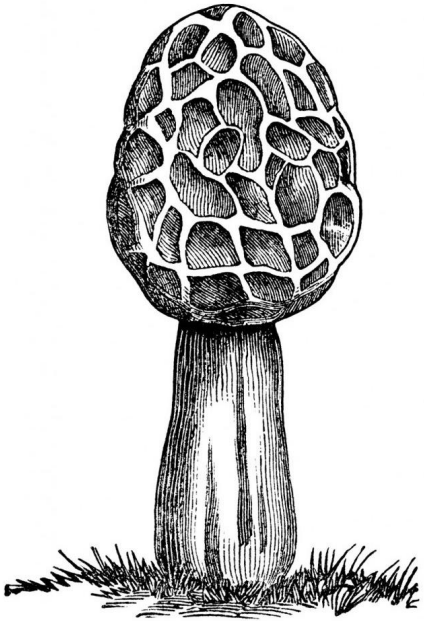

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Morel, a data-parallel programming language

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Title

Morel, a data-parallel programming language

Abstract

What would the perfect data-parallel programming language look like? It would be as expressive as a general-purpose functional programming language, as powerful and concise as SQL, and run programs just as efficiently on a laptop or a thousand-node cluster.

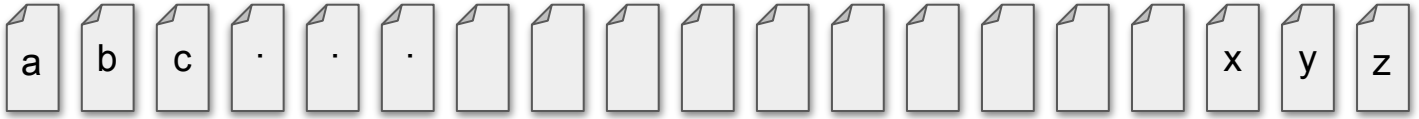
We present Morel, a functional programming language with relational extensions, working towards that goal. Morel is implemented in the Apache Calcite community on top of Calcite's relational algebra framework. In this talk, we describe Morel's evolution, including how we are pushing Calcite's capabilities with graph and recursive queries.

What is the difference between a query and a program?

Text files
(input)

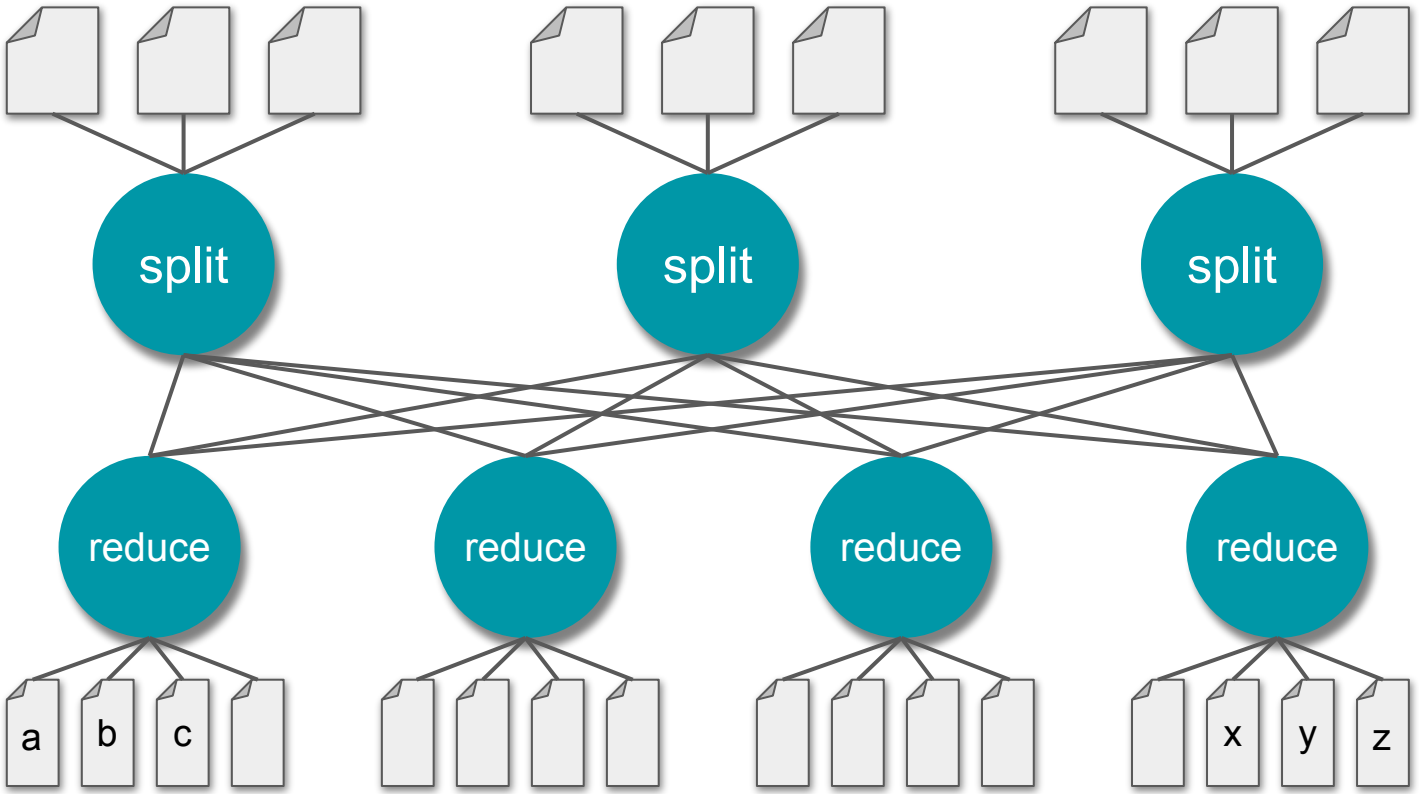
Building a document index

Text files
(input)



Index files
(output)

