MercuryDB

Main Memory Single-Schema DB Generator

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Outline

- Why MercuryDB?
- Modules
- The API
- Query and Join Optimizations
- Building the Database
- Target Module Generator

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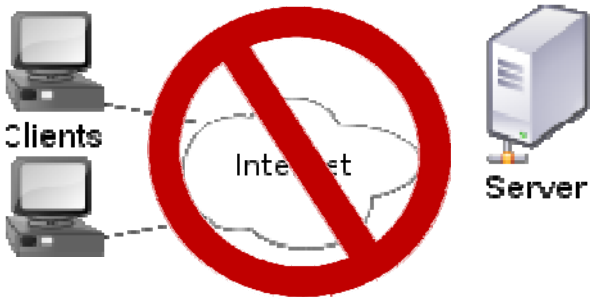
Motivation

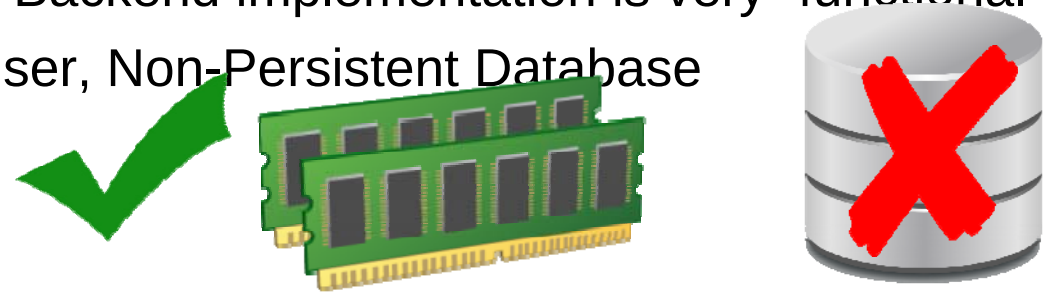
- Most relational database systems
  - have 1 or more schemas that can also change
  - are bottlenecked by I/O in queries of small complexity
  - provide a layer of abstraction between the client and the data



- Would be nice to have an API that is schema-dependent
  - Interesting opportunities for optimization

The Answer: MercuryDB (for Java)

- Schema is generated in Java source code
- Generated code exposes an API to the client
- All queries are done using anonymous Iterators
  - no stream objects are buffered while processing queries
    - (except for hash joins)
  - Backend implementation is very “functional”
- 1-User, Non-Persistent Database



The Answer: MercuryDB (for Java)

- The generated database is compiled with the source program
- 4 steps for use:
  - Compile target package
  - Run MercuryDB on target to create a schema
  - Add Mercury hooks to original program
  - Client application uses the Mercury Schema to query facts about the target

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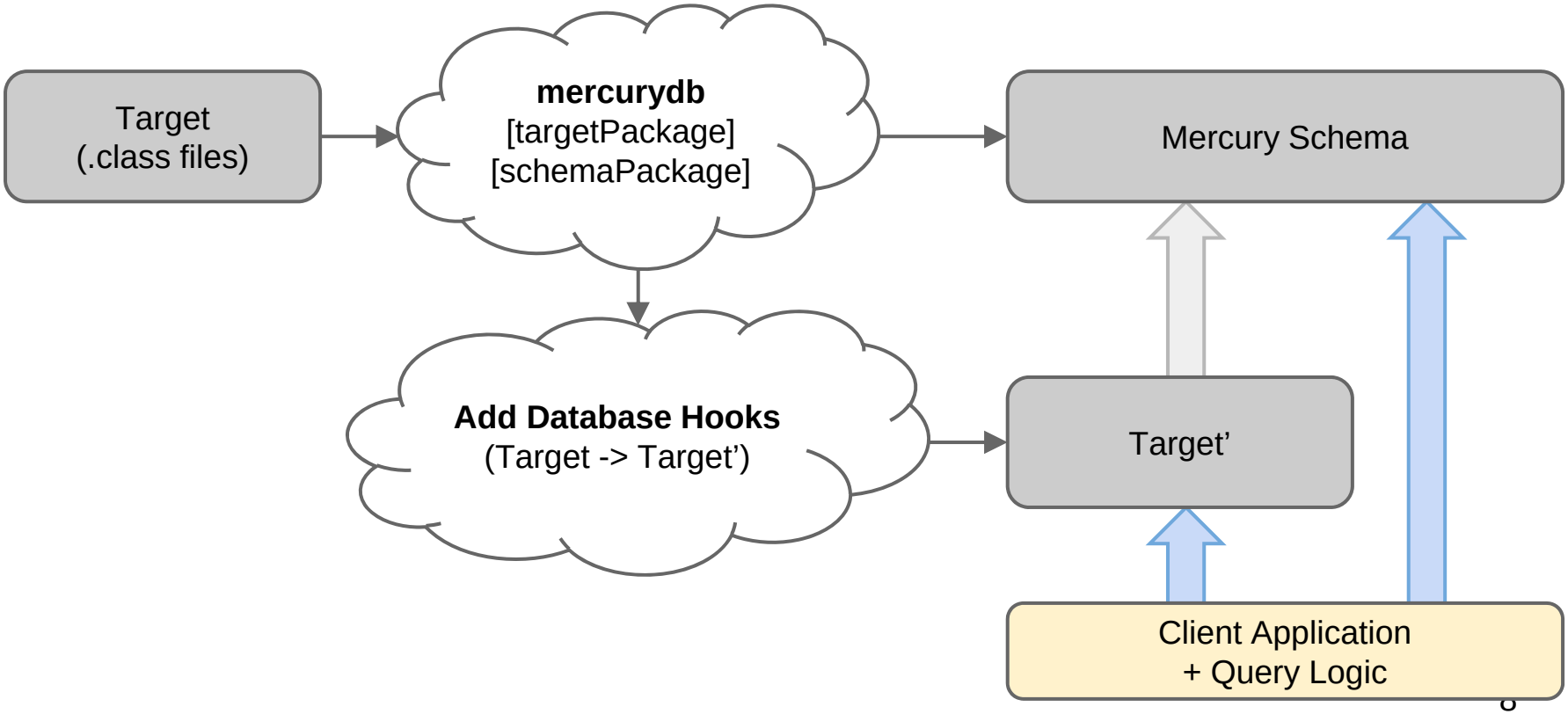
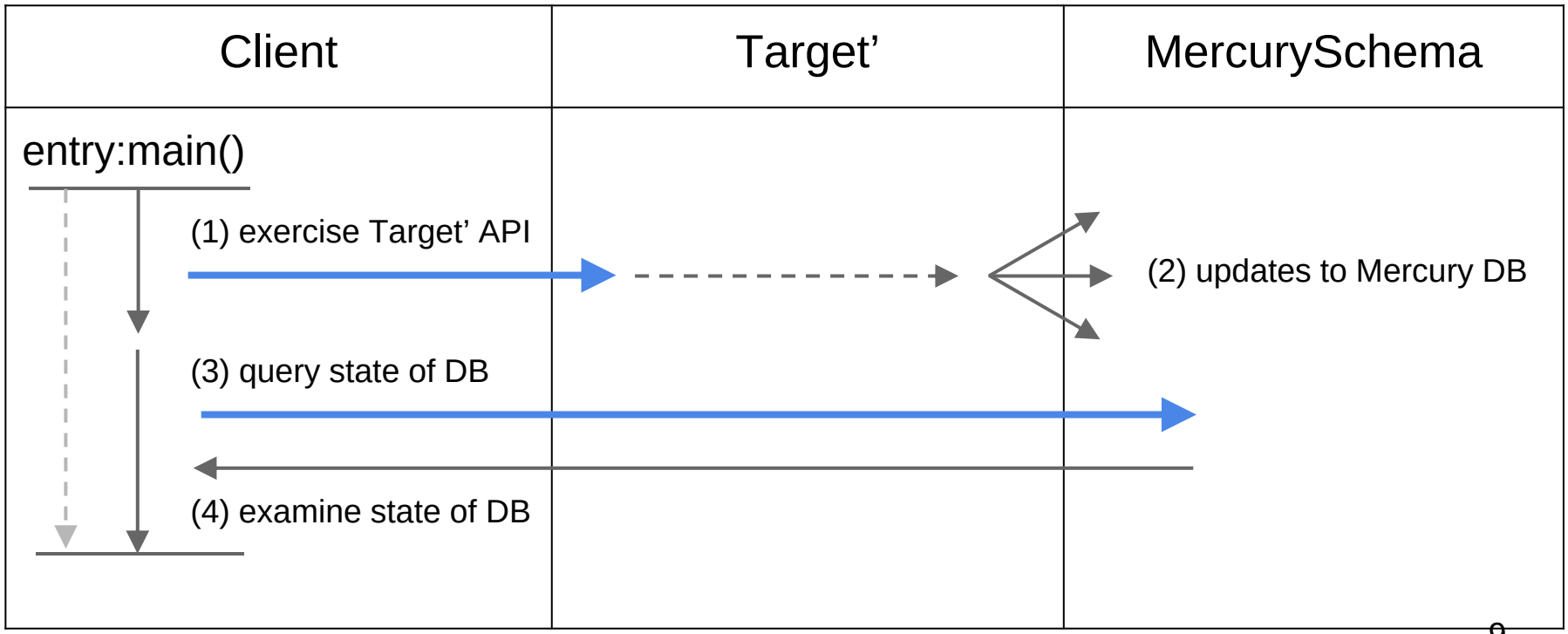
Modules

