRICT;
```

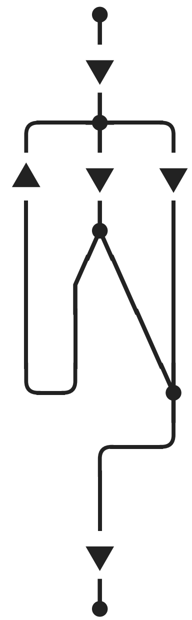
Elements of PL/SQL: Stateful Variables

```
CREATE FUNCTION f(…) RETURNS τ AS
$$
  DECLARE
    v1 τ1;
    v2 τ2;
  BEGIN
    …
    v1 = …;
    v2 = …v1…;
    …
    v1 = …v1…v2…;
    …
  END;
$$
```

- Statement sequencing (straight-line control flow)
- Variable references and variable updates

Elements of PL/SQL: Complex and Iterative Control Flow

```
CREATE FUNCTION f(…) RETURNS τ AS
$$
  ┄┄┄┄
  WHILE ┄┄┄ LOOP
  │ ┄┄┄┄┄┄
  │ IF ┄┄┄ THEN
  │ │ ┄┄┄
  │ ELSE
  │ │ EXIT;
  │ END IF;
  │ ┄┄┄┄
  END LOOP;
  ┄┄┄
$$
```



- Arbitrarily complex control flow (via **IF…THEN…ELSIF**, **CASE…WHEN**, **LOOP**, **WHILE**, **FOR**, **EXIT**, **CONTINUE**, …)

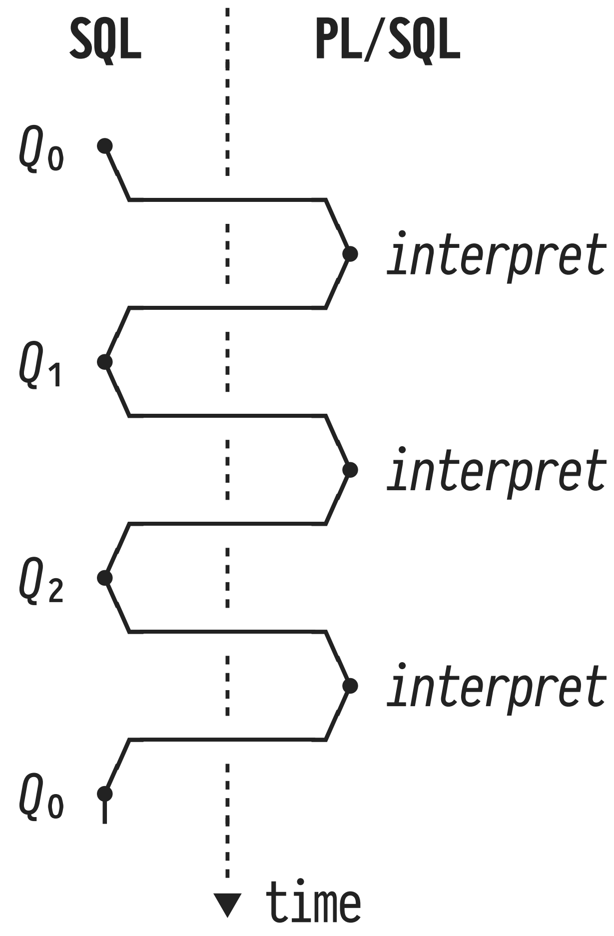
Elements of PL/SQL: Embedded SQL Expressions