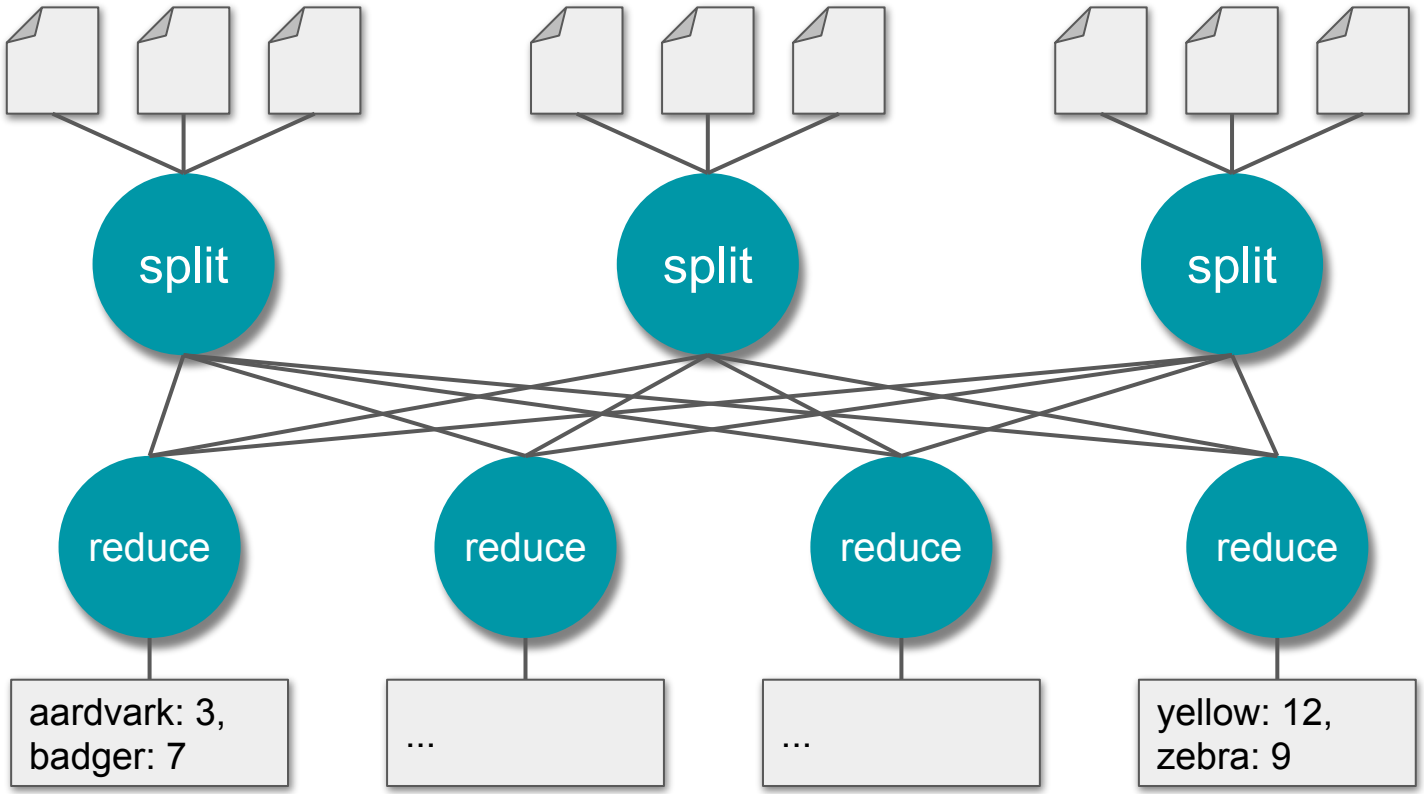
Building a document index



Text files
(input)

Index files
(output)

WordCount



Text files
(input)

Word counts
(output)

Data-parallel programming

Batch processing

Input is a large, immutable data sets

Processing can be processed in parallel pipelines

Significant chance of hardware failure during execution

Related programming models:

- Stream and incremental processing
- Deductive and graph programming

Data-parallel programming

Data-parallel framework (e.g. MapReduce, FlumeJava, Apache Spark)

```
(*) You write two small functions
fun wc_mapper line =
  List.map (fn w => (w, 1)) (split line);

fun wc_reducer (key, values) =
  List.foldl (fn (x, y) => x + y) 0 values;

(*) The framework provides mapReduce
fun mapReduce mapper reducer list = ...;

(*) Combine them to build your program
fun wordCount list = mapReduce wc_mapper wc_reducer list;
```

Data-parallel programming

Data-parallel framework (e.g. MapReduce, FlumeJava, Apache Spark)

```
(*) You write two small functions
fun wc_mapper line =
  List.map (fn w => (w, 1)) (split line);

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(*) The framework provides mapReduce
fun mapReduce mapper reducer list = ...;

(*) Combine them to build your program
fun wordCount list = mapReduce wc_mapper wc_reducer list;
```

SQL

```
SELECT word, COUNT(*) AS c
FROM Documents AS d,
  LATERAL TABLE (split(d.text)) AS word   // requires a 'split' UDF
GROUP BY word;
```

Data-parallel programming

Data-parallel framework (e.g. MapReduce, FlumeJava, Apache Spark)

```
(*) You write two small functions
fun wc_mapper line =
  List.map (fn w => (w, 1)) (split line);

fun wc_reducer (key, values) =
  List.foldl (fn (x, y) => x + y) 0 values;

(*) The framework provides mapReduce
fun mapReduce mapper reducer list = ...;

(*) Combine them to build your program
fun wordCount list = mapReduce wc_mapper wc_reducer list;
```

SQL

```
SELECT word, COUNT(*) AS c
FROM Documents AS d,
  LATERAL TABLE (split(d.text)) AS word   // requires a 'split' UDF
GROUP BY word;
```

Morel

```
from line in lines,
    word in split line   (*) requires 'split' function - see later...
group word compute c = count
```

What are our options?

