Problem 1:

For problem 1, I have discussed the solutions with Srinivas since I was not able to understand some of the details.

The TRC can be converted into the following query to compute NOT ALL .

select p.x, q.x from P p, Q q where exists (select r.y from R r where r.x = p.x and p.x not in (select s.z from S s where s.x = q.x));

Working memory = 1GB, All sorting enabled.

```
QUERY PLAN
-------------------------------------------

 Hash Semi Join
   Hash Cond: (p.x = r.x)
   ->  Nested Loop
         Join Filter: (NOT (SubPlan 1))
         ->  Seq Scan on p
         ->  Materialize
               -> Seq Scan on q
         SubPlan 1
           ->  Seq Scan on s
                 Filter: (x = q.x)
   ->  Hash
         ->  Seq Scan on r
(12 rows)
```

Here the postgres uses hash table to speed up the operation and only materialize the Q in memory since it's smallest of all. Thus resulting in performance boost.

Here we will be disabling the hash join and merge join, since the both merge join and hash join are disallowed the postgres has to materialize both the tables in memory and used nested loop join to execute the query.

```
                QUERY PLAN
-------------------------------------------

 Nested Loop
   Join Filter: (NOT (SubPlan 1))
   ->  Nested Loop
         Join Filter: (p.x = r.x)
         ->  HashAggregate
               Group Key: r.x
               ->  Seq Scan on r
         ->  Materialize
               ->  Seq Scan on p
   ->  Materialize
         -> Seq Scan on q
   SubPlan 1
     ->  Seq Scan on s
           Filter: (x = q.x)
(14 rows)
```

Problem 2:

- A) optimized Q4

select distinct p.a from P p join R r1 on (p.a = r1.a) join R r2 on(r1.b = r2.a) join R r3 on (r2.b = r3.a) join S s on(r3.b = S.b);

- B) Compare queries Q3 and Q4 in a similar way as we did for Q1 and Q2 in Example 1.

Q3

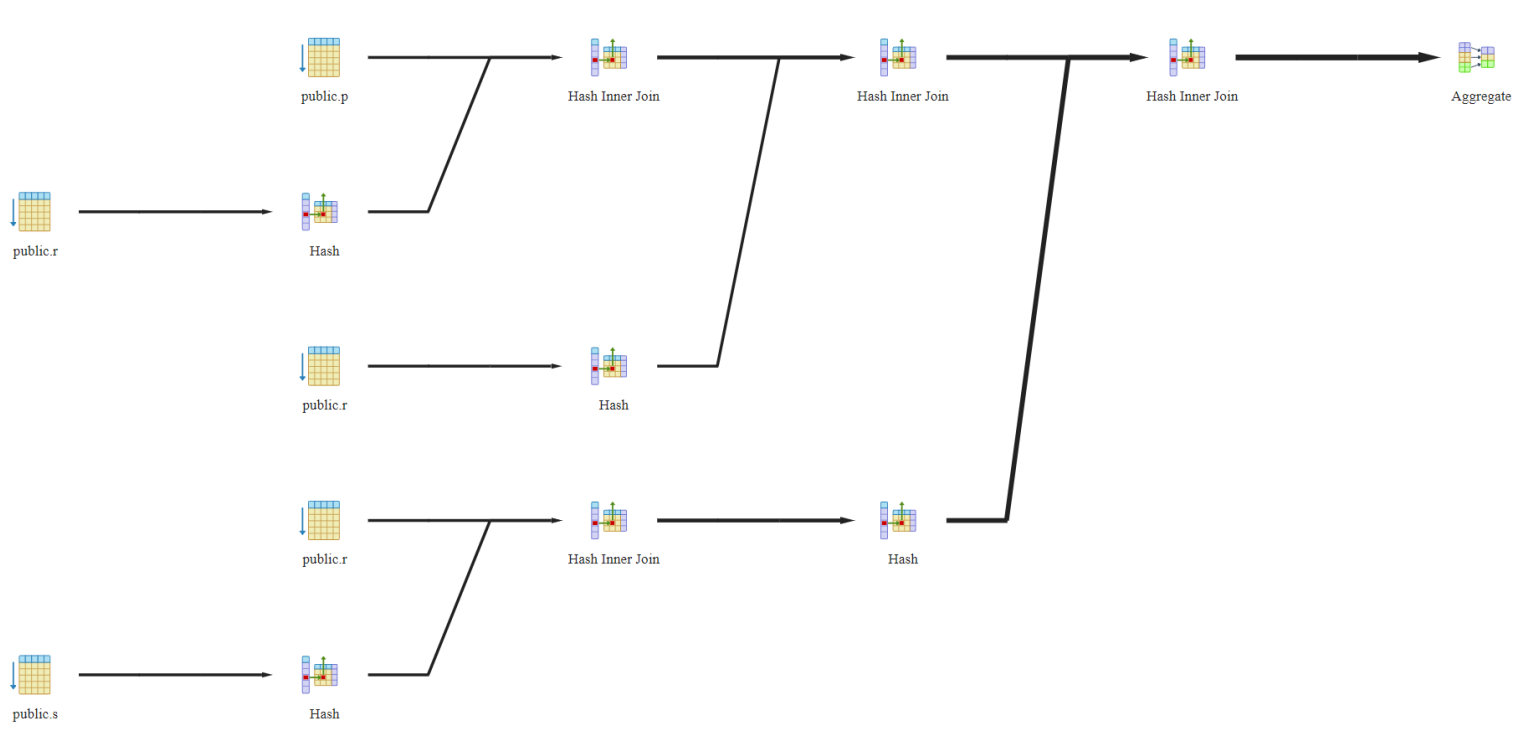
Data Output | Explain | Messages | Notificati