```
CREATE FUNCTION f(⋯) RETURNS τ AS
$$
  :::::
  v₁ = ;                          ] simple SQL expression
  ::::::::
  ::::
  v₂ = (                          ] embedded
               );                 ] SQL query Q
  ::::::::
$$
```

- PL/SQL expressions:
  1. “Simple” SQL expressions (evaluated w/o planning)
  2. Embedded SQL queries (require planning + execution)

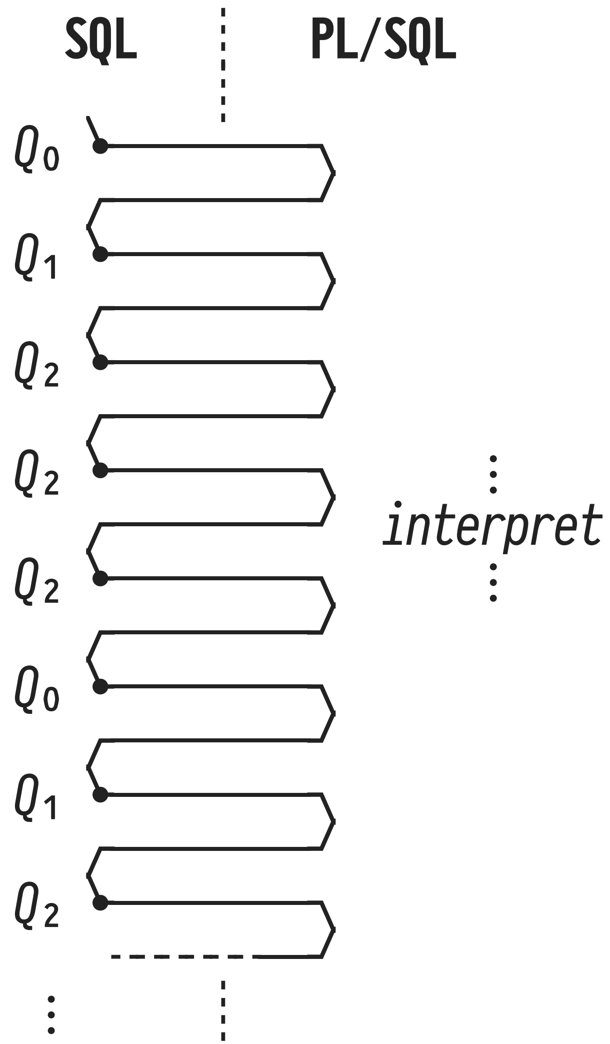
From SQL to PL/SQL And Back Again

```
CREATE FUNCTION f(···) RETURNS τ AS
$$
  ======
  v₁ = (
            );                 ] embedded
                               ] SQL Q₁
  ==============
  ===============================
    ===============
    ===============
  ====
    ======
    v₂ = (
                  );           ] embedded
                               ] SQL Q₂
    ======
  =============
$$

SELECT f(···);                 ] top-level
                               ] SQL Q₀
```



SQL↔PL/SQL (And Again, Again, Again, Again, Again, …)

```
CREATE FUNCTION f(…) RETURNS τ AS
$$
   ======
   v1 = (                         ]  embedded
                  );              ]  SQL Q1
   ==============
   WHILE ==== LOOP
     ===============
       ===============
     ====
       =======
       v2 = (                     ]  embedded
                        );        ]  SQL Q2
   LOOP END
   =============
$$