Extend SQL

We'll need to:

- Allow functions defined in queries
- Add relations-as-values
- Add functions-as-values
- Modernize the type system (adding type variables, function types, algebraic types)
- Write an optimizing compiler

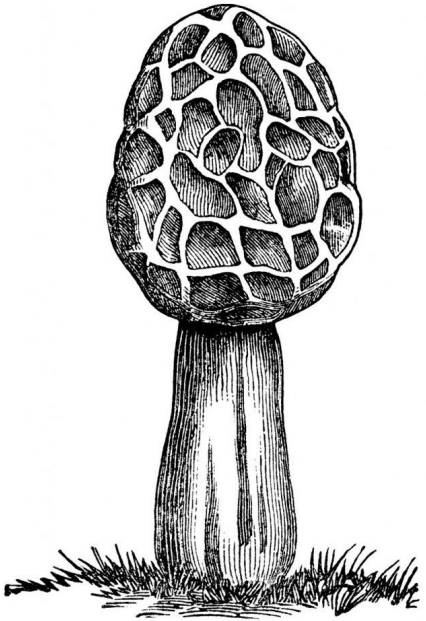
Extend a functional programming language

We'll need to:

- Add syntax for relational operations
- Map onto external data
- Write a query optimizer

Nice stuff we get for free:

- Algebraic types
- Pattern matching
- Inline function and value declarations



Morel is a functional programming language. It is derived from Standard ML, and is extended with list comprehensions and other relational operators. Like Standard ML, Morel has parametric and algebraic data types with Hindley-Milner type inference. Morel is implemented in Java, and is optimized and executed using a combination of techniques from functional programming language compilers and database query optimizers.

Themes

Early stage language

The target audience is SQL users

Less emphasis on abstract algebra

Program compilation + query optimization

Functional programming in-the-small + in-the-large

Quick intro to Standard ML

(All of the following examples work in both Standard ML and Morel.)

Standard ML: values and types

```
- "Hello, world!";
val it = "Hello, world!" : string

- 1 + 2;
val it = 3 : int

- ~1.5;
val it = ~1.5 : real

- [1, 1, 2, 3, 5];
val it = [1,1,2,3,5] : int list

- fn i => i mod 2 = 1;
val it = fn : int -> bool

- (1, "a");
val it = (1,"a") : int * string

- {name = "Fred", empno = 100};
val it = {empno=100,name="Fred"} : {empno:int, name:string}
```

Standard ML: variables and functions

```
- val x = 1;
val x = 1 : int

- val isOdd = fn i => i mod 2 = 1;
val isOdd = fn : int -> bool

- fun isOdd i = i mod 2 = 0;
val isOdd = fn : int -> bool

- isOdd x;
val it = true : bool

- let
=   val x = 6
=   fun isOdd i = i mod 2 = 1
= in
=   isOdd x
= end;
val it = false : bool
```

`val` assigns a value to a variable.

`fun` declares a function.

- `fun` is syntactic sugar for
  `val ... = fn ... => ...`

`let` allows you to make several declarations before evaluating an expression.

Standard ML: recursive functions

```
- fun factorial 0 = 1
=   | factorial n = n * (factorial (n - 1));
val factorial = fn : int -> int

- factorial 5;
val it = 120 : int
```

A `fun` declaration can refer to itself.

Recursive functions are Standard ML's main way of looping.

Standard ML: higher-order functions

```
- val integers = [0, 1, 2, 3, 4, 5, 6, 7, 8, 9];
val it = [0,1,2,3,4,5,6,7,8,9] : int list

- List.filter (fn i => i mod 2 = 0) integers;
val it = [0,2,4,6,8] : int list

- List.filter isOdd integers;
val it = [0,2,4,6,8] : int list

- List.map (fn i => i * 3) integers;
val it = [0,3,6,9,12,15,18,21,24,27] : int list
```

A *higher-order function* is a function whose arguments or result are functions.

`List.map` and **`List.filter`** are standard library functions.

Relational expressions

```
- val emps = [
=   {id = 100, name = "Fred", deptno = 10},
=   {id = 101, name = "Velma", deptno = 20},
=   {id = 102, name = "Shaggy", deptno = 30},
=   {id = 103, name = "Scooby", deptno = 30}];

- List.filter (fn e => #deptno e = 30) emps;
val it = [{deptno=30,id=102,name="Shaggy"},
  {deptno=30,id=103,name="Scooby"}]
  : {deptno:int, id:int, name:string} list
```

Equivalent SQL

```
SELECT *
FROM emps AS e
WHERE e.deptno = 30
```

Relational expressions #2

```
- List.map (fn e => {name = #name e, x = #id e - 100})
    (List.filter (fn e => #deptno e = 30) emps);
val it = [{name="Shaggy",x=2},{name="Scooby",x=3}]
  : {name:string, x:int} list
```

Standard ML (and Morel)

Relational expressions #2

```
- List.map (fn e => {name = #name e, x = #id e - 100})
    (List.filter (fn e => #deptno e = 30) emps);
val it = [{name="Shaggy",x=2},{name="Scooby",x=3}]
  : {name:string, x:int} list
```

Standard ML (and Morel)

```
SELECT e.name, e.id - 100 AS x
FROM emps AS e
WHERE e.deptno = 30
```

SQL

Relational expressions #2

```
- List.map (fn e => {name = #name e, x = #id e - 100})
  (List.filter (fn e => #deptno e = 30) emps);
val it = [{name="Shaggy",x=2},{name="Scooby",x=3}]
  : {name:string, x:int} list
```

Standard ML (and Morel)

```
SELECT e.name, e.id - 100 AS x
FROM emps AS e
WHERE e.deptno = 30
```

SQL

```
emps.filter(_.deptno = 30)
  .select(e => Row(e.name, e.id - 100))
```

Apache Spark / Scala

Relational expressions #2

```
- List.map (fn e => {name = #name e, x = #id e - 100})
  (List.filter (fn e => #deptno e = 30) emps);
val it = [{name="Shaggy",x=2},{name="Scooby",x=3}]
  : {name:string, x:int} list
```

Standard ML (and Morel)

```
SELECT e.name, e.id - 100 AS x
FROM emps AS e
WHERE e.deptno = 30
```

SQL

```
emps.filter(_.deptno = 30)
  .select(e => Row(e.name, e.id - 100))
```

Apache Spark / Scala

Relational algebra

Relational expressions #2

```
- List.map (fn e => {name = #name e, x = #id e - 100})
  (List.filter (fn e => #deptno e = 30) emps);
val it = [{name="Shaggy",x=2},{name="Scooby",x=3}]
  : {name:string, x:int} list
```

Standard ML (and Morel)

```
SELECT e.name, e.id - 100 AS x
FROM emps AS e
WHERE e.deptno = 30
```