	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.094
2	100	0.254
3	1000	2.286
4	10000	28.753
5	100000	351.578

Q4

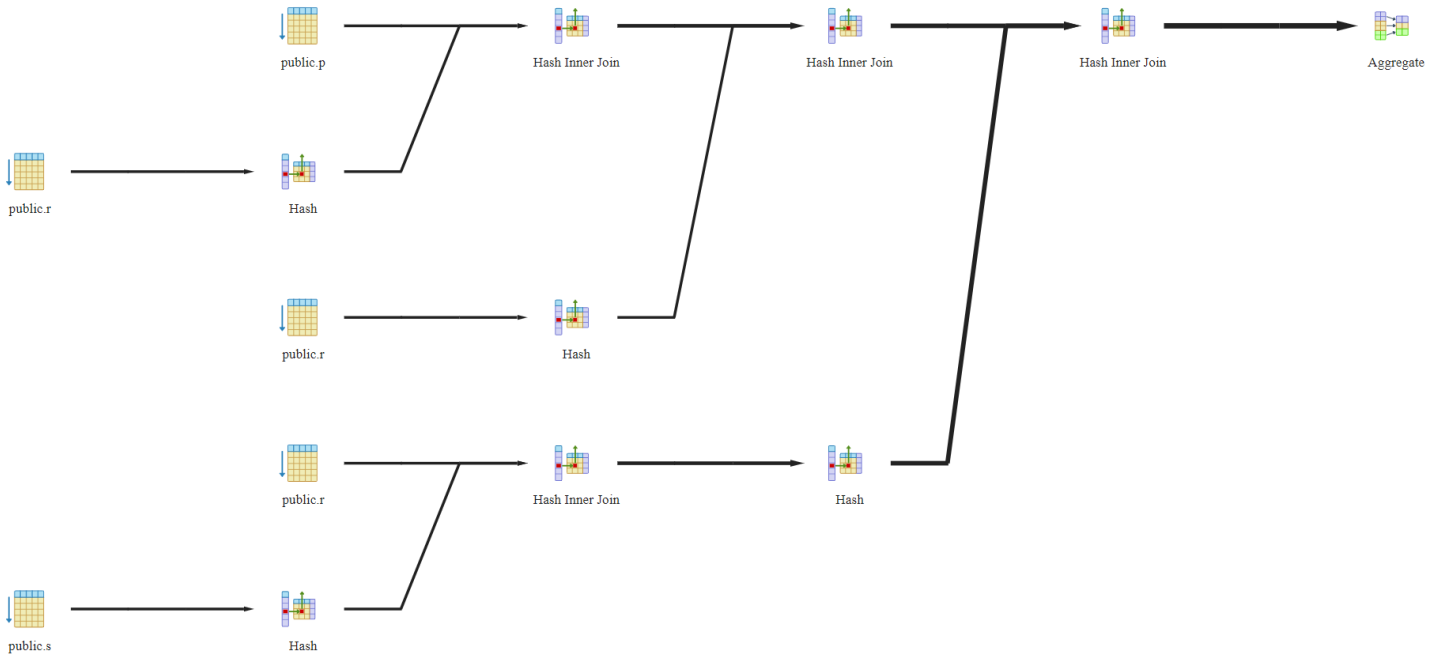
	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.097
2	100	0.266
3	1000	2.201
4	10000	27.496
5	100000	350.705

Execution plan for query 3:



#	Node	Rows Plan	
	1.	Aggregate (cost=26.78..27.45 rows=67 width=4)	67
	2.	Hash Inner Join (cost=15.54..26.05 rows=290 width=4) • **Hash Cond**: (r2.b = r3.a)	290
	3.	Hash Inner Join (cost=6.5..12.88 rows=166 width=8) • **Hash Cond**: (r1.b = r2.a)	166
	4.	Hash Inner Join (cost=3.25..7.17 rows=129 width=8) • **Hash Cond**: (p.a = r1.a)	129
	5.	Seq Scan on public.p as p (cost=0..2 rows=100 width=4)	100
	6.	Hash (cost=2..2 rows=100 width=8)	100
	7.	Seq Scan on public.r as r1 (cost=0..2 rows=100 width=8)	100
	8.	Hash (cost=2..2 rows=100 width=8)	100
	9.	Seq Scan on public.r as r2 (cost=0..2 rows=100 width=8)	100
	10.	Hash (cost=7.35..7.35 rows=135 width=4)	135
	11.	Hash Inner Join (cost=3.25..7.35 rows=135 width=4) • **Hash Cond**: (r3.b = s.b)	135