SELECT f(…,t,…);                  ]  top-level
FROM   T AS t                     ]  SQL Q0
```



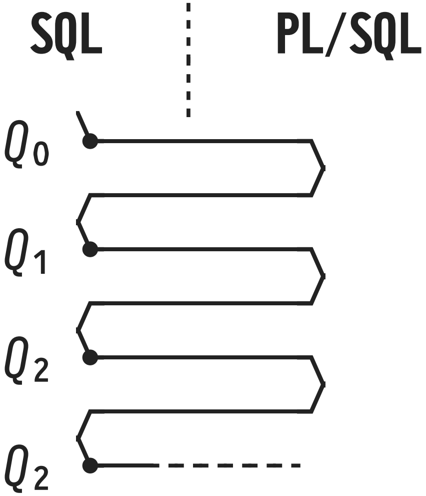
SQL↔PL/SQL Context Switches Are Costly

plan + optimize + **instantiate** + run + **teardown** ··· Q_0

plan + optimize + **instantiate** + run + **teardown** ··· Q_1

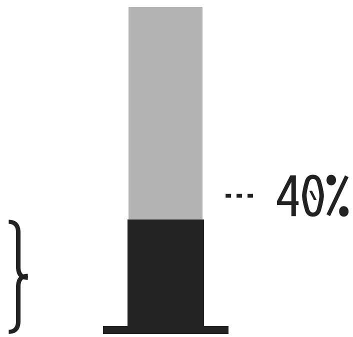
plan + optimize + **instantiate** + run + **teardown** ··· Q_2

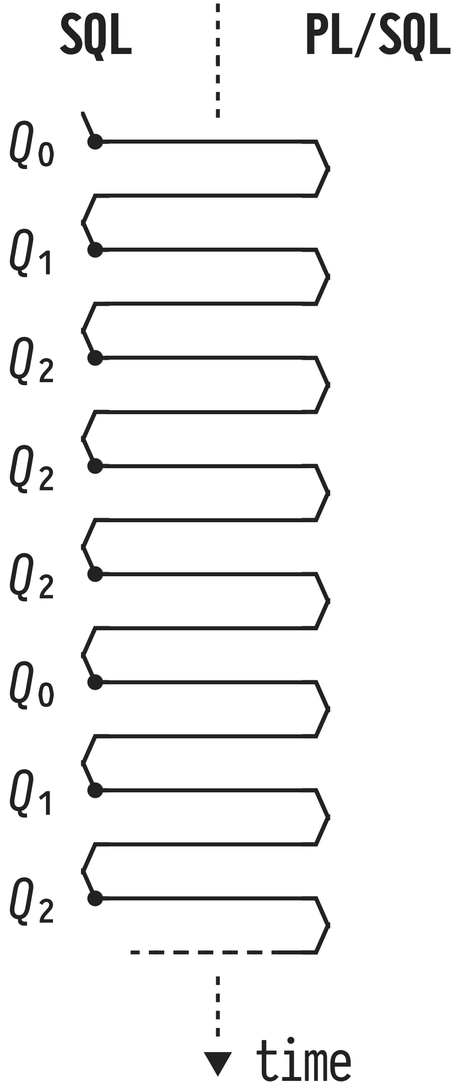
instantiate + run + **teardown** ··· Q_2

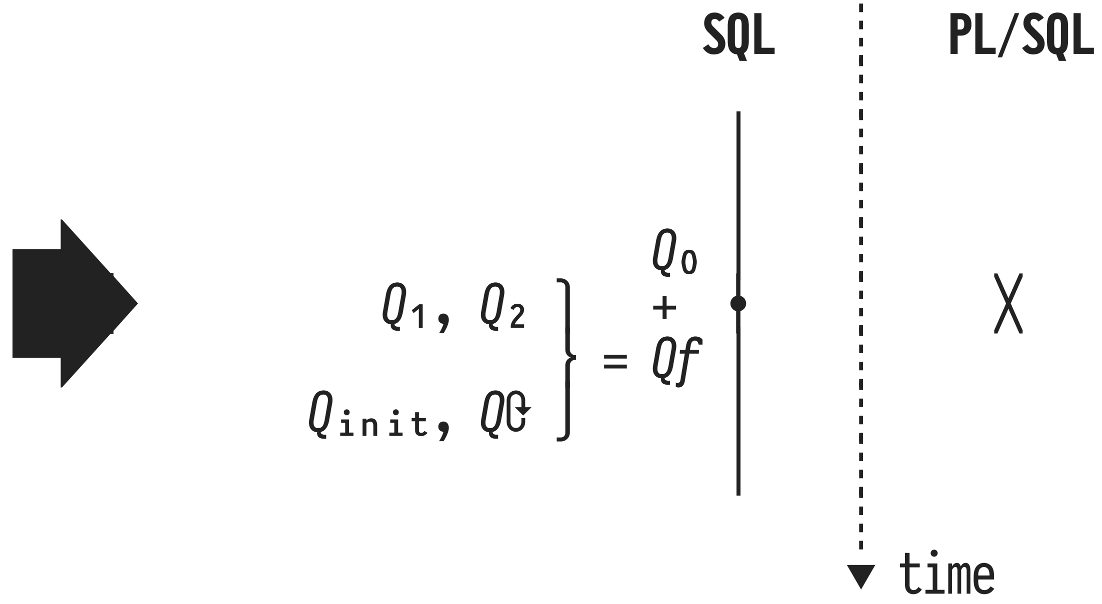


PostgreSQL 11.3 Runtime Profile ⏰

ExecutorStart()
ExecutorEnd()







||| **Main Goal:**

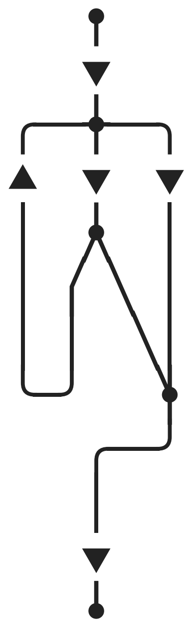
- Compile PL/SQL UDF f into plain SQL query Qf
- Inline Qf into top-level Q_0 at f's call sites: plan, optimize, instantiate, run, teardown **once**

No SQL↔PL/SQL context switches

If f Is Iterative, Qf Is Recursive

PL/SQL ➧ **Plain SQL**