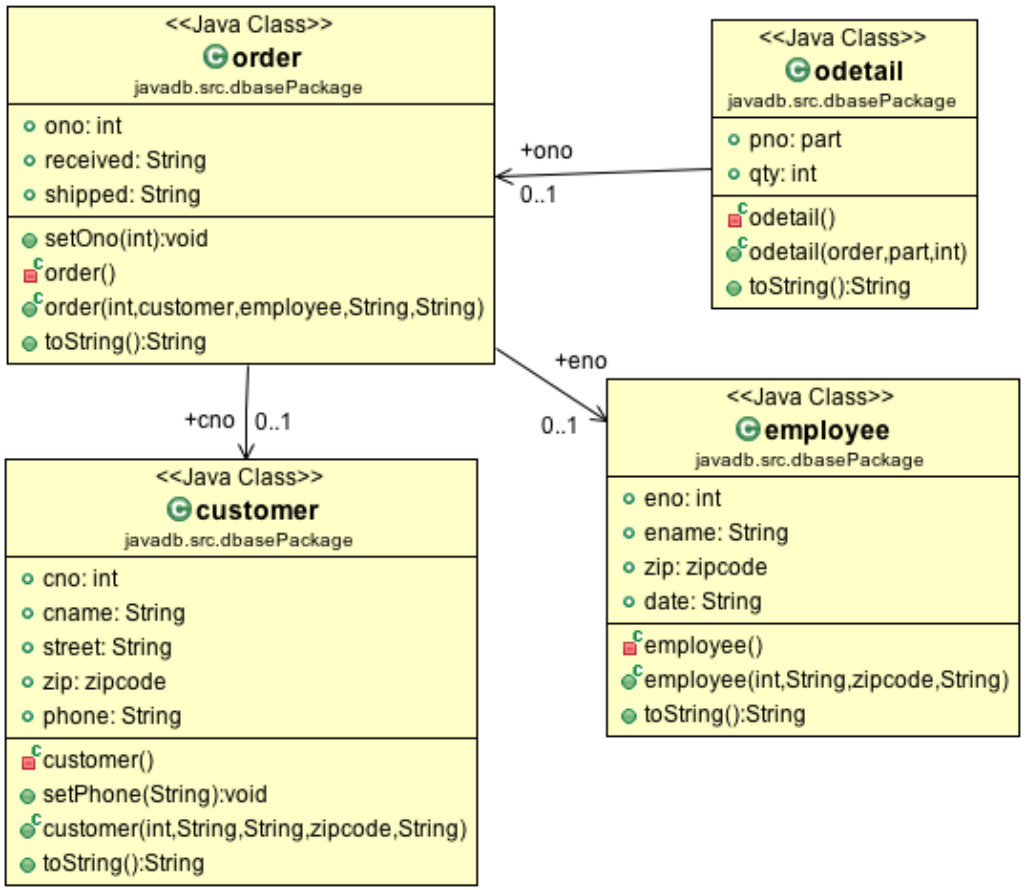

Target
(.class files)
mercurydb
[targetPackage]
[schemaPackage]
Mercury Schema
Add Database Hooks
(Target -> Target')
Target'
Client Application
+ Query Logic