SQL

```
emps.filter(_.deptno = 30)
  .select(e => Row(e.name, e.id - 100))
```

Apache Spark / Scala

Relational algebra

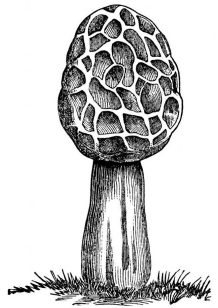
```
from e in emps
  where e.deptno = 30
  yield {e.name, x = e.id - 100};
```

Morel

Morel

Morel extensions to Standard ML:

- `from` operator creates a list comprehension
- `x.field` is shorthand for `#field x`
- `{#field}` is shorthand for `{field = #field x}`



Implementing Join in Morel using `from`

Morel extensions to Standard ML:

- **`from`** operator creates a list comprehension
- **`x.field`** is shorthand for `#field x`
- **`{#field}`** is shorthand for **`{field = #field x}`**

```
List.map
  (fn (d, e) => {deptno = #deptno d, name = #name e})
  (List.filter
    (fn (d, e) => #deptno d = #deptno e)
    (flatMap
      (fn e => (List.map (fn d => (d, e)) depts))
      emps));
```

Equivalent SQL

```
SELECT d.deptno, e.name
FROM emps AS e,
  depts AS d
WHERE d.deptno = e.deptno
```

Implementing Join in Morel using `from`

Morel extensions to Standard ML:

- **`from`** operator creates a list comprehension
- **`x.field`** is shorthand for `#field x`
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```
List.map
  (fn (d, e) => {deptno = #deptno d, name = #name e})
  (List.filter
    (fn (d, e) => #deptno d = #deptno e)
    (flatMap
      (fn e => (List.map (fn d => (d, e)) depts))
      emps));
```

```
from e in emps,
    d in depts
  where #deptno e = #deptno d
  yield {deptno = #deptno d, name = #name e};
```

Equivalent SQL

```
SELECT d.deptno, e.name
FROM emps AS e,
  depts AS d
WHERE d.deptno = e.deptno
```

Implementing Join in Morel using `from`

Morel extensions to Standard ML:

- **`from`** operator creates a list comprehension
- **`x.field`** is shorthand for `#field x`
- **`{#field}`** is shorthand for **`{field = #field x}`**

Equivalent SQL

```
SELECT d.deptno, e.name
FROM emps AS e,
  depts AS d
WHERE d.deptno = e.deptno
```

```
List.map
  (fn (d, e) => {deptno = #deptno d, name = #name e})
  (List.filter
    (fn (d, e) => #deptno d = #deptno e)
    (flatMap
      (fn e => (List.map (fn d => (d, e)) depts))
      emps));
```

```
from e in emps,
    d in depts
  where #deptno e = #deptno d
  yield {deptno = #deptno d, name = #name e};
```

```
from e in emps,
    d in depts
  where e.deptno = d.deptno
  yield {d.deptno, e.name};
```

WordCount

```
let
  fun split0 [] word words = word :: words
    | split0 (#" " :: s) word words = split0 s "" (word :: words)
    | split0 (c :: s) word words = split0 s (word ^ (String.str c)) words
  fun split = List.rev (split0 (String.explode s) "" [])
in
  from line in lines,
    word in split line
  group word compute c = count
end;
```

WordCount

```
- let
=   fun split0 [] word words = word :: words
=     | split0 (#" " :: s) word words = split0 s "" (word :: words)
=     | split0 (c :: s) word words = split0 s (word ^ (String.str c)) words
=   fun split = List.rev (split0 (String.explode s) "" [])
= in
=   from line in lines,
=     word in split line
=   group word compute c = count
= end;
val wordCount = fn : string list -> {c:int, word:string} list

- wordCount ["a skunk sat on a stump",
=     "and thunk the stump stunk",
=     "but the stump thunk the skunk stunk"];
val it =
  [{c=2,word="a"},{c=3,word="the"},{c=1,word="but"},
   {c=1,word="sat"},{c=1,word="and"},{c=2,word="stunk"},
   {c=3,word="stump"},{c=1,word="on"},{c=2,word="thunk"},
   {c=2,word="skunk"}] : {c:int, word:string} list
```

Functional programming “in the small”

Functional programming “in the large”

Functions as views, functions as values

```
- fun emps2 () =
=    from e in emps
=      yield {e.id,
=        e.name,
=        e.deptno,
=        comp = fn revenue => case e.deptno of
=            30 => e.id + revenue / 2
=          | _ => e.id};
val emps2 = fn : unit -> {comp:int -> int,
    deptno:int, id:int, name:string} list
```

Functions as views, functions as values

emps2 is a function that returns a collection

```
- fun emps2 () =
=    from e in emps
=      yield {e.id,
=        e.name,
=        e.deptno,
=        comp = fn revenue => case e.deptno of
=            30 => e.id + revenue / 2
=          | _ => e.id};
val emps2 = fn : unit -> {comp:int -> int,
    deptno:int, id:int, name:string} list
```

Functions as views, functions as values

`emps2` is a function that returns a collection

```
- fun emps2 () =
=     from e in emps
=       yield {e.id,
=         e.name,
=         e.deptno,
=         comp = fn revenue => case e.deptno of
=             30 => e.id + revenue / 2
=           | _ => e.id};
val emps2 = fn : unit -> {comp:int -> int,
    deptno:int, id:int, name:string} list
```

The `comp` field is a function value (in fact, it's a closure)

Functions as views, functions as values

`emps2` is a function that returns a collection

```
- fun emps2 () =
=    from e in emps
=      yield {e.id,
=        e.name,
=        e.deptno,
=        comp = fn revenue => case e.deptno of
=            30 => e.id + revenue / 2
=          | _ => e.id};
val emps2 = fn : unit -> {comp:int -> int,
    deptno:int, id:int, name:string} list

- from e in emps2 ()
=   yield {e.name, e.id, c = e.comp 1000};
```

The `comp` field is a function value (in fact, it's a closure)

Functions as views, functions as values

```
- fun emps2 () =
=    from e in emps
=      yield {e.id,
=        e.name,
=        e.deptno,
=        comp = fn revenue => case e.deptno of
=            30 => e.id + revenue / 2
=          | _ => e.id};
val emps2 = fn : unit -> {comp:int -> int,
    deptno:int, id:int, name:string} list