Execution plan for query 4



#	Node	Timings Exclusive	Inclusive	Rows Rows X	Actual	Plan	Loops	
	1.	Aggregate (cost=26.78..27.45 rows=67 width=4) (actual=0.141..0.144 rows=33 loops=1) • **Buckets**: **Batches**: **Memory Usage**: 24 kB	0.016 ms	0.144 ms	↑ 2.04	33	67	1

#	Node	Timings		Rows				
		Exclusive	Inclusive	Rows X	Actual	Plan	Loops	
2.		Hash Inner Join (cost=15.54..26.05 rows=290 width=4) (actual=0.087..0.128 rows=117 loops=1) • **Hash Cond**: (r2.b = r3.a)	0.015 ms	0.128 ms	↑ 2.48	117	290	1
3.		Hash Inner Join (cost=6.5..12.88 rows=166 width=8) (actual=0.045..0.074 rows=103 loops=1) • **Hash Cond**: (r1.b = r2.a)	0.016 ms	0.074 ms	↑ 1.62	103	166	1
4.		Hash Inner Join (cost=3.25..7.17 rows=129 width=8) (actual=0.02..0.036 rows=95 loops=1) • **Hash Cond**: (p.a = r1.a)	0.017 ms	0.036 ms	↑ 1.36	95	129	1
5.		Seq Scan on public.p as p (cost=0..2 rows=100 width=4) (actual=0.004..0.007 rows=100 loops=1)	0.007 ms	0.007 ms	↑ 1	100	100	1
6.		Hash (cost=2..2 rows=100 width=8) (actual=0.012..0.012 rows=100 loops=1) • **Buckets**: 1024 **Batches**: 1 **Memory Usage**: 12 kB	0.006 ms	0.012 ms	↑ 1	100	100	1
7.		Seq Scan on public.r as r1 (cost=0..2 rows=100 width=8) (actual=0.003..0.006 rows=100 loops=1)	0.006 ms	0.006 ms	↑ 1	100	100	1
8.		Hash (cost=2..2 rows=100 width=8) (actual=0.022..0.022 rows=100 loops=1) • **Buckets**: 1024 **Batches**: 1 **Memory Usage**: 12 kB	0.008 ms	0.022 ms	↑ 1	100	100	1
9.		Seq Scan on public.r as r2 (cost=0..2 rows=100 width=8) (actual=0.01..0.014 rows=100 loops=1)	0.014 ms	0.014 ms	↑ 1	100	100	1
10.		Hash (cost=7.35..7.35 rows=135 width=4) (actual=0.04..0.04 rows=96 loops=1) • **Buckets**: 1024 **Batches**: 1 **Memory Usage**: 12 kB	0.006 ms	0.04 ms	↑ 1.41	96	135	1
11.		Hash Inner Join (cost=3.25..7.35 rows=135 width=4) (actual=0.019..0.034 rows=96 loops=1) • **Hash Cond**: (r3.b = s.b)	0.015 ms	0.034 ms	↑ 1.41	96	135	1
12.		Seq Scan on public.r as r3 (cost=0..2 rows=100 width=8) (actual=0.003..0.006 rows=100 loops=1)	0.006 ms	0.006 ms	↑ 1	100	100	1
13.		Hash (cost=2..2 rows=100 width=4) (actual=0.014..0.014 rows=100 loops=1) • **Buckets**: 1024 **Batches**: 1 **Memory Usage**: 12 kB	0.007 ms	0.014 ms	↑ 1	100	100	1
14.		Seq Scan on public.s as s (cost=0..2 rows=100 width=4) (actual=0.004..0.007 rows=100 loops=1)	0.007 ms	0.007 ms	↑ 1	100	100	1

Conclusion

Here we are not able to see any drastic improvements in query performance since both the queries uses hash joins to perform the selection operation. However, performance may vary as data size increases significantly.

Problem 3:

- A) Optimized Q 6

-- step 1 Optimization

```
select p.a from P p where exists (select 1 from R r where r.a = p.a and not exists (select 1 from S s where r.b = s.b));
```

-- step 2 Optimization

```
select p.a from P p where exists ((select r.a, r.b from R r where r.a = p.a) except (select r.a, r.b from R r, S s where r.a
                = p.a and r.b = s.b));
```

-- step 3: Optimization

select distinct q. a from (select p. a, r. a as ra, r. b from P p natural join R r except select p. a, r. a as ra, r. b from P p natural join R

B) Compare Q5, Q6, Q7

Q5

	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.046
2	100	0.075
3	1000	0.477
4	10000	4.706
5	100000	72.319
6	1000000	1065.781