```
CREATE FUNCTION f(…)
RETURNS τ AS
$$
```



```
$$
```

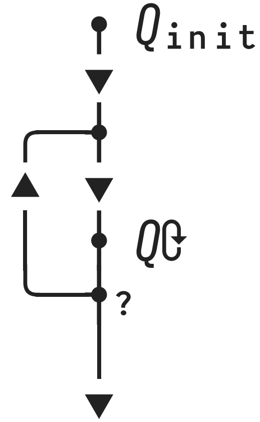
WITH RECURSIVE *run* **AS**

Q_{init} [

UNION ALL

Q↻ [

Qf



||| **Challenge:**

Map arbitrary control flow into **WITH RECURSIVE**

PL/SQL to Plain SQL: Left to Right

	❶	❷	❸	❹	
f ➧	**PL/SQL**	**SSA**	**ANF**	**Plain SQL**	➧ *Qf*
	arbitrary iterative control flow	**goto**-based control flow	mutually tail-recursive functions	**WITH RECURSIVE/ ITERATE**	

(⚠ Compiler folks tend to go right to left ⬅ instead…)

❶ From PL/SQL to Single Static Assignment Form

PL/SQL (x^n) ➧ **SSA**

```
CREATE FUNCTION f(x int, n int)
RETURNS int AS
$$
  DECLARE
    i int = 0;
    p int = 1;
  BEGIN
    WHILE i < n LOOP
      p = p * x;
      i = i + 1;
    END LOOP;
    RETURN p;
  END;
$$
```

```
f(x,n):
         i0 ← 0;
         p0 ← 1;
 while:  i1 ← φ(i0,i2);
         p1 ← φ(p0,p2);
         if i1 < n then
           goto loop;
         else
           goto exit;
  loop:  p2 ← p1 * x;
         i2 ← i1 + 1;
         goto while;
  exit:  return p1;
```

- Control flow expressed via **goto**, variables assigned once

❷ From SSA to Administrative Normal Form

SSA ➧ **ANF**

```
f(x,n):
          i₀ ← 0;
          p₀ ← 1;
while:    i₁ ← ϕ(i₀,i₂);
          p₁ ← ϕ(p₀,p₂);
          if i₁ < n then
            goto body;
          else
            goto exit;
 body:    p₂ ← p₁ * x;
          i₂ ← i₁ + 1;
          goto while;
 exit:    return p₁;
```

```
f(x,n) =
  let i₀ = 0 in
   let p₀ = 1 in
    while(i₀,p₀,x,n)

while(i₁,p₁,x,n) =
  let t₀ = i₁ ⩾ n in
   if t₀ then p₁                    [← exit]
         else body(i₁,p₁,x,n)

body(i₁,p₁,x,n) =
  let p₂ = p₁ * x in
   let i₂ = i₁ + 1 in
    while(i₂,p₂,x,n)
```

- Mutually recursive functions, **tail calls** only

❸ From Mutual to Direct Recursion

ANF ⟲	➧	ANF ↻

```
f(x,n) =
  let i₀ = 0 in
   let p₀ = 1 in
    while(i₀,p₀,x,n)

while(i₁,p₁,x,n) =
  let t₀ = i₁ ⩾ n in
   if t₀ then p₁
         else body(i₁,p₁,x,n)

body(i₁,p₁,x,n) =
  let p₂ = p₁ * x in
   let i₂ = i₁ + 1 in
    while(i₂,p₂,x,n)
```

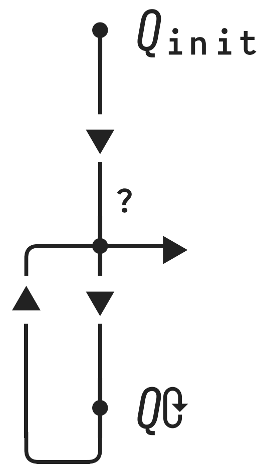
```
f(x,n) =
  let i₀ = 0 in
   let p₀ = 1 in
    run(i₀,p₀,x,n)

run(i₁,p₁,x,n) =
  let t₀ = i₁ ⩾ n in
   if t₀ then p₁
         else
          let p₂ = p₁ * x in
           let i₂ = i₁ + 1 in
            run(i₂,p₂,x,n)
```

- Single recursive function *run*(), **tail calls** only

❹ From Tail Recursion to WITH RECURSIVE

ANF ↻