Control Flow



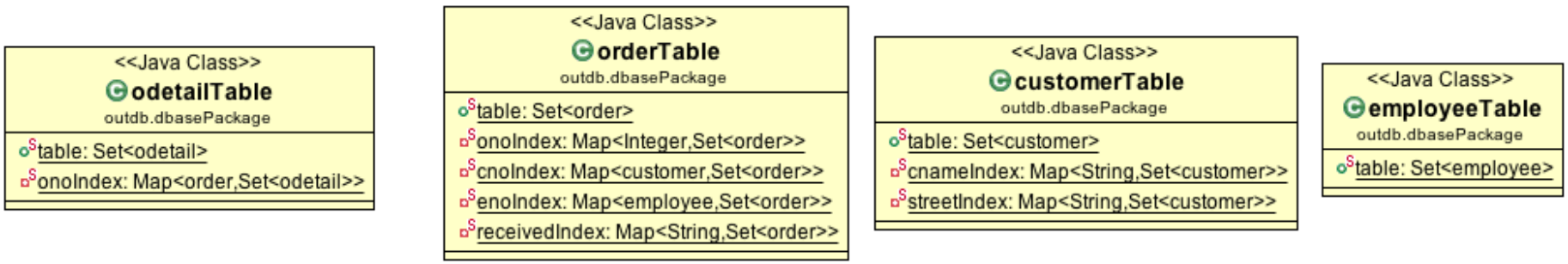
Example Input

- Possible input package to javadb.Main



Example Output

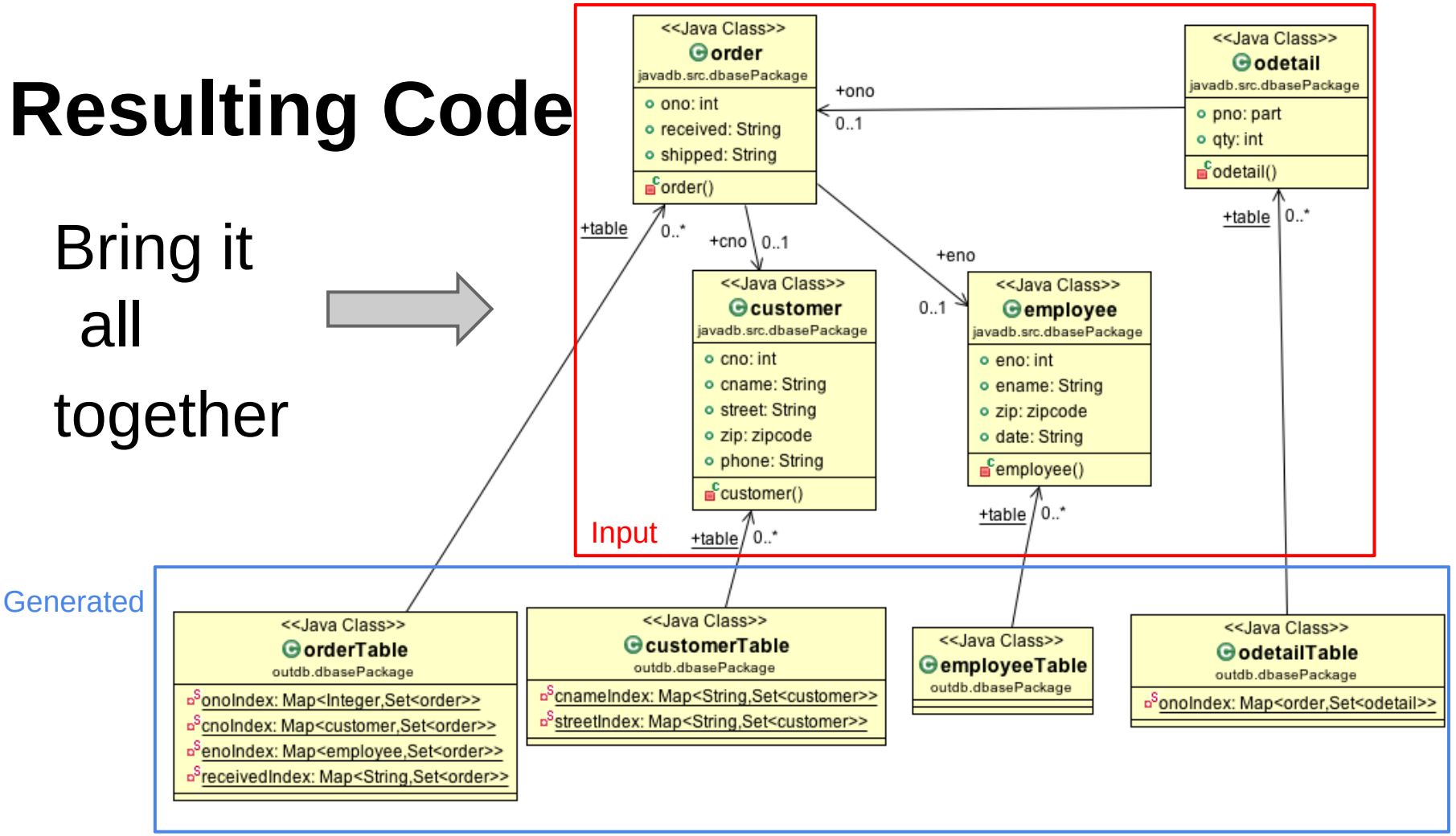
- 1 output table per input class



*public operations omitted for brevity

Resulting Code

Bring it all together



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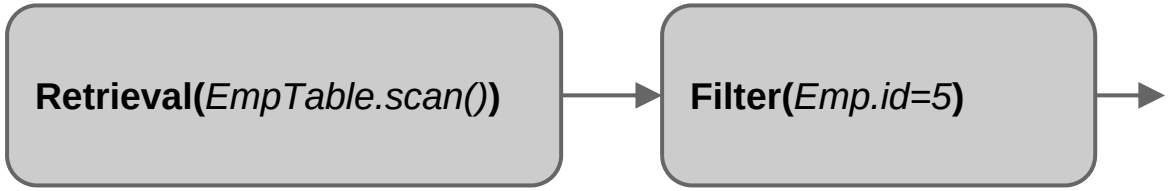
Filter Plumbing Diagram

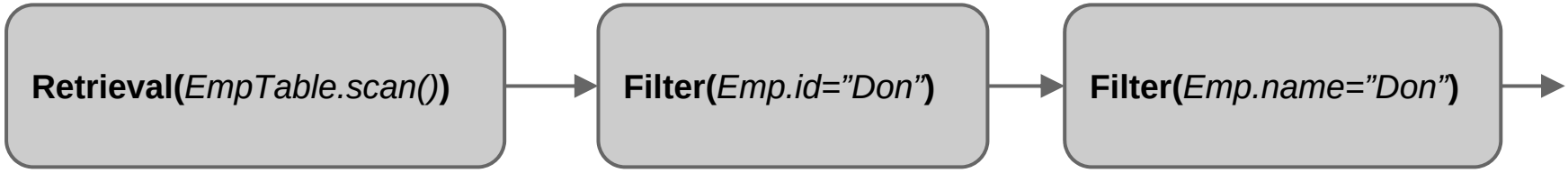
SELECT * FROM EMP WHERE ID=5




```
EmpTable.scan()
    .filter(EmpTable.fieldId(), 5)
```

Filter Plumbing Diagram

SELECT * FROM EMP WHERE ID=5 AND NAME=”Don”




```
EmpTable.scan()
    .filter(EmpTable.fieldId(), 5)
    .filter(EmpTable.fieldName(), “Don”);
```

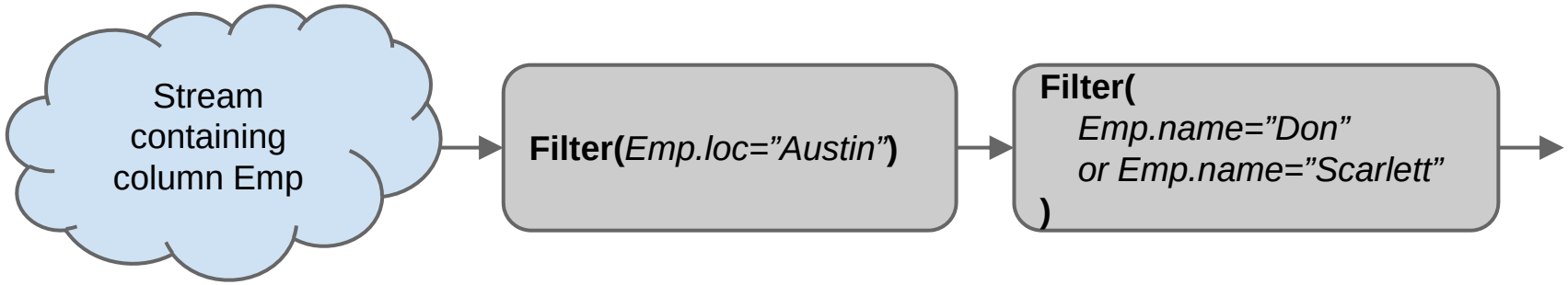
Filter - Value Unions

- Retrieve objects where a field could be a set of values
- filter(FieldExtractable fe, Object… values)
  - accepts any number of values, validates with .equals()

```
select * from emp
where id=5 and (name="Don" or name="Scarlett");
->
EmpTable.scan()
    .filter(Emp.fieldId(), 5)
    .filter(Emp.fieldName(),"Don","Scarlett");
```

Filter - General Plumbing Diagram

```
select * from emp,
where  and loc="Austin" and
   (name="Don" or name="Scarlett");
```



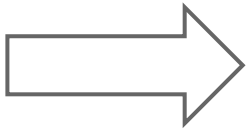

```
Emp.
    .filter(Emp.fieldLoc(),"Austin")
    .filter(Emp.fieldName(),"Don","Scarlett");
```

Indexes

- Must use @Index attribute for fields you want indexed in the db

Input Class to javadb.Create

```
Class Emp {
   @Index
   public int id;
   public String name;
   …
}
```



Output Table

```
Class EmpTable {
   //standard table
   static Set<Emp> table

   //generated index, values are also in table
   static Map<Integer, Emp> idIndex = ...
   …
}
```

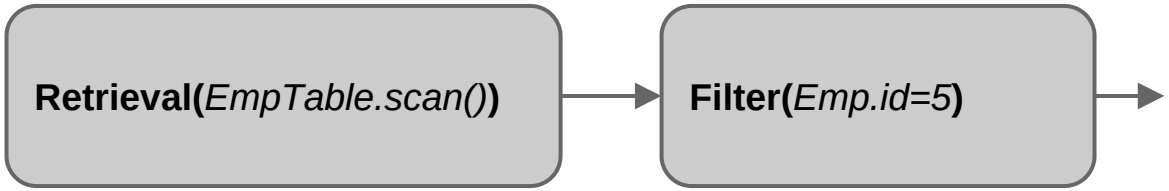
- Utilized in queries and joins

Query Plumbing Diagram

SELECT * FROM EMP WHERE ID=5

```
before: -> EmpTable.scan().filter(EmpTable.fieldId(), 5)
   now: -> EmpTable.queryId(EmpTable.fieldId(), 5)
```

No Index

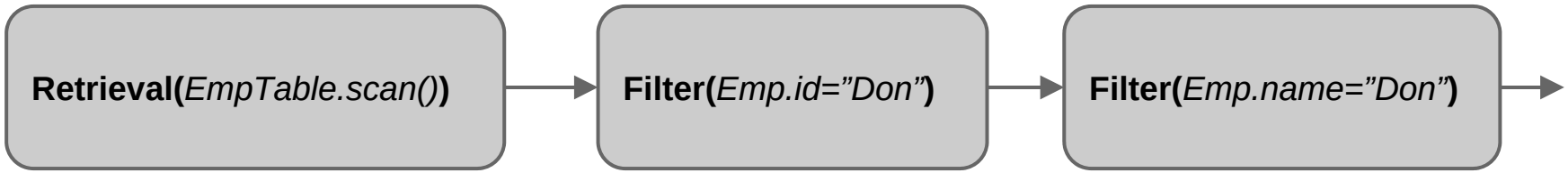


With Index on Emp.id

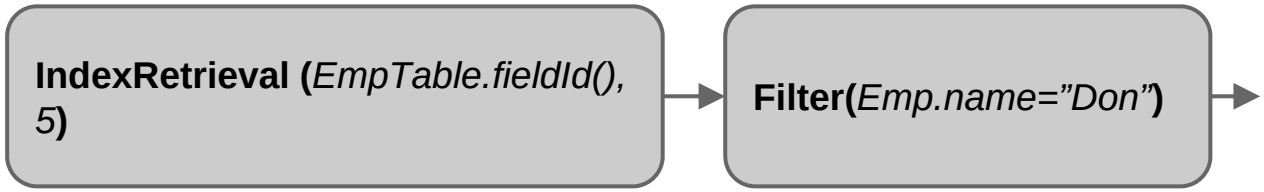
Query Plumbing Diagram

```
SELECT * FROM EMP WHERE ID=5 AND NAME=”Don”
-> EmpTable.queryIdName(5, “Don”)
```