- from e in emps2 ()
=   yield {e.name, e.id, c = e.comp 1000};
val it =
  [{c=100,id=100,name="Fred"},
   {c=101,id=101,name="Velma"},
   {c=602,id=102,name="Shaggy"},
   {c=603,id=103,name="Scooby"}]
  : {c:int, id:int, name:string} list
```

Chaining relational operators

```
- from e in emps
=   order e.deptno, e.id desc
=   yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
=   where nameLength > 4
=   group deptno compute c = count, s = sum of nameLength
=   where s > 10
=   yield c + s;

val it = [14] : int list
```

Chaining relational operators - step 1

```
- from e in emps;




val it =
  [{deptno=10,id=100,name="Fred"},
   {deptno=20,id=101,name="Velma"},
   {deptno=30,id=102,name="Shaggy"},
   {deptno=30,id=103,name="Scooby"}]
  : {deptno:int, id:int, name:string} list
```

Chaining relational operators - step 2

```
- from e in emps
=   order e.deptno, e.id desc;



val it =
  [{deptno=10,id=100,name="Fred"},
   {deptno=20,id=101,name="Velma"},
   {deptno=30,id=103,name="Scooby"},
   {deptno=30,id=102,name="Shaggy"}]
  : {deptno:int, id:int, name:string} list
```

Chaining relational operators - step 3

```
- from e in emps
=   order e.deptno, e.id desc
=   yield {e.name, nameLength = String.size e.name, e.id, e.deptno};



val it =
  [{deptno=10,id=100,name="Fred",nameLength=4},
   {deptno=20,id=101,name="Velma",nameLength=5},
   {deptno=30,id=103,name="Scooby",nameLength=6},
   {deptno=30,id=102,name="Shaggy",nameLength=6}]
  : {deptno:int, id:int, name:string, nameLength:int} list
```

Chaining relational operators - step 4

```
- from e in emps
=   order e.deptno, e.id desc
=   yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
=   where nameLength > 4;



val it =
  [{deptno=20,id=101,name="Velma",nameLength=5},
   {deptno=30,id=103,name="Scooby",nameLength=6},
   {deptno=30,id=102,name="Shaggy",nameLength=6}]
  : {deptno:int, id:int, name:string, nameLength:int} list
```

Chaining relational operators - step 5

```
- from e in emps
=   order e.deptno, e.id desc
=   yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
=   where nameLength > 4
=   group deptno compute c = count, s = sum of nameLength;



val it =
  [{c=1,deptno=20,s=5},
   {c=2,deptno=30,s=12}]
  : {c:int, deptno:int, s:int} list
```

Chaining relational operators - step 6

```
- from e in emps
=   order e.deptno, e.id desc
=   yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
=   where nameLength > 4
=   group deptno compute c = count, s = sum of nameLength
=   where s > 10;


val it =
  [{c=2,deptno=30,s=12}]
  : {c:int, deptno:int, s:int} list
```

Chaining relational operators

```
= from e in emps
=   order e.deptno, e.id desc
=   yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
=   where nameLength > 4
=   group deptno compute c = count, s = sum of nameLength
=   where s > 10
=   yield c + s;

val it = [14] : int list
```

Chaining relational operators

Morel

```
from e in emps
  order e.deptno, e.id desc
  yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
  where nameLength > 4
  group deptno compute c = count, s = sum of nameLength
  where s > 10
  yield c + s;
```

Chaining relational operators

Morel

```
from e in emps
  order e.deptno, e.id desc
  yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
  where nameLength > 4
  group deptno compute c = count, s = sum of nameLength
  where s > 10
  yield c + s;
```

SQL (almost equivalent)

```
SELECT c + s
FROM (SELECT deptno, COUNT(*) AS c, SUM(nameLength) AS s
  FROM (SELECT e.name, CHAR_LENGTH(e.ename) AS nameLength, e.id, e.deptno
    FROM (SELECT *
      FROM emps AS e
      ORDER BY e.deptno, e.id DESC))
  WHERE nameLength > 4
  GROUP BY deptno
  HAVING s > 10)
```

Chaining relational operators

Morel

```
from e in emps
  order e.deptno, e.id desc
  yield {e.name, nameLength = String.size e.name, e.id, e.deptno}
  where nameLength > 4
  group deptno compute c = count, s = sum of nameLength
  where s > 10
  yield c + s;
```

SQL (almost equivalent)

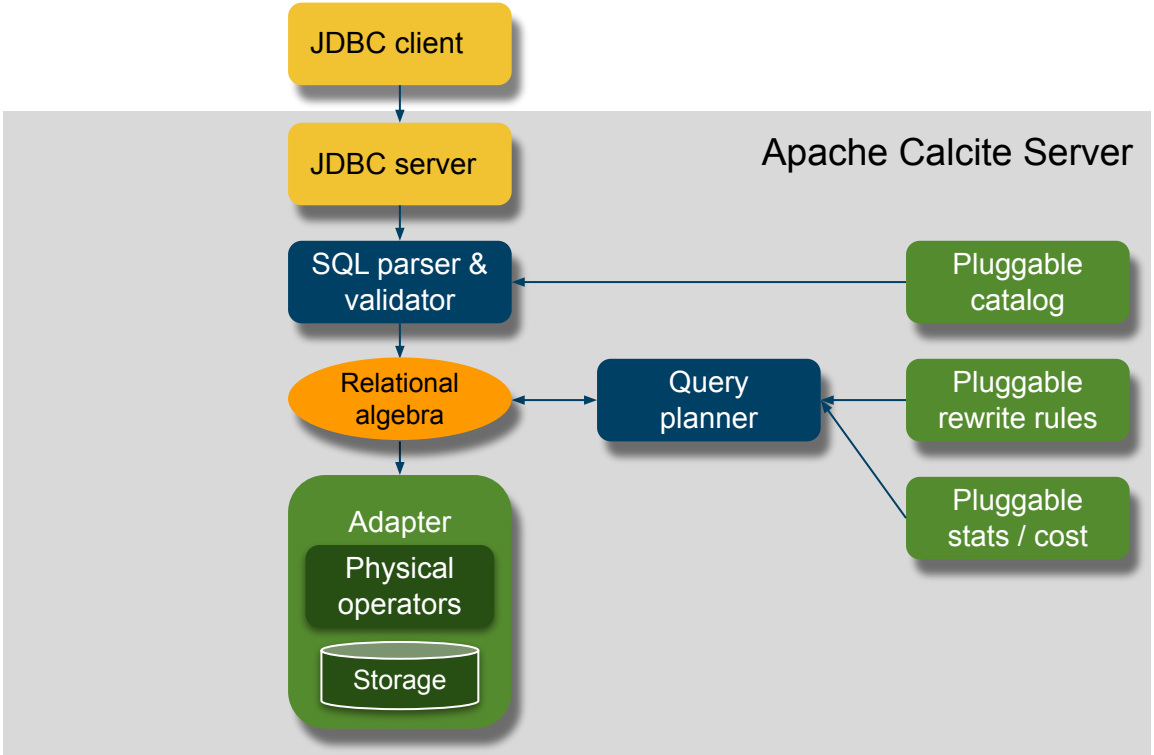
```
SELECT c + s
FROM (SELECT deptno, COUNT(*) AS c, SUM(nameLength) AS s
  FROM (SELECT e.name, CHAR_LENGTH(e.ename) AS nameLength, e.id, e.deptno
    FROM (SELECT *
      FROM emps AS e
      ORDER BY e.deptno, e.id DESC))
  WHERE nameLength > 4
  GROUP BY deptno
  HAVING s > 10)
```

Java (very approximately)