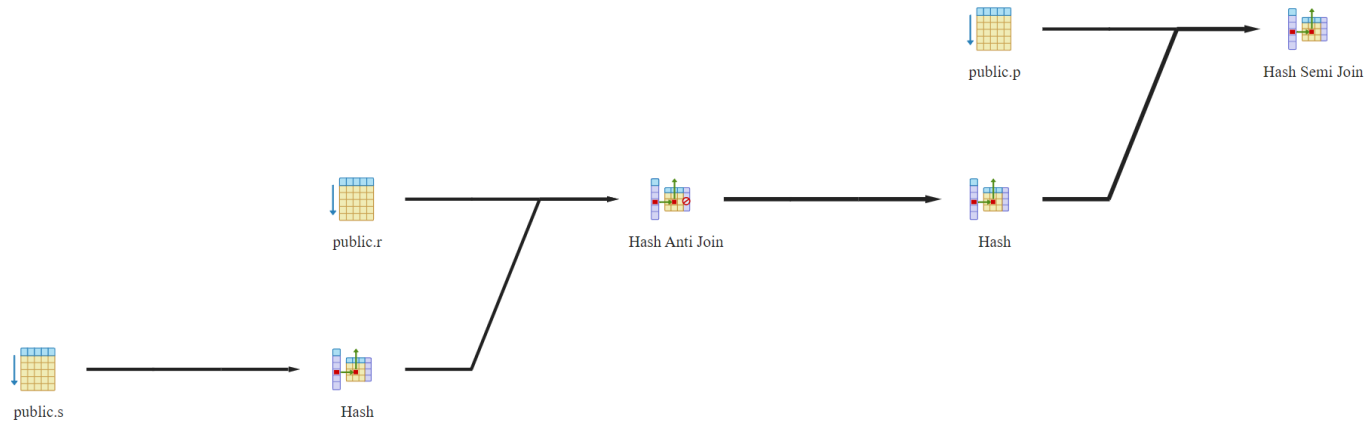
Q6

	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.331
2	100	0.375
3	1000	2.436
4	10000	26.079
5	100000	318.059

Q7

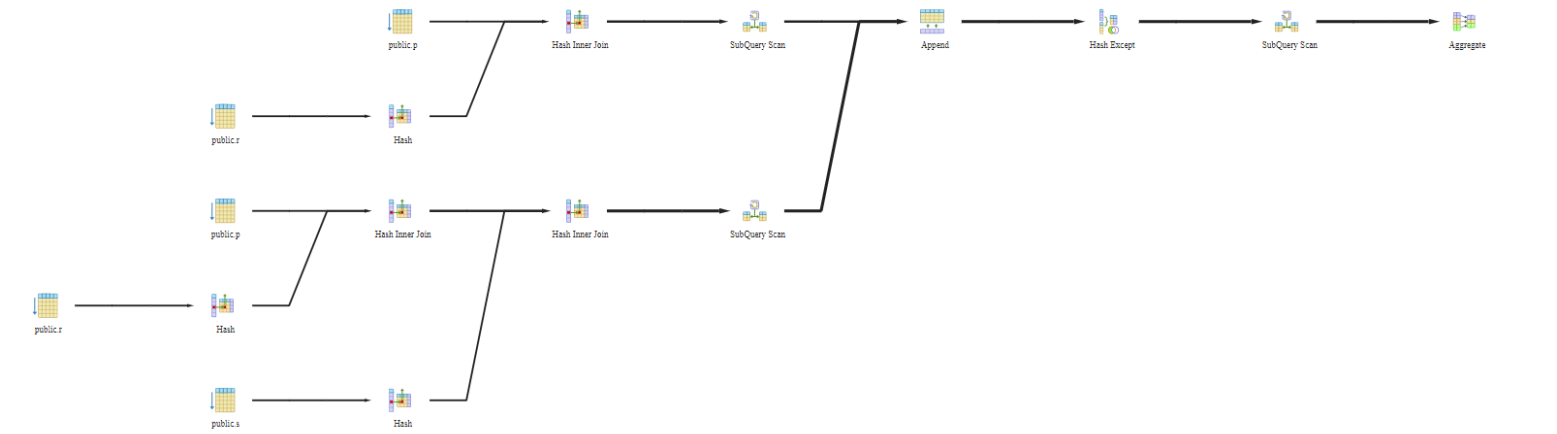
	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.052
2	100	0.130
3	1000	2.570
4	10000	170.665
5	100000	17003.946