```
f(x,n) =
  let i₀ = 0 in                      ⎤
   let p₀ = 1 in                     ⎥ Q_init
    run(i₀,p₀,x,n)                   ⎦

run(i₁,p₁,x,n) =
  let t₀ = i₁ ⩾ n in
   if t₀ then p₁                     ] ?
         else
          let p₂ = p₁ * x in         ⎤
           let i₂ = i₁ + 1 in        ⎥ Q↻
            run(i₂,p₂,x,n)           ⎦
```



- Resulting tail recursion now matches the restricted control flow implemented by **WITH RECURSIVE** ✔

❹ From Tail Recursion to WITH RECURSIVE

ANF ⟲ ➧ **Plain SQL**

```
f(x,n) =
 let i₀ = 0 in
  let p₀ = 1 in
   run(i₀,p₀,x,n)                          ] Q_init
```

```
run(i₁,p₁,x,n) =
 let t₀ = i₁ ⩾ n in
  if t₀ then p₁
        else
         let p₂ = p₁ * x in
          let i₂ = i₁ + 1 in
           run(i₂,p₂,x,n)                  ] Q⟲
```

```
WITH RECURSIVE
run("call?",i₁,p₁,x,n,result) AS (
  SELECT true, 0, 1, x, n, □
 UNION ALL
  SELECT iter.*
  FROM   run, LATERAL (
          SELECT false, □, □, □, □, p₁
          WHERE  i₁ >= n
            UNION ALL