```
for (Emp e : emps) {
  String name = e.name;
  int nameLength = name.length();
  int id = e.id;
  int deptno = e.deptno;
  if (nameLength > 4) {
    ...
```

Apache Calcite

Apache Calcite



Toolkit for writing a DBMS

Many parts are optional or pluggable

Relational algebra is the core

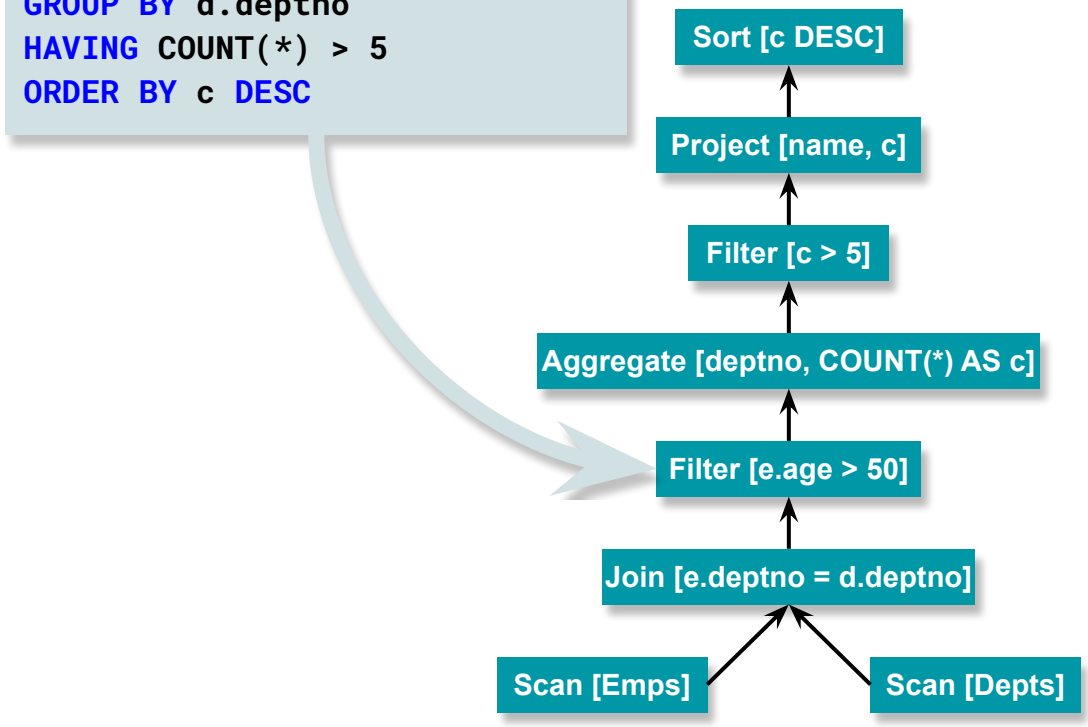
Relational algebra

Based on set theory, plus operators: Project, Filter, Aggregate, Union, Join, Sort

Calcite provides:

- SQL to relational algebra
- Query planner
- Physical operators to execute plan
- An adapter system to make external data sources look like tables

```
SELECT d.name, COUNT(*) AS c
FROM Emps AS e
JOIN Depts AS d USING (deptno)
WHERE e.age > 50
GROUP BY d.deptno
HAVING COUNT(*) > 5
ORDER BY c DESC
```

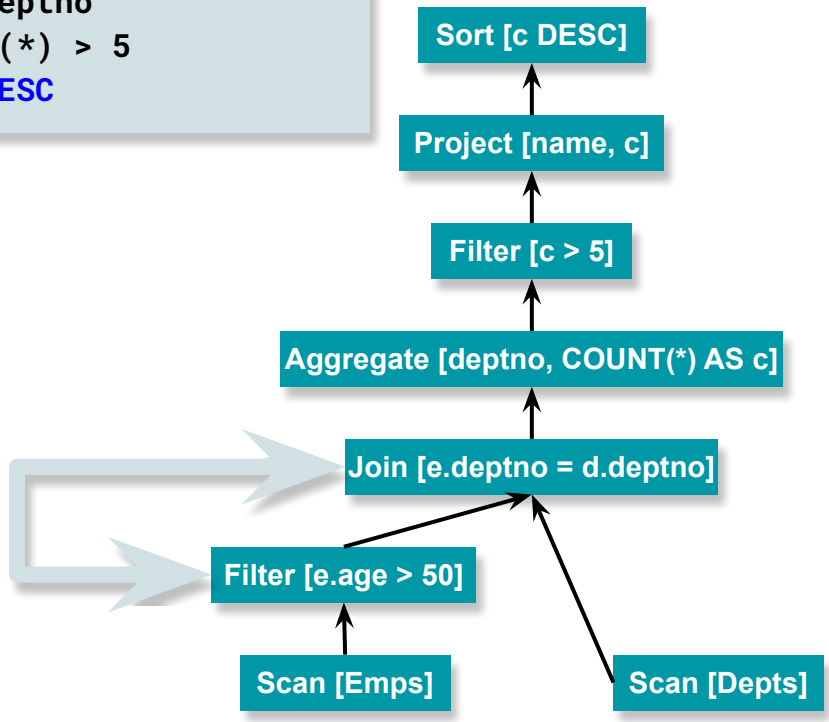


Algebraic rewrite

Calcite optimizes queries by applying rewrite rules that preserve semantics.

Planner uses dynamic programming, seeking the lowest total cost.