No Index



With Index on Emp.id



Query Methods

- Queries can query one or more fields in a Class

```
Class EmpTable {          // Has fields Emp.Id and Emp.name
    queryId(int id)       // All Emps where Emp.id=id
    queryName(Str name)   // All Emps where Emp.name=name
    queryIdName(int id, Str name) // All Emps where Emp.id=id
                                  // and Emp.name=name
}
```

- M = || (P([fields in Emp]) \ Ø) ||
- Aggressively uses indexes

$$M = \sum_{i=1}^{n} \binom{n}{i} = 2^n - 1$$

Query Methods

$$M = \sum_{i=1}^{n} \binom{n}{i} = 2^n - 1$$

- Reasonable for small *n*
- Consider class with 30 fields
  - M = 2^30 = 1 GB (assuming 1 byte per method - laughable)
- Are such unwieldy signatures practical?
  - No! Too complicated for users
  - Generate only “reaso lity” methods (*k* fields)
- Let *k* be configurable $M = \sum_{i=1}^{k} \binom{n}{i}$
  - By default *k*=4

Query Methods

- Consider n=30 and k=4

$$M = \sum_{i=1}^{k} \binom{n}{i} = \sum_{i=1}^{4} \binom{30}{i} = 31930$$

- Still huge, but given enough memory might at least be possible

Query Methods

- What about all the methods not generated?
  - “I want to restrict results on more fields!”
- You still can, by chaining the queries with filters

```
queryABCD(a, b, c, d)
    .filter(onFieldE, eVal)
    .filter(onFieldF, fVal) ... ; // pseudocode
```

- The query call is optimized over those fields (using best index)
- Filters continue to filter on additional fields
  - Up to the client to know which fields are less likely candidates for optimal index retrieval

Query Methods - Future Work

- Problems with the current scheme
  - Too many methods
  - Complicated signatures
  - Limited number of fields
- Be more general
  - We want to create a single query(...) method
  - Deduce which fields from the params, like filter(...)
  - Less generated code
  - Less cognitive load for the programmer

Joins

- Filters can be applied before or after the join operation

select * from Emp, Order where Emp.id=5 and Emp.id=Order.id

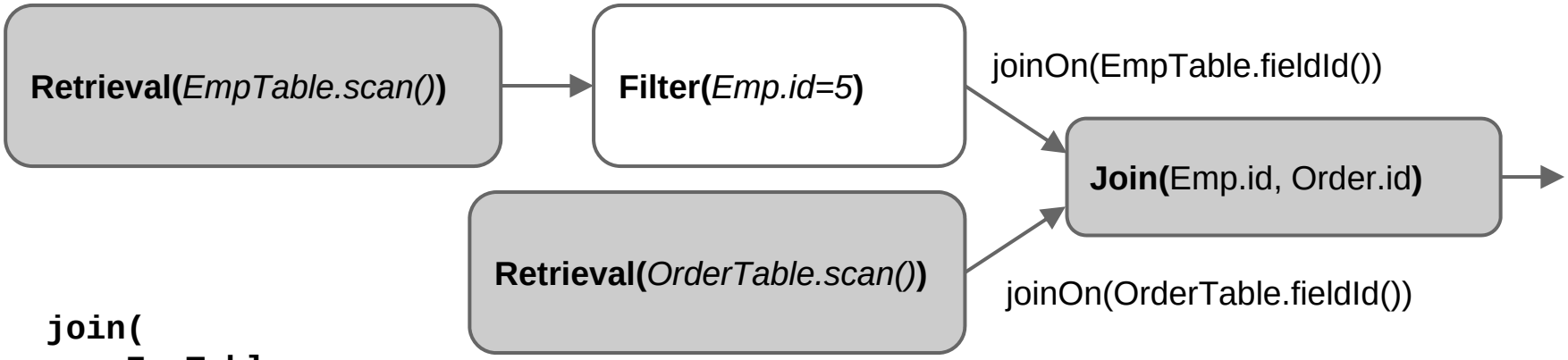
```
join(
    EmpTable
        .queryId(5)
        .joinOn(EmpTable.fieldId(),
    OrderTable.joinOnFieldEid()
)
```

```
join(
    EmpTable.joinOnFieldId()),
    OrderTable.joinOnFieldEid()
).filter(EmpTable.fieldId(), 5)
```

Produce the same result with different plumbing diagrams.

Join Plumbing Diagram

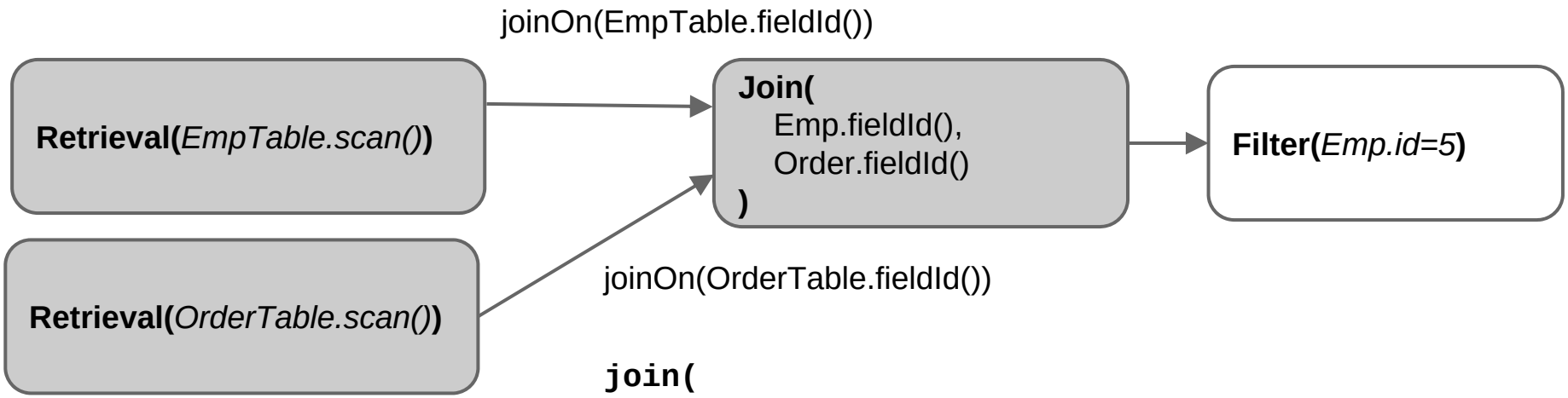
select * from Emp,Order where Emp.id=5 and Emp.id=Order.id




```
join(
    EmpTable
        .queryId(5) // id not indexed
        .joinOn(EmpTable.fieldId(),
    OrderTable.joinOnFieldEid()
)
```

Join Plumbing Diagram

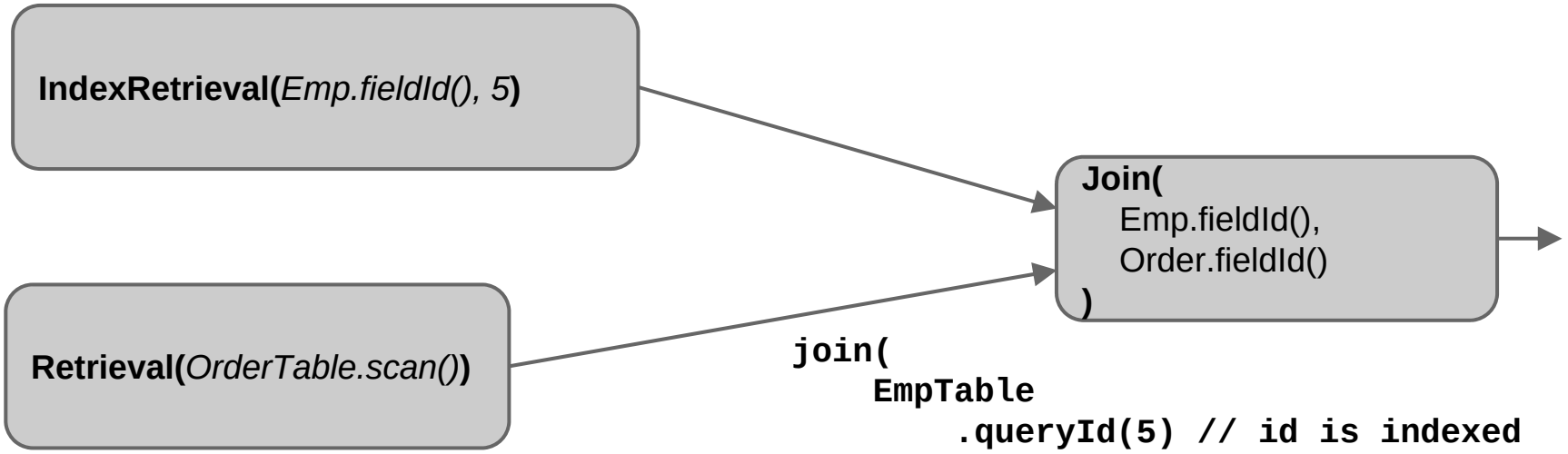
select * from Emp,Order where Emp.id=5 and Emp.id=Order.id




```
join(
    EmpTable
        .joinOn(EmpTable.fieldId(),
    OrderTable.joinOnFieldEid()
).filter(EmpTable.fieldId(), 5)
```