          SELECT true, i₁+1, p₁*x, x, n, □
          WHERE  i₁ < n
         ) AS iter("call?",i₁,p₁,x,n,result)
  WHERE  run."call?")
TABLE run;
```

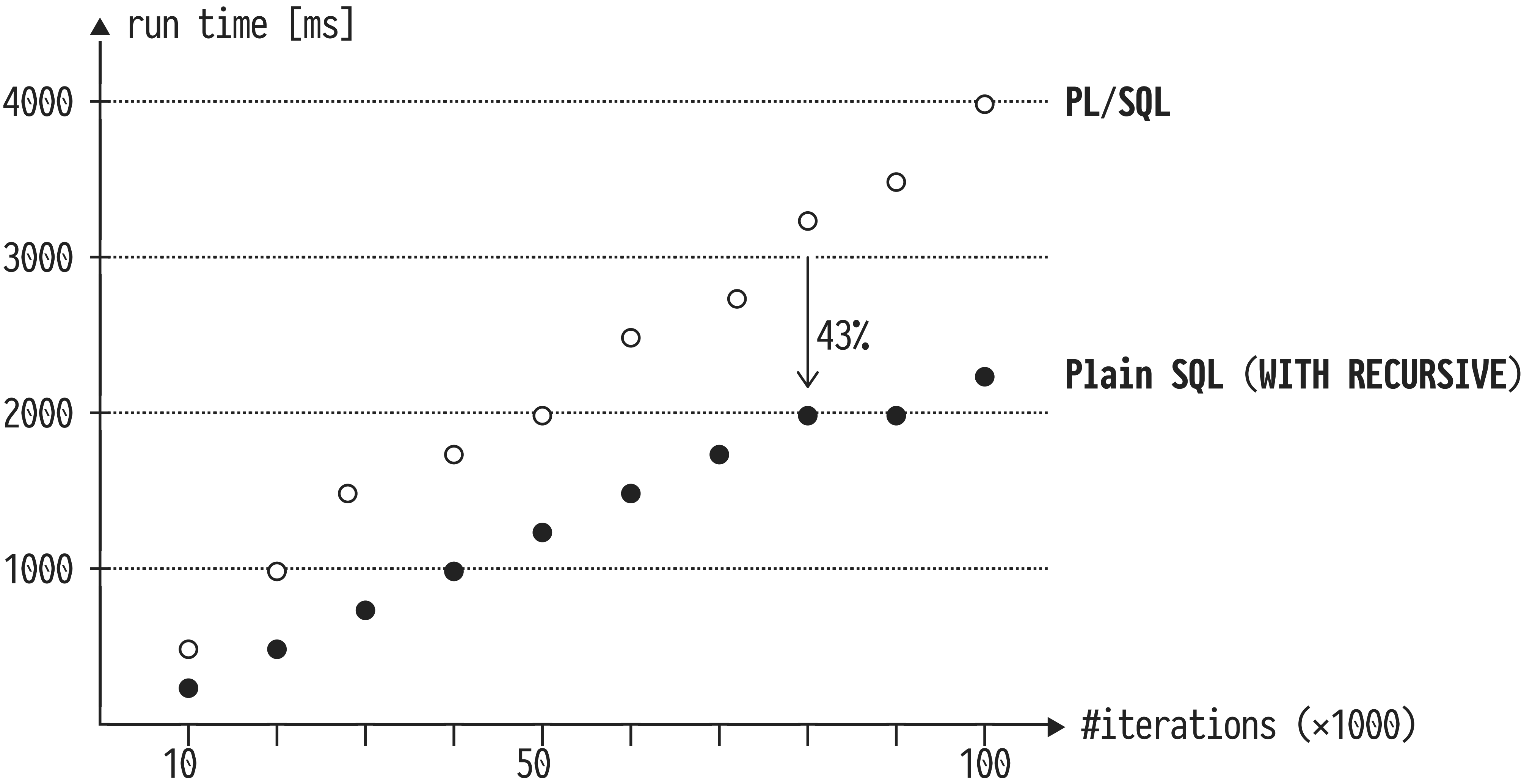
Invoking a PL/SQL Function ≡ Running the Recursive CTE

Table *run* (for $f(2,5) = 2^5$)

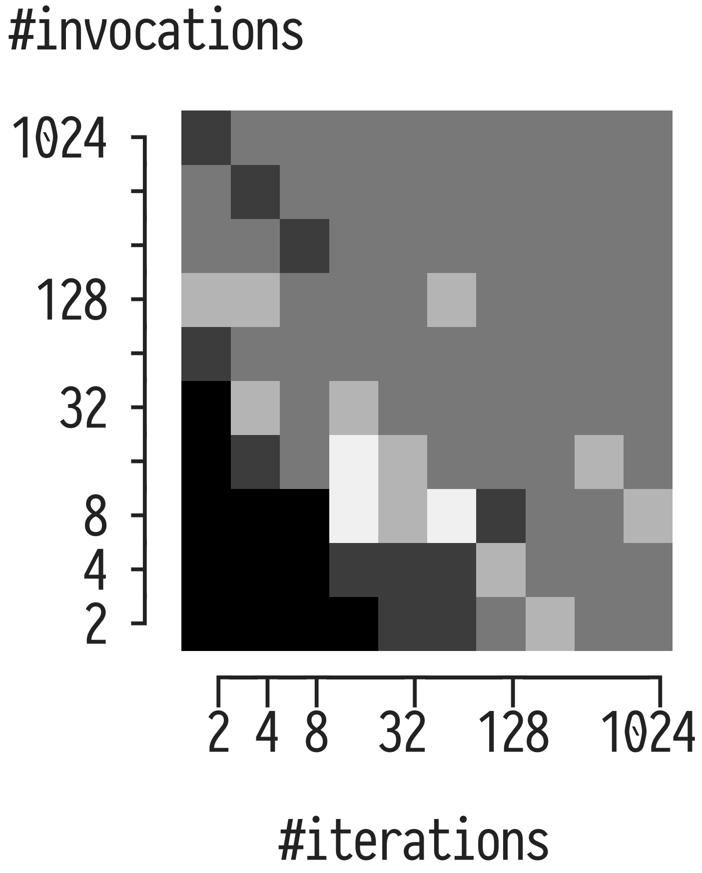
call?	i_1	p_1	x	n	result
true	0	1	2	5	□
true	1	2	2	5	□
true	2	4	2	5	□
true	3	8	2	5	□
true	4	16	2	5	□
true	5	32	2	5	□
false	□	□	□	□	32◀

- Look at this table either as…
  - … the SSA function's **trace of variable states**, or
  - … the ANF function's **call stack**

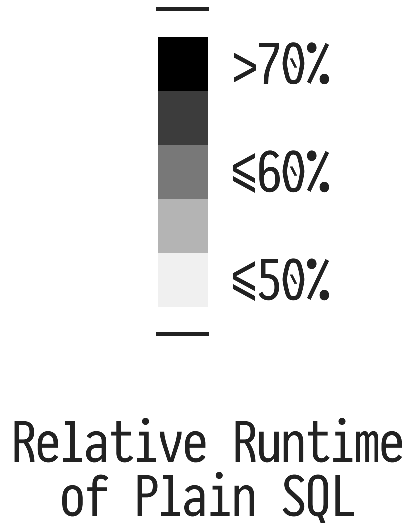
SQL Recursion vs. PL/SQL Iteration (Intra-Function)

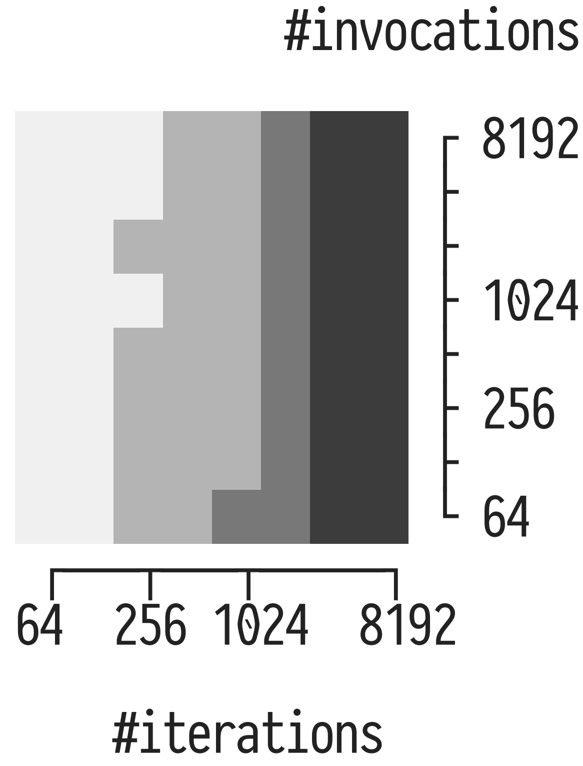


Scaling the Number of PL/SQL↔SQL Context Switches



Markov DP-based Robot Walk





N-Body Simulation

When WITH RECURSIVE Does Too Much

Table *run*

#iter	call?	i_1	p_1	x	n	result	
↓	true	0	1	2	5	□	X
	true	1	2	2	5	□	X
	true	2	4	2	5	□	X
⋮	true	3	8	2	5	□	X
	true	4	16	2	5	□	X
	true	5	32	2	5	□	X
	false	□	□	□	□	32	◀