```
SELECT d.name, COUNT(*) AS c
FROM (SELECT * FROM Emps
      WHERE e.age > 50) AS e
JOIN Depts AS d USING (deptno)
GROUP BY d.deptno
HAVING COUNT(*) > 5
ORDER BY c DESC
```



Integration of Morel with Apache Calcite - schemas

Expose Calcite schemas as named records, each field of which is a table.

A default Morel connection has variables `foodmart` and `scott` (connections to hsqldb via Calcite's JDBC adapter).

Connections to other Calcite adapters (Apache Cassandra, Druid, Kafka, Pig, Redis) are also possible.

```
- foodmart;
val it = {account=<relation>, currency=<relation>,
  customer=<relation>, ...} : ...;

- scott;
val it = {bonus=<relation>, dept=<relation>,
  emp=<relation>, salgrade=<relation>} : ...;

- scott.dept;
val it =
  [{deptno=10,dname="ACCOUNTING",loc="NEW YORK"},
   {deptno=20,dname="RESEARCH",loc="DALLAS"},
   {deptno=30,dname="SALES",loc="CHICAGO"},
   {deptno=40,dname="OPERATIONS",loc="BOSTON"}]
  : {deptno:int, dname:string, loc:string} list

- from d in scott.dept
=   where notExists (from e in scott.emp
=     where e.deptno = d.deptno
=     andalso e.job = "CLERK");
val it =
  [{deptno=40,dname="OPERATIONS",loc="BOSTON"}]
  : {deptno:int, dname:string, loc:string} list
```

Integration of Morel with Apache Calcite - relational algebra

```
- Sys.set ("hybrid", true);
val it = () : unit

- from d in scott.dept
=   where notExists (from e in scott.emp
=     where e.deptno = d.deptno
=     andalso e.job = "CLERK");
val it = [{deptno=40,dname="OPERATIONS",loc="BOSTON"}]
  : {deptno:int, dname:string, loc:string} list
```

In “hybrid” mode, Morel’s compiler identifies sections of Morel programs that are relational operations and converts them to Calcite relational algebra.

Calcite can them optimize these and execute them on their native systems.

Integration of Morel with Apache Calcite - relational algebra

```
- Sys.set ("hybrid", true);
val it = () : unit

- from d in scott.dept
=   where notExists (from e in scott.emp
=     where e.deptno = d.deptno
=     andalso e.job = "CLERK");
val it = [{deptno=40,dname="OPERATIONS",loc="BOSTON"}]
  : {deptno:int, dname:string, loc:string} list

- Sys.plan();
val it = "calcite(plan
LogicalProject(deptno=[$0], dname=[$1], loc=[$2])
  LogicalFilter(condition=[IS NULL($4)])
    LogicalJoin(condition=[=($0, $3)], joinType=[left])
      LogicalProject(deptno=[$0], dname=[$1], loc=[$2])
        JdbcTableScan(table=[[scott, DEPT]])
      LogicalProject(deptno=[$0], $f1=[true])
        LogicalAggregate(group=[{0}])
          LogicalProject(deptno=[$1])
            LogicalFilter(condition=[AND(=($5, 'CLERK'), IS NOT NULL($1))])
              LogicalProject(comm=[$6], deptno=[$7], empno=[$0],ename=[$1], hiredate=[$4], job=[$2]
                JdbcTableScan(table=[[scott, EMP]]))" : string
```

In “hybrid” mode, Morel’s compiler identifies sections of Morel programs that are relational operations and converts them to Calcite relational algebra.

Calcite can them optimize these and execute them on their native systems.

Optimization

Relational query optimization

- Applies to relational operators (~10 core operators + UDFs) not general-purpose code
- Transformation rules that match patterns (e.g. Filter on Project)
- Decisions based on cost & statistics
- Hybrid plans - choose target engine, sort order
- Materialized views
- Macro-level optimizations

Functional program optimization

- Applies to typed lambda calculus
- Inline constant lambda expressions
- Eliminate dead code
- Defend against mutually recursive groups
- Careful to not inline expressions that are used more than once (increasing code size) or which bind closures more often (increasing running time)
- Micro-level optimizations

[GM] “The Volcano Optimizer Generator: Extensibility and Efficient Search” (Graefe, McKenna 1993)
[PJM] “Secrets of the Glasgow Haskell Compiler inliner” (Peyton Jones, Marlow 2002)

Recursively-defined sets

Recursively-defined sets in mathematics

Example 1. Fibonacci numbers

$$f_0 = 1$$
$$f_1 = 1$$
$$f_n = f_{n-2} + f_{n-1} \quad (n \geq 2)$$

$F = \{f_i\} = [1, 1, 2, 3, 5, 8, 13, 21, 34, \ldots]$

Romanesco broccoli (wikimedia)

Recursively-defined sets in mathematics

Example 2. Transitive closure

Given a binary relation (set of pairs) R, we can define its *transitive closure* S using set operations

$$S = R \cup (R \bowtie S)$$

or, in terms of set membership

$$(x, y) \in S \leftrightarrow (x, y) \in R \vee \exists z.((x, z) \in R \wedge (z, y) \in S)$$

or, in computerese

```
inS(x, y) = inR(x, y) orelse exists z suchthat (inR(x, z) and inS(z, y))
```

(These dual ways to define a set have a long history, and are the roots of the split between relational algebra and relational calculus.)

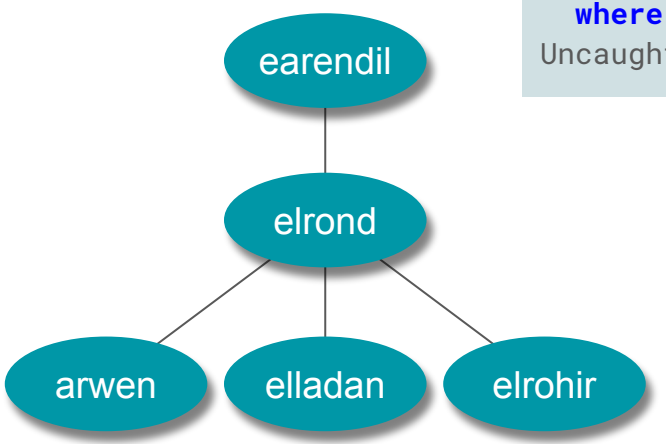
Recursively-defined sets in Morel - attempt #1