Join Plumbing Diagram

select * from Emp,Order where Emp.id=5 and Emp.id=Order.id




```
join(
    EmpTable
        .queryId(5) // id is indexed
        .joinOn(EmpTable.fieldId(),
    OrderTable.joinOnFieldEid()
)
```

Joins

- Can join on any field of a class instance, including the instance itself
- Join operations take one or more equality predicates
  - Each predicate holds two streams

```
select * from A, B where A.x=B.y ->
JoinDriver.join(ATable.joinOnFieldX(),BTable.joinOnFieldY())
```

- Only equality join relations are currently supported
- Could also use output of a filter or retrieval as input
  - everything is a stream!

Join Results

- Streams typically return table elements
  - Stream<A>, Stream<B>, etc.
- Still a stream, but a stream of what?
  - **JoinRecord**
- A **JoinRecord** is essentially an alias for Map<Class<?>, Object>
  - Values are always instances of the type defined in the key
- Provides an easy mechanism for retrieving elements from a tuple

```
for (JoinResult jr : JoinDriver.join(
    ATable.joinOnFieldX(),
    BTable.joinOnFieldY()).elements()) {
        A a = (A)jr.get(A.class);
        B b = (B)jr.get(B.class);
}
```

Joins (Use Case)

*select * from Order, Odetail*
where Order.ono=Odetail.ono;

```
JoinDriver.join(
    OrderTable.joinOn(OrderTable.fieldOno()),
    OdetailTable.joinOn(OdetailTable.fieldOno());
```

*select * from Order, Odetail*
where Order.ono=Odetail.ono and Order.ono=5

```
JoinDriver.join(
    OrderTable.queryOno(5)
        .joinOn(OrderTable.fieldOno()),
    OdetailTable.joinOn(OdetailTable.fieldOno());
```

```
public class Order {
    @Index
    public int ono;
    public Customer cno;
    ...
}
```

```
public class Odetail {
    @Index
    public int ono;
    public int qty;
    ...
}
```

Joins (Use Case)

*select * from Order, Odetail*
where Order=Odetail.ono;

```
JoinDriver.join(
    OrderTable.joinOn(OrderTable.itself()),
    OdetailTable.joinOn(OdetailTable.fieldOno());
```

*select * from Order, Odetail*
where Order=Odetail.ono and Order.ono=5

```
JoinDriver.join(
    OrderTable.queryOno(5)
        .joinOn(OrderTable.itself()),
    OdetailTable.joinOn(OdetailTable.fieldOno());
```

```
public class Order {
    @Index
    public int ono;
    public Customer cno;

}
```

```
public class Odetail {
    @Index
    public Order ono;      -- more likely
    public int qty;

}
```

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Query Optimizations

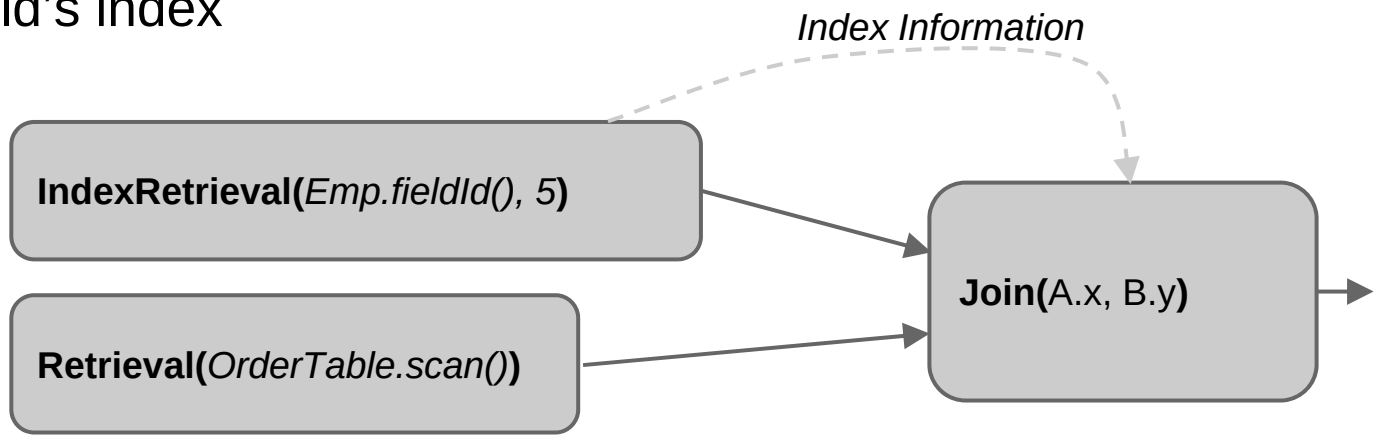
- Determine the best code to execute depending on indexes etc.
  - No fields have an index?
    - Apply a filter
  - Does only one of the fields have an index?
    - Use the index
  - Do multiple fields have an indexes?
    - Use the one for table with smallest cardinality
- Main memory database
  - Don’t worry about disk I/O latency or locality
  - Random memory access for reading tuples means indexes should ALWAYS be used

Single Predicate Join Algorithm

- Given two streams, there are **3** primary cases
  - **Join fields of both streams are indexed**
    - Do index intersection
  - **Only one stream is indexed**
    - Scan over non-indexed stream, getting join columns using other stream's index
  - **Neither stream is indexed**
    - Use hash join
    - Hash the stream with smaller cardinality

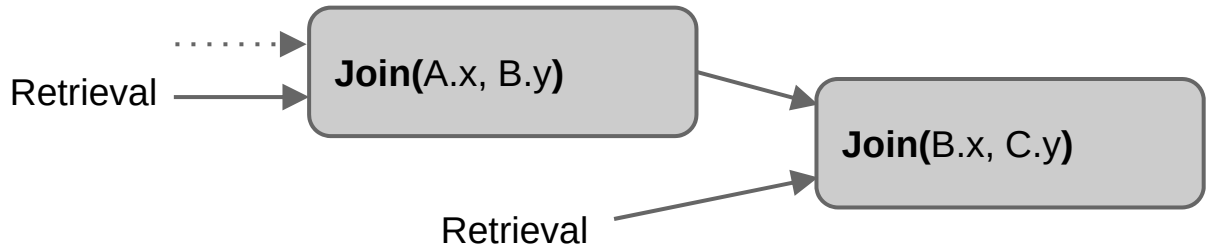
Sideways Information Passing

- Def. — sending information from one query operator to another in a fashion not specified by the query evaluation tree
- Index information is passed through to join operations
- Join algorithm makes a runtime decision on whether or not to use a field's index



Multi-Predicate Join Algorithm

- Users can also specify their own join execution plans
  - Could have bushy joins
  - Or right-deep or left-deep joins
- Everything is a stream
  - Could add support for other join strategies
- Current default join strategy follows System R strategy



Multi-Predicate Join Optimization

```
// select * from order, odetail, emp
// where order=odetail.ono and order.eno=emp.eno;
// JoinDriver will join the predicates like System R
JoinDriver.join(
    new JoinPredicate(
        OrderTable.joinOnItself()),
        OdetailTable.joinOnFieldOno()),
    new JoinPredicate(
        OrderTable.joinOnFieldEno(),
        EmpTable.joinOnItself())));
```

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Constraints on Source Package

- Only public fields are included in database
  - Could use reflection to retrieve private fields, but this is slow and cumbersome
- To index a field, must use @Index annotation
- Must not use class names that conflict with those created by the database creator
- Must maintain consistency in the database by using update calls defined by the tables
  - Bytecode modification makes this simple!