```
WITH RECURSIVE run AS (
  ⋮
)
SELECT result
FROM   run
WHERE  NOT "call?"
```

- Since tail recursion *does not look upwards the stack*, a single-row “stack” suffices

If We Had “WITH TAIL RECURSIVE”…

Table *run*

#iter

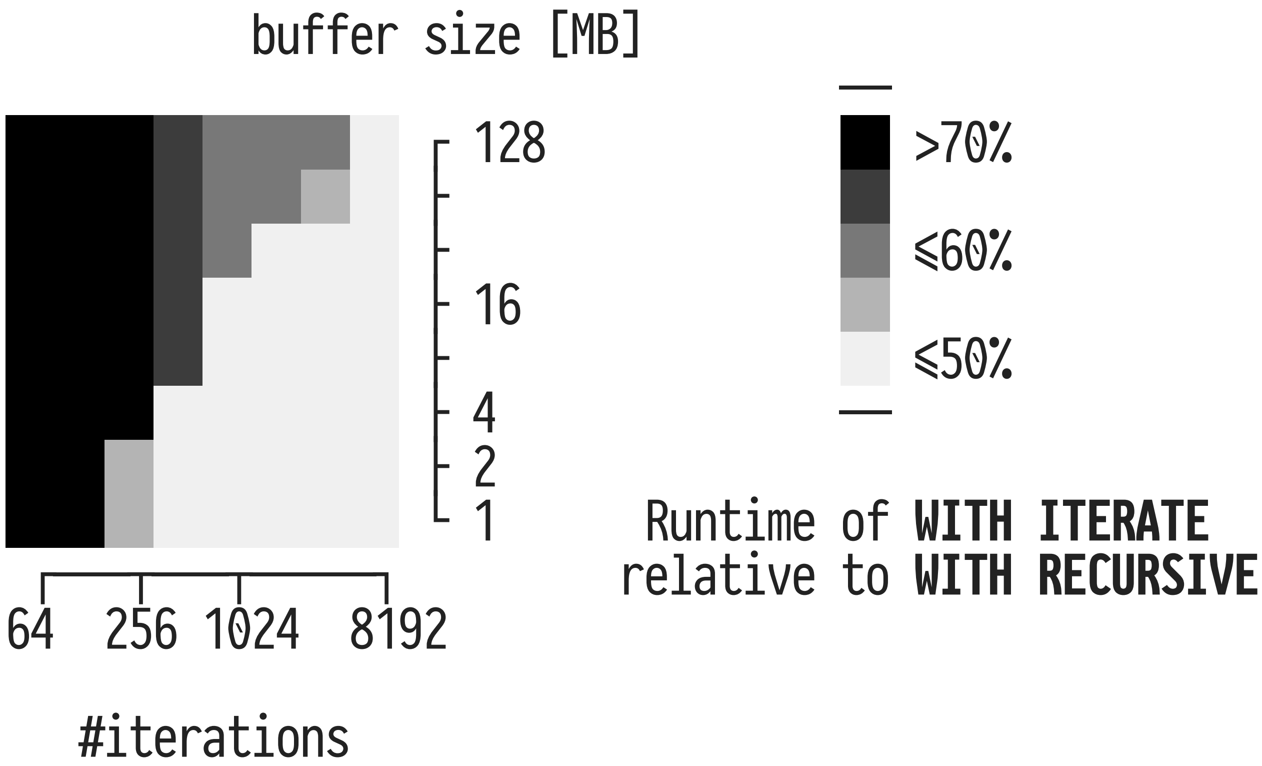
call?	i_1	p_1	x	n	result
true	0	1	2	5	□
true	1	2	2	5	□
⋮					
true	5	32	2	5	□
false	□	□	□	□	32