Execution plan for Q5,



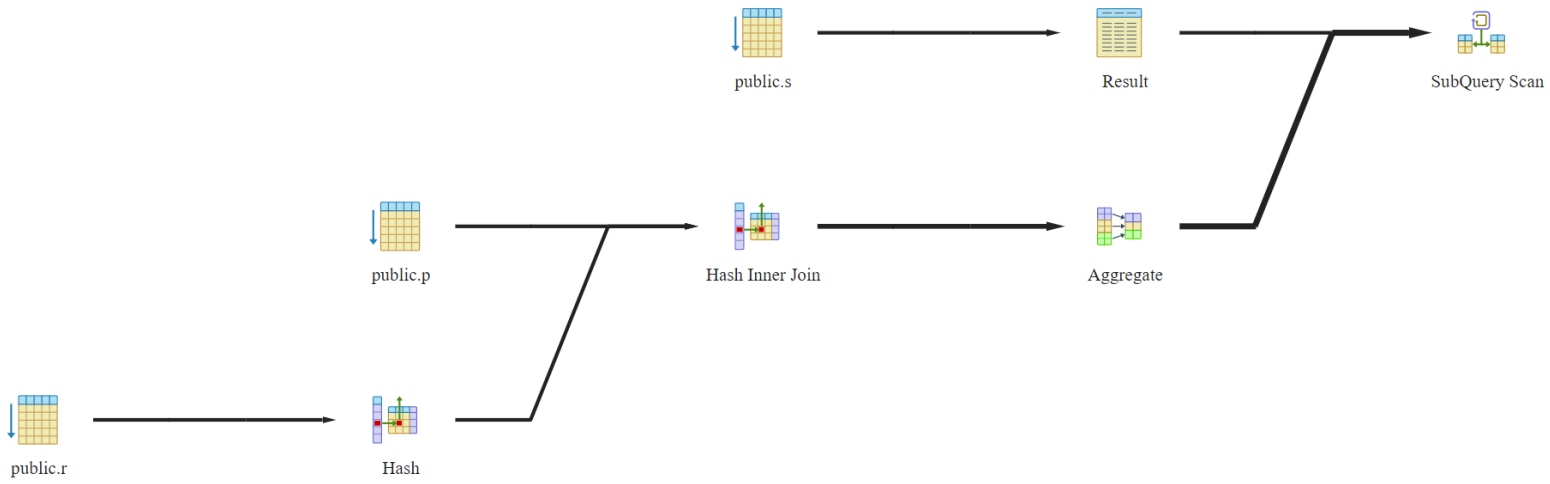
#	Node	Plan	Rows
1.		Hash Semi Join (cost=5.89..8.16 rows=1 width=4) • **Hash Cond**: (p.a = r.a)	1
2.		Seq Scan on public.p as p (cost=0..2 rows=100 width=4)	100
3.		Hash (cost=5.88..5.88 rows=1 width=4)	1
4.		Hash Anti Join (cost=3.25..5.88 rows=1 width=4) • **Hash Cond**: (r.b = s.b)	1
5.		Seq Scan on public.r as r (cost=0..2 rows=100 width=8)	100
6.		Hash (cost=2..2 rows=100 width=4)	100
7.		Seq Scan on public.s as s (cost=0..2 rows=100 width=4)	100

Execution plan for Q6,



#	Node	Rows Plan	
	1.	Aggregate (cost=28.75..30.04 rows=129 width=4)	129
	2.	Subquery Scan (cost=3.25..28.43 rows=129 width=4)	129
	3.	Hash Except (cost=3.25..27.14 rows=129 width=16)	129
	4.	Append (cost=3.25..24.86 rows=304 width=16)	304
	5.	Subquery Scan (cost=3.25..8.46 rows=129 width=16)	129
	6.	Hash Inner Join (cost=3.25..7.17 rows=129 width=12) • **Hash Cond**: (p.a = r.a)	129
	7.	Seq Scan on public.p as p (cost=0..2 rows=100 width=4)	100
	8.	Hash (cost=2..2 rows=100 width=8)	100
	9.	Seq Scan on public.r as r (cost=0..2 rows=100 width=8)	100
	10.	Subquery Scan (cost=6.5..14.88 rows=175 width=16)	175
	11.	Hash Inner Join (cost=6.5..13.13 rows=175 width=12) • **Hash Cond**: (r_1.b = s.b)	175
	12.	Hash Inner Join (cost=3.25..7.17 rows=129 width=12) • **Hash Cond**: (p_1.a = r_1.a)	129
	13.	Seq Scan on public.p as p_1 (cost=0..2 rows=100 width=4)	100
	14.	Hash (cost=2..2 rows=100 width=8)	100
	15.	Seq Scan on public.r as r_1 (cost=0..2 rows=100 width=8)	100
	16.	Hash (cost=2..2 rows=100 width=4)	100
	17.	Seq Scan on public.s as s (cost=0..2 rows=100 width=4)	100

Execution plan for Q7,



#	Node	Plan	Rows
	1.	Subquery Scan (cost=9.82..11.5 rows=67 width=4)	67
	2.	Result (cost=2..2.01 rows=1 width=32)	1
	3.	Seq Scan on public.s as s (cost=0..2 rows=100 width=4)	100
	4.	Aggregate (cost=7.81..8.82 rows=67 width=36) • **Filter**: (NOT (array_agg(r.b) <@ $1))	67
	5.	Hash Inner Join (cost=3.25..7.17 rows=129 width=8) • **Hash Cond**: (p.a = r.a)	129
	6.	Seq Scan on public.p as p (cost=0..2 rows=100 width=4)	100
	7.	Hash (cost=2..2 rows=100 width=8)	100

Conclusion

Here we can see substantial improvement using RA optimized query and worst performance with array aggregation query Q7. Since all the three queries were implemented using hash, the RA optimized in super in terms of multiple hash tables and hash except.