Javassist Bytecode Generation

- Javassist is a class library for modifying bytecodes in Java
- Allows us to insert hooks in the client code that update the db
  - o injects table insert operation at the end of each constructor
    - ex. EmpTable.insert(this) in class Emp
  - o injects a table update method at the end of every setter method **for fields that are indexed**

```
Class Emp {
    @Index
    int id;
    String name;

public void setId(int id) {
    this.id=id; }}
```

```
Class Emp {
    @Index
    int id;
    String name;
//Note: type sig could be anything
public void setId(int id) {
    this.id=id; EmpTable.setId(this, id);}}
```

Table Field Declarations

- Every generated table class has a set whose elements are weakly referenced to store all instances of its mapped class
  - public static Set<WeakReference<Foo>> table;
- Since only id and name are indexed, two maps are generated
  - private static Map<Integer, Set<WeakReference<Foo>> idIndex;
  - private static Map<String, Set<WeakReference<Foo>>> nameIndex;

Database Consistency

- How are objects added to the database?
  - via bytecode modification
- How are indices kept consistent?
  - must use setters in database
- What happens when instances in the table go out of scope?
  - Garbage Collected (deleted)
  - Tables hold WeakReferences
  - Garbage Collector ignores the references in tables

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Mercury Retrograde

Single-Schema Database
Target Module Generator
(for MercuryDB)

JavaDatabase implements **IDatabase**

- Converts MDB SQL scripts to Java classes
- Modified MDB Project
- Same Parser
- New IDatabase implementation for JavaDB
- Mustache to format output

JavaDatabase implements **IDatabase**

```
public interface IDatabase {

  // target module class defs
  public void create(...);
  public void index(...);

  // client module actions
  public void insert(...);
  public void update(...);
  public void delete(...);
  public void selectAll(...);
  public void select(...);

  // format templates
  public void commit();

  // reset data
  public void abort();

  // do nothing
  public void close();

}
```

JavaDatabase - Target Module

- **create …;**
  - 1-to-1 target package class definition
- **index …;**
  - add @Index annotations to above class definitions

JavaDatabase - Target Mustache

```
public class {{tableName}} {
  {{#fields}}
  {{#isIndexed}}
  @Index
  {{/isIndexed}}
  {{#isInteger}}
  public int {{name}};
  {{/isInteger}}
  {{#isString}}
  public String {{name}};
  {{/isString}}
  {{/fields}}
```

```
  public {{tableName}}(
   {{#fields}}
   {{#isInteger}}
   int {{name}},
   {{/isInteger}}
   {{#isString}}
   String {{name}},
   {{/isString}}
   {{/fields}}
   )
  {
   {{#fields}}
   this.{{name}} = {{name}};
   {{/fields}}
  }
}
```

JavaDatabase - Target Code

```
create table emp (
             empno int,
             age   int
          );
.
index emp.age;
.
commit;
.
```

```
public class EmpTable {
  public int empno;
  @Index
  public int age;

  public EmpTable(
    int empno,
    int age
  )
  {
    this.empno = empno;
    this.age = age;
  }
}
```

JavaDatabase - Client Module

- **insert …;**
  - insert a record into the table (e.g. ATable)
  - create new instance of class (of e.g. ATable) corresponding to table
  - insert into an ArrayList to keep reference live
- **update …;**
  - use setters to update objects
- **delete …;**
  - delete matching objects from ArrayList

JavaDatabase - Client Module

- **select …;**
  - Return references to entire tuples
    - select [fields] = select *
    - simplifies code generation somewhat
  - Uses API generated by JavaDB

JavaDatabase - Target Code

```
insert into emp values (1, 25);
insert into emp values (2, 47);
.

update emp set age=26 where
empno=1;
.

select emp where empno=1;
.

delete emp where empno=2;
.
```

```
ArrayList<Emp> emps = new ...;

emps.insert(new Emp(1, 25));
emps.insert(new Emp(2, 47));

... i = EmpTable.queryEmpno(1);
for (Emp e : i.elements())  // update
        e.setAge(26);

i = EmpTable.queryEmpno(1);
for (Emp e : i.elements())  // select
        ...  // do something

i = EmpTable.queryEmpno(2);
for (Emp e : i.elements())  // delete
        emps.remove(e);
```

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References

[1] Zachary G. Ives and Nicholas E. Taylor,
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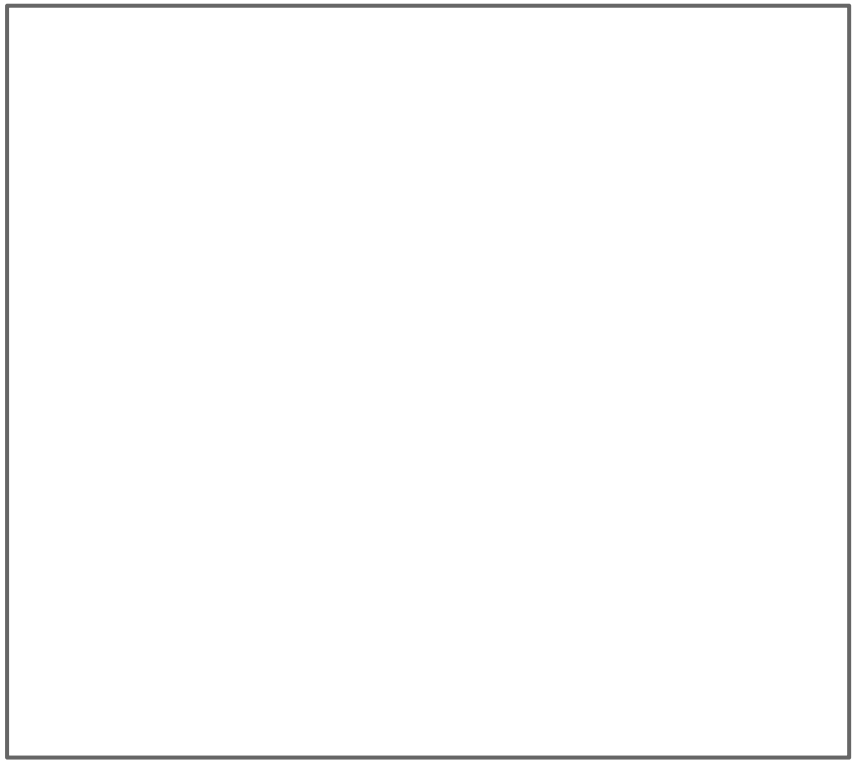
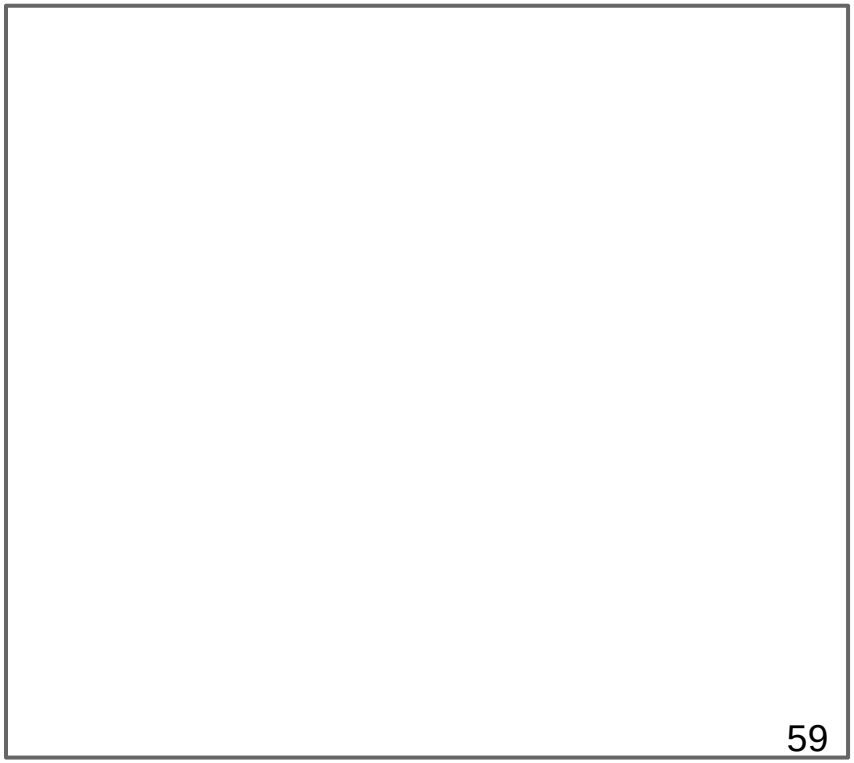
Questions?