```
WITH ITERATE run AS (
  ⋮
)
SELECT result
FROM   run
WHERE  NOT "call?"
```

||| WITH ITERATE:

- Singleton table *run*
- Allocates no buffer space

WITH ITERATE: Space-Efficient Iteration



- Local change to PostgreSQL, two implementation avenues

Compiling PL/SQL Away

- Once compiled, **no traces of PL/SQL remain**
  - Thus, zero PL/SQL↔SQL context switches occur

- **Source-to-source compilation** *on top* of the RDBMS
  - Applies to Oracle and SQL Server just as well

- Run compilation chain…
  - …up to ANF: derive plain SQL UDFs from PL/SQL
  - …all the way: execute PL/SQL on RDBMSs that implement SQL:1999 but do not support UDFs at all (**SQLite3**)

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From Mutual to Direct Recursion

ANF ⟲	➧	ANF ↻

```
f(x,n) =
  let i₀ = 0 in
   let p₀ = 1 in
    while(i₀,p₀,x,n)

while(i₁,p₁,x,n) =
  let t₀ = i₁ ⩾ n in
   if t₀ then p₁
         else loop(i₁,p₁,x,n)

loop(i₁,p₁,x,n) =
  let p₂ = p₁ * x in
   let i₂ = i₁ + 1 in
    while(i₂,p₂,x,n)
```

```
f(x,n) =
  let i₀ = 0 in
   let p₀ = 1 in
    run(❶,i₀,p₀,x,n)

run(fn,i₁,p₁,x,n) =
  if fn = ❶ then
   let t₀ = i₁ ⩾ n in
    if t₀ then p₁
          else run(❷,i₁,p₁,x,n)
  else
   let p₂ = p₁ * x in
    let i₂ = i₁ + 1 in
     run(❶,i₂,p₂,x,n)
```

- Single recursive function *run*(), **tail calls** only