Problem 4:

- A) Optimized Q 9

  -- step 1

  ```
  select p.a from P p where exists (select 1 from S s where not exists (select 1 from R where p.a = r.a and r.b
                  = s.b));
  ```

  -- step 2

select p. a from P p where exists (select p. a, s. b from S s except select r. a, r. b from S s, R r where p. a = r. a and r. b = s. b);

-- step 3

select distinct q. a from (select p. a, s. b from P p cross join S s except select p. a, s. b from P p natural join R r natural join S s)q;

- Compare Q8, Q9, Q10

Q8

	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.043
2	100	0.072
3	1000	0.421
4	10000	4.433
5	100000	47.520

Q9

Data Output Explain Messages Notificat

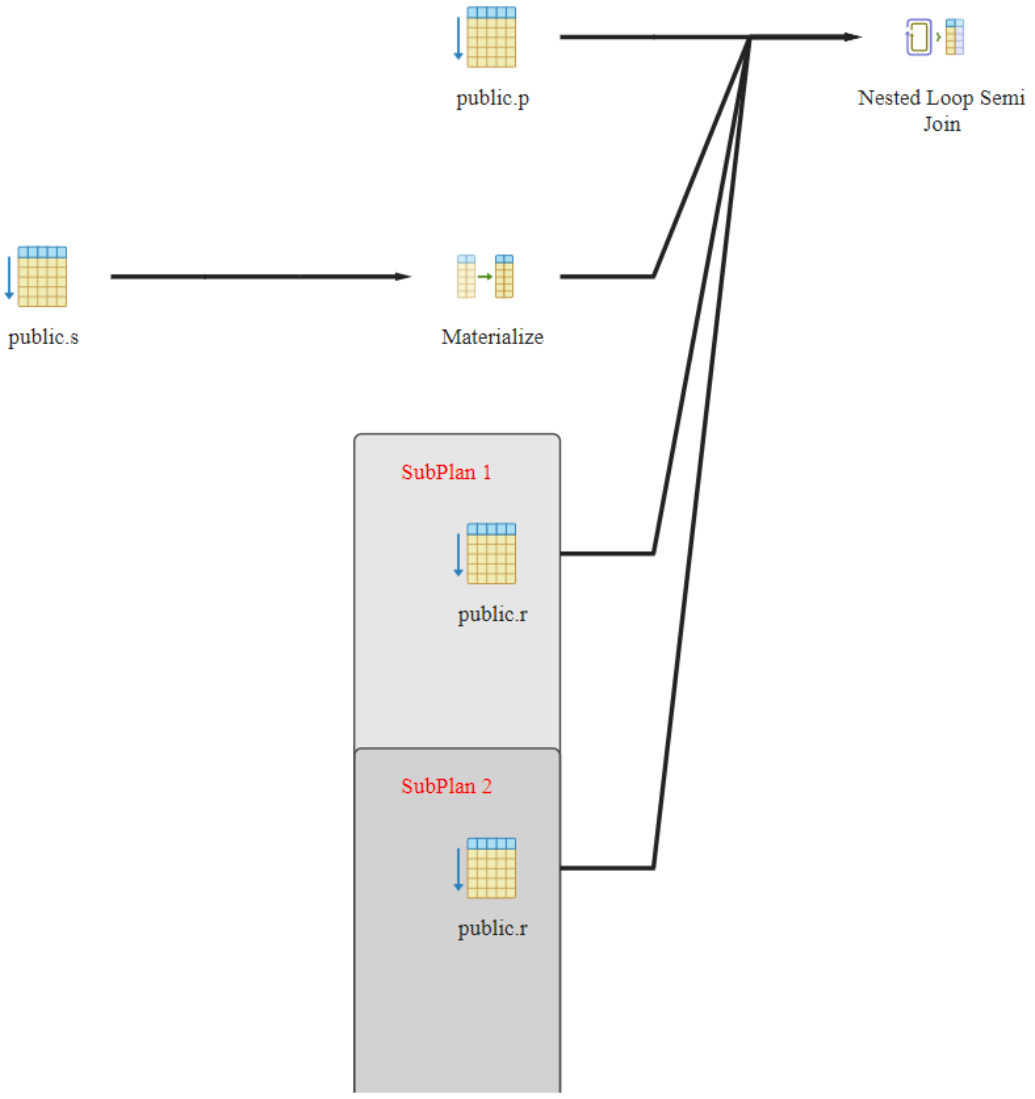
	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.704
2	100	4.080
3	1000	457.181
4	10000	70403.532