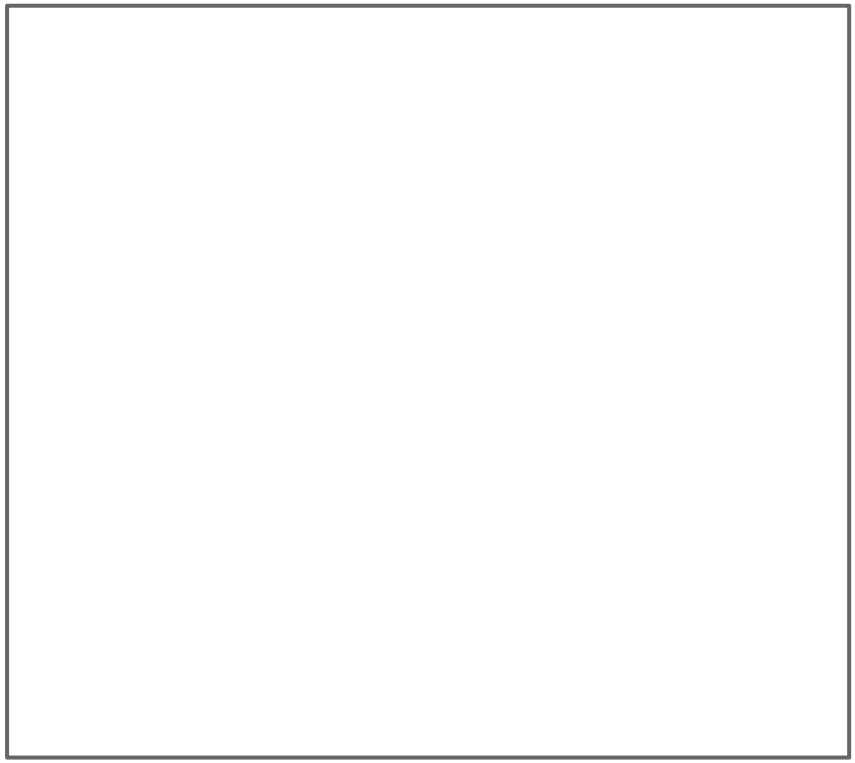
[Backup Slides]

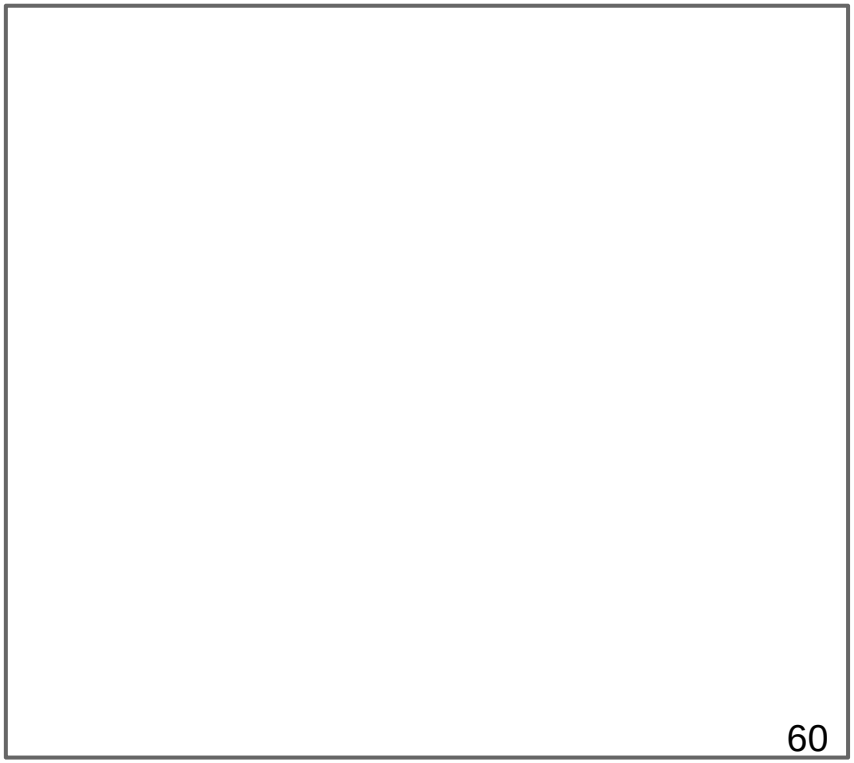
JavaDatabase - Client Mustache





JavaDatabase - Client Module





What the Target Doesn’t Know

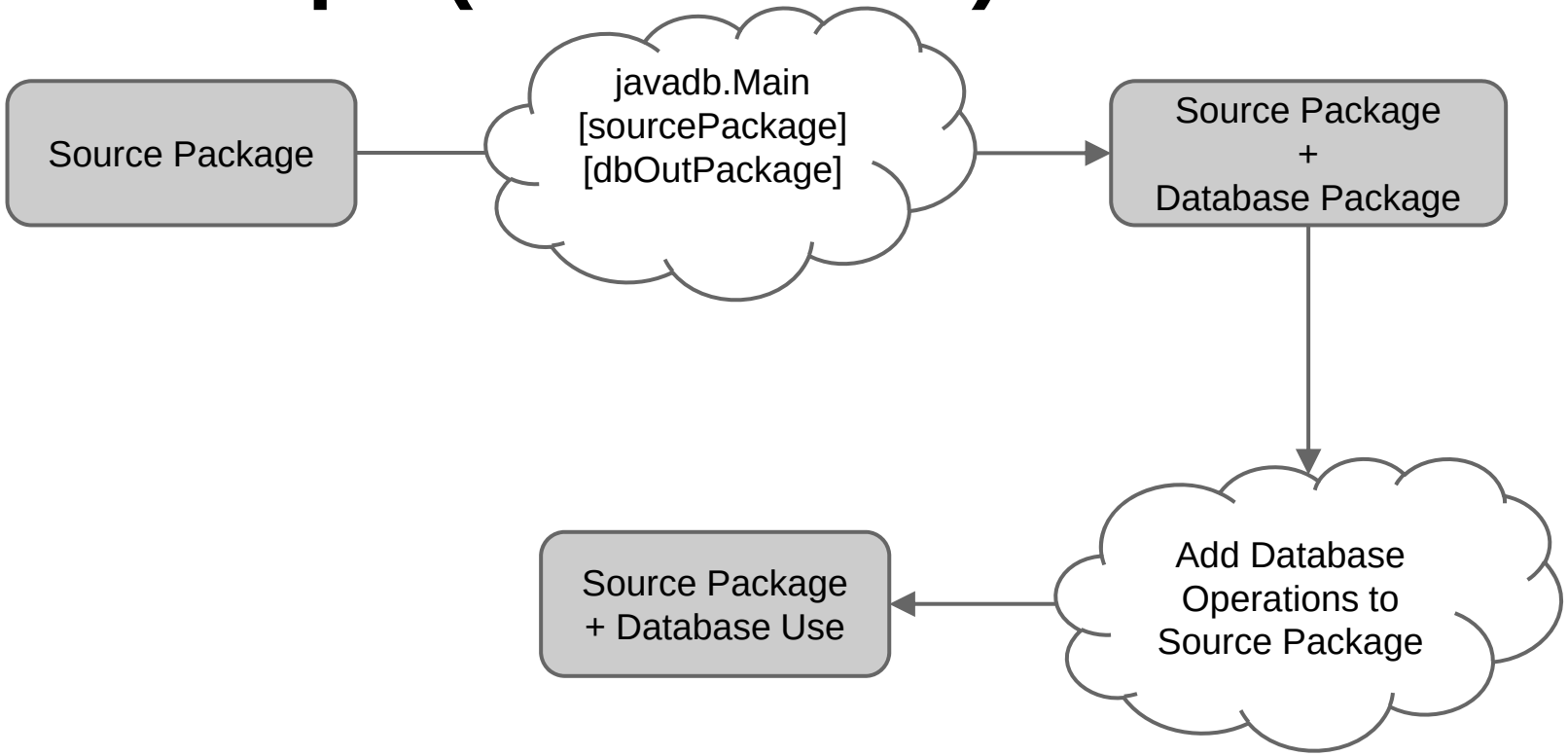
- Q: If the authors of the target module don’t know about JavaDB, how do @Index annotations get added?
- A: We can allow the author of the client to specify which fields to add Indexes to, and use reflection to add that information to the generated API.