```
val parents =
  [("earendil", "elrond"), ("elrond", "arwen"),
   ("elrond", "elladan"), ("elrond", "elrohir")];

from (parent, child) in parents
  where parent = "elrond";
[("elrond", "arwen"), ("elrond", "elladan"),
 ("elrond", "elrohir")];
```

```
fun ancestors () =
    (from (x, y) in parents)
    union
    (from (x, y) in parents,
        (y2, z) in ancestors ()
      where y = y2
      yield (x, z));

from (ancestor, descendant) in ancestors ()
  where descendant = "arwen";
Uncaught exception: StackOverflowError
```



Recursively-defined sets in SQL

```
# SQL
SELECT * FROM parents
WHERE parent = 'elrond';
parent child
====== =======
elrond arwen
elrond elladan
elrond elrohir
```

```
# SQL
CREATE VIEW ancestors AS
  WITH RECURSIVE a AS (
    SELECT parent AS ancestor,
      child AS descendant
    FROM parents
  UNION ALL
    SELECT a.ancestor, p.child
    FROM parents AS p
    JOIN a ON a.descendant = p.parent)
  SELECT * FROM a;

SELECT * FROM ancestors
WHERE descendant = 'arwen';
ancestor descendant
======== =======
earendil arwen
elrond   arwen
```

SQL treats `UNION` as a special operator, and knows how to terminate when it reaches a fixed point

Recursively-defined sets in Datalog

```
# Datalog
is_parent(earendil, elrond).
is_parent(elrond, arwen).
is_parent(elrond, elladan).
is_parent(elrond, elrohir).

answer(X) :- is_parent(elrond, X).
X = arwen
X = elladan
X = elrohir
```

```
# Datalog
is_ancestor(X, Y) :- is_parent(X, Y).
is_ancestor(X, Y) :- is_parent(X, Z),
                     is_ancestor(Z, Y).

answer(X) :- is_ancestor(X, arwen).
X = earendil
X = elrond
```

- Morel's first attempt failed because the recursive function didn't know when to stop
- SQL allows only one operation (**`UNION`** over set), and therefore fixed point is well-defined
- That won't work for Morel; we want recursive functions over all types, not just sets
- Datalog operates in the dual space, "Can I prove that x is a member of a set"? Functions reach a fixed point when the set of (arg, result) pairs stops growing

Recursively-defined set in Morel via a recursive predicate

```
# Morel
fun isAncestor (x, y) =
  (x, y) elem parents
  orelse exists (
    from z suchthat (x, z) elem parents
        andalso isAncestor (z, y));

from ancestor suchthat isAncestor (ancestor, "arwen");
[“earendil”, “elrond”];
```

The `suchthat` operator performs ***constrained iteration***. It assigns to `ancestor` every value for which `isAncestor (ancestor, "arwen")` will evaluate to true.

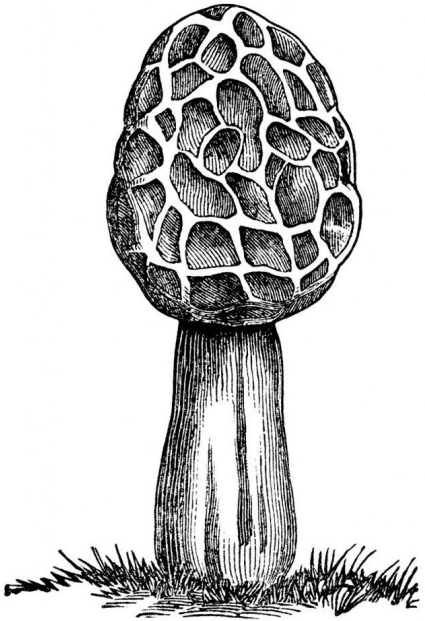
Basically, it runs the machine backwards. Seems like magic, but surprisingly, the compiler can usually figure out what to do.

There are deep connections with how SQL handles correlated queries.

Q. What is the difference between a query and a program?

A. There's no difference if you have the right programming language, a seamless blend of

- functional (elegant type system, Turing power),
- query (data-parallel evaluation, optimizer) and
- deductive (concisely express recursive sets) languages



Morel

Functional query language

Rich type system, concise as SQL, Turing complete

Combines (relational) query optimization with (lambda) FP optimization techniques

Execute in Java interpreter and/or data-parallel engines

```
from e in emps,
    d in depts
  where e.deptno = d.deptno
  yield {d.deptno, e.name};
```

```
from line in lines,
   word in split line
 group word compute c = count;
```

Lots to be done! (Contributions welcome)

Tail-call elimination

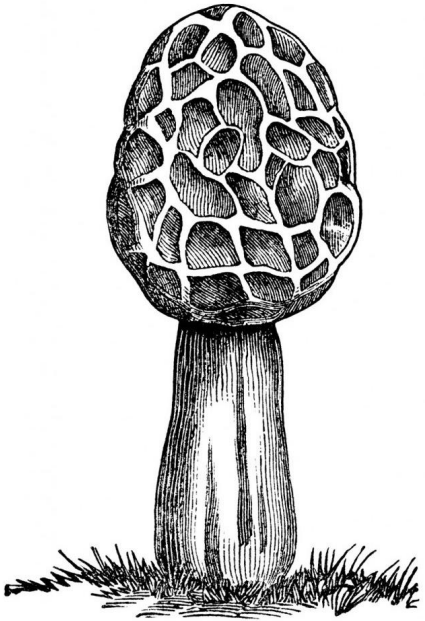
Improve type deduction for record types

Pair with a distributed compute engine (e.g. Apache Spark, Google Dremel, DuckDB) perhaps via Apache Arrow + Substrait

Complete `suchthat` operator

Efficiently compute recursive sets (semi-naïve evaluation)

Cost-based optimization via Apache Calcite



Thank you!
Questions?