Q10

Data Output Explain Messages Notifications

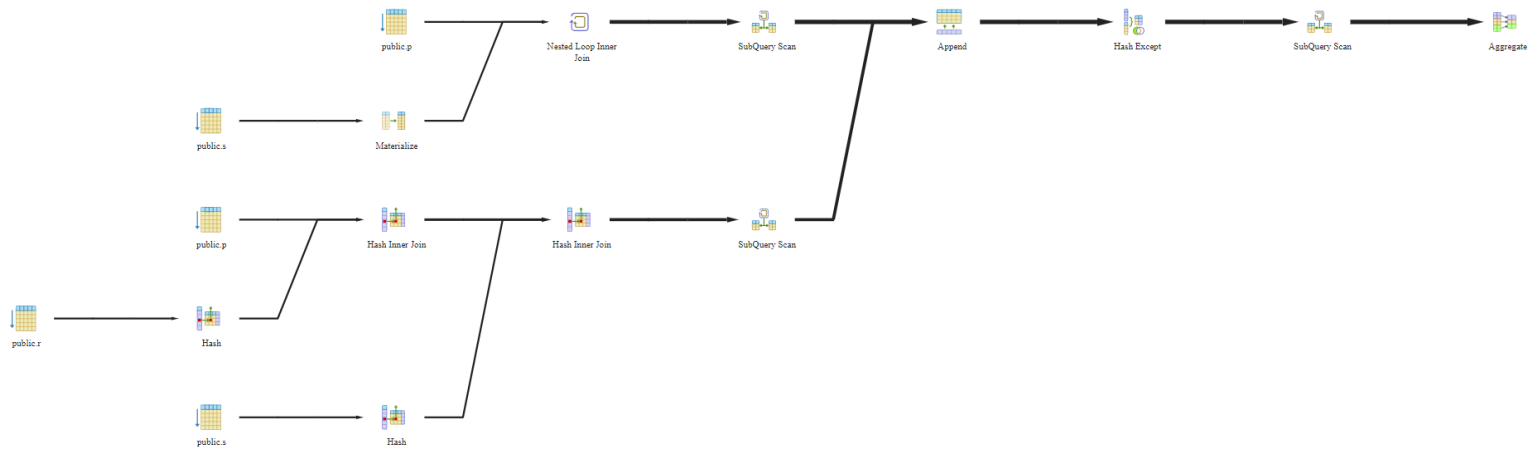
	Size of relation integer	Avg execution time (in ms) numeric
1	10	0.104
2	100	0.190
3	1000	1.355
4	10000	14.499
5	100000	179.541

Execution plan Q8



#	Node	Plan	Rows
1.		Nested Loop Semi Join (cost=0..12815.51 rows=50 width=4) • **Join Filter**: (NOT (alternatives: SubPlan 1 or hashed SubPlan 2))	50
2.		Seq Scan on public.p as p (cost=0..2 rows=100 width=4)	100
3.		Materialize (cost=0..2.5 rows=100 width=4)	100
4.		Seq Scan on public.s as s (cost=0..2 rows=100 width=4)	100
5.		Seq Scan on public.r as r (cost=0..2.5 rows=1 width=0) • **Filter**: ((p.a = r.a) AND (r.b = s.b))	1
6.		Seq Scan on public.r as r_1 (cost=0..2 rows=100 width=8)	100