[Removed Slides]

Client API Introduction

- Every public field has a corresponding query method in the table
- Every query method returns an instance of the type its table contains
- Some fields can be indexed
  - generated query methods will utilize these where possible
  - index is essentially a Map<[FieldVarType],[ClassVarType]>
- Queries can be chained and filtered together

The Steps (old version)

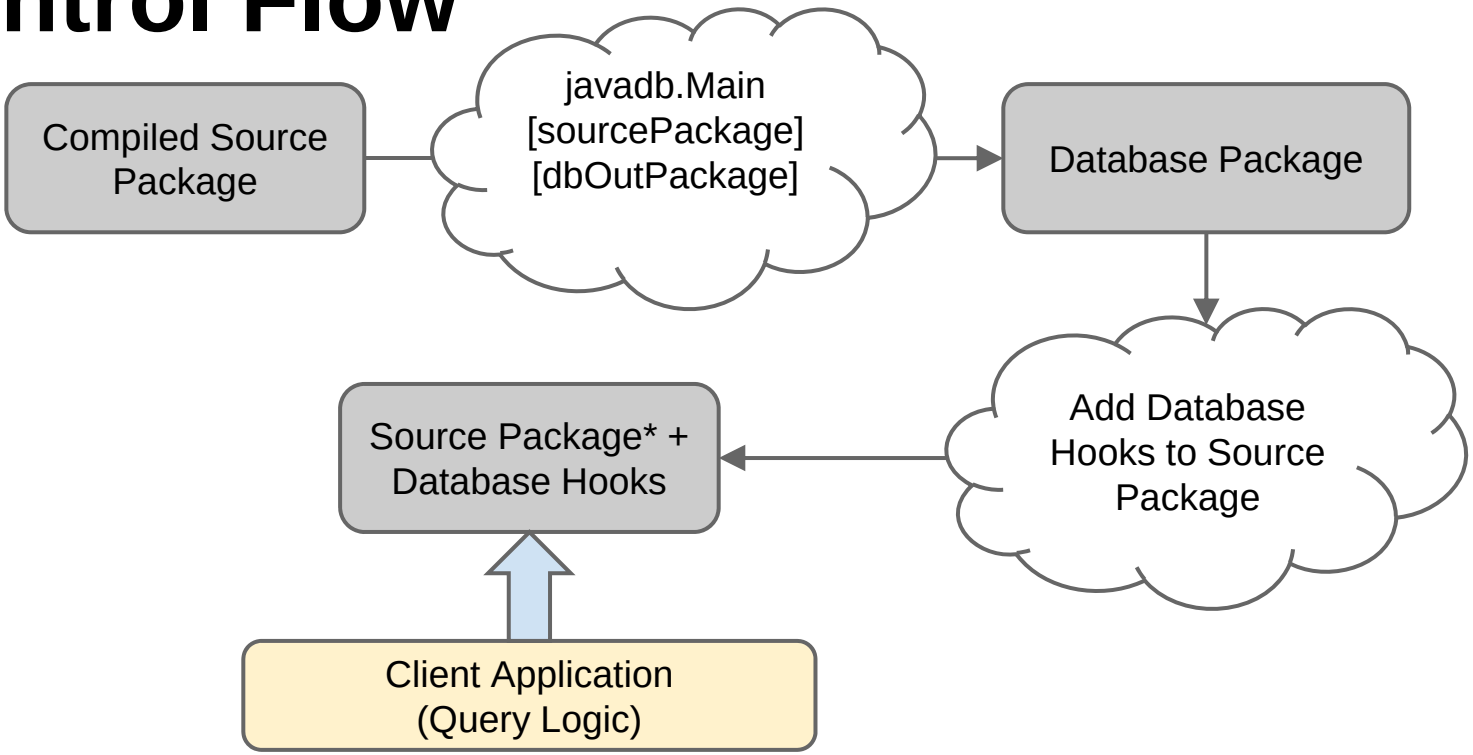


Multi-Predicate Join Optimization

- Given a join operation with multiple predicates, in what order are they processed?
  - Look at System R
- Look at JoinPredicate's compareTo method to see the order in which joins are processed

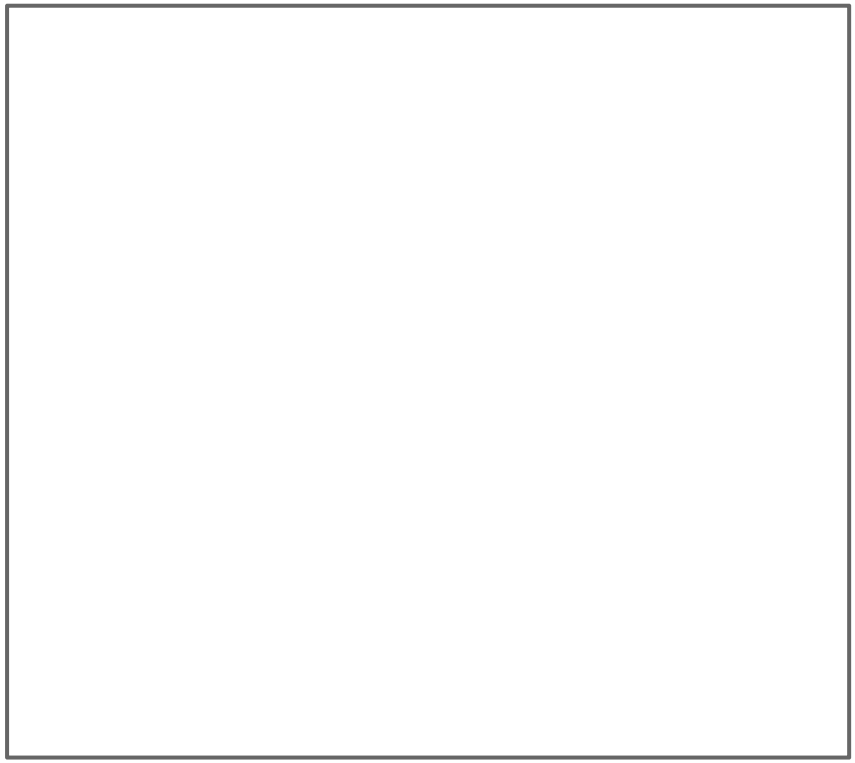
```
/**
 * 1. Number of indices (greater first, i.e. descending)
 * 2. Cardinality of its streams (smaller first, i.e. ascending [natural])
 */
@Override
public int compareTo(JoinPredicate o) { … }
```

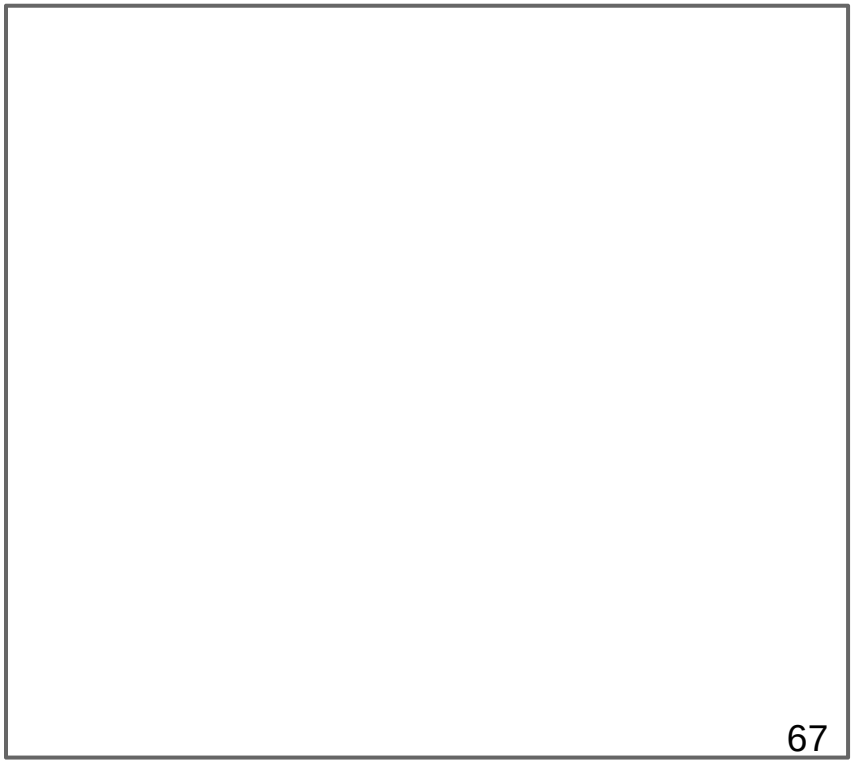
Control Flow



* may or may not be modified from the original source package depending on implementation

Code Template





Self Joins

- select * from A as A1, A as A2 where A1.x=A2.y
- Not currently possible in JavaDB
  - Aliases are not possible
- A solution would be interesting...