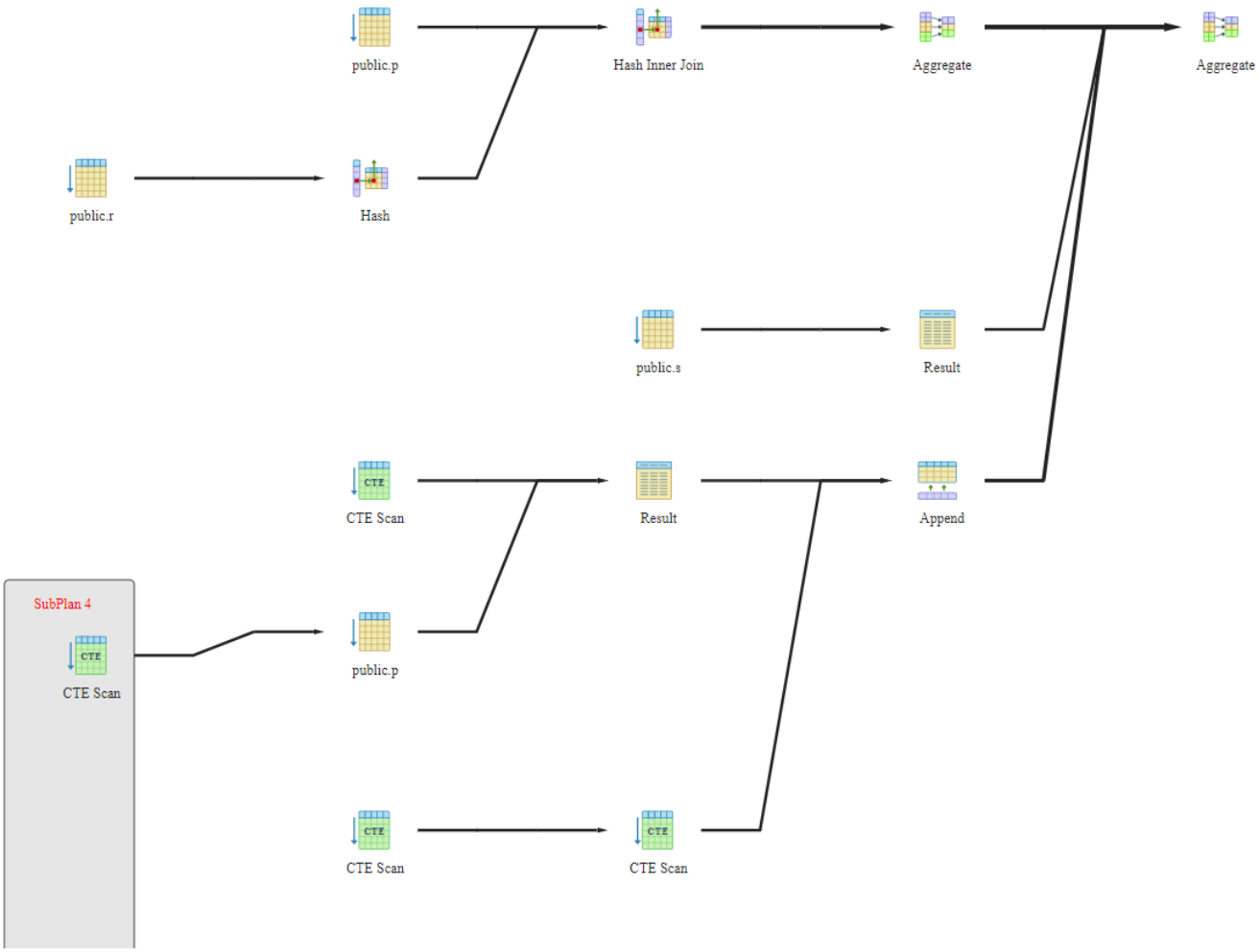
Execution plan Q9



#	Node	Plan	Rows
1.		Aggregate (cost=399.48..401.48 rows=200 width=4)	200
2.		Subquery Scan (cost=0..388.76 rows=4288 width=4)	4288
3.		Hash Except (cost=0..345.88 rows=4288 width=12)	4288
4.		Append (cost=0..295.01 rows=10175 width=12)	10175
5.		Subquery Scan (cost=0..229.25 rows=10000 width=12)	10000
6.		Nested Loop Inner Join (cost=0..129.25 rows=10000 width=8)	10000
7.		Seq Scan on public.p as p (cost=0..2 rows=100 width=4)	100
8.		Materialize (cost=0..2.5 rows=100 width=4)	100
9.		Seq Scan on public.s as s (cost=0..2 rows=100 width=4)	100
10.		Subquery Scan (cost=6.5..14.88 rows=175 width=12)	175
11.		Hash Inner Join (cost=6.5..13.13 rows=175 width=8) • **Hash Cond**: (r.b = s_1.b)	175
12.		Hash Inner Join (cost=3.25..7.17 rows=129 width=8) • **Hash Cond**: (p_1.a = r.a)	129
13.		Seq Scan on public.p as p_1 (cost=0..2 rows=100 width=4)	100

#	Node	Plan	Rows
14.		Hash (cost=2..2 rows=100 width=8)	100
15.		Seq Scan on public.r as r (cost=0..2 rows=100 width=8)	100
16.		Hash (cost=2..2 rows=100 width=4)	100
17.		Seq Scan on public.s as s_1 (cost=0..2 rows=100 width=4)	100

Execution plan Q10



#	Node	Plan	Rows
1.		Aggregate (cost=18.01..19.18 rows=117 width=4)	117
2.		Aggregate (cost=7.81..8.65 rows=67 width=36)	67
3.		Hash Inner Join (cost=3.25..7.17 rows=129 width=8) • **Hash Cond**: (p_1.a = r.a)	129

#	Node	Plan	Rows
	4.	Seq Scan on public.p as p_1 (cost=0..2 rows=100 width=4)	100
	5.	Hash (cost=2..2 rows=100 width=8)	100
	6.	Seq Scan on public.r as r (cost=0..2 rows=100 width=8)	100
	7.	Result (cost=2..2.01 rows=1 width=32)	1
	8.	Seq Scan on public.s as s (cost=0..2 rows=100 width=4)	100
	9.	Append (cost=1.53..7.06 rows=117 width=4)	117
	10.	Result (cost=1.53..3.78 rows=50 width=4)	50
	11.	CTE Scan (cost=0..0.02 rows=1 width=32)	1
	12.	Seq Scan on public.p as p (cost=1.53..3.78 rows=50 width=4) • **Filter**: (NOT (hashed SubPlan 4))	50
	13.	CTE Scan (cost=0..1.34 rows=67 width=4)	67
	14.	CTE Scan (cost=0.02..1.53 rows=67 width=4) • **Filter**: (NOT ($5 <@ nestedr.bs))	67
	15.	CTE Scan (cost=0..0.02 rows=1 width=32)	1

Conclusion:

Here the optimized RA query the longest time with data size above 10 ^ 5 impossible to execute, this is attributed presence of multiple joins including nested inner loop join and hash inner join, compared to original query which had single nested inner loop join. The array agg method performing way better than the RA optimized query as well.

Problem 5:

For queries in problem 3, all queries had hash inner joins and variations of it. Resulting in Fastest query being RA optimized query this can be attributed to multiple hash tables being used to speed up the performance. Compared to queries in problem 4, all queries involved nested inner loop join resulting in poor performance with RA optimized query performing worst. This is due to presence of nested inner loop joins in RA optimized query. The array agg query used Cte scan resulting in better performance over the RA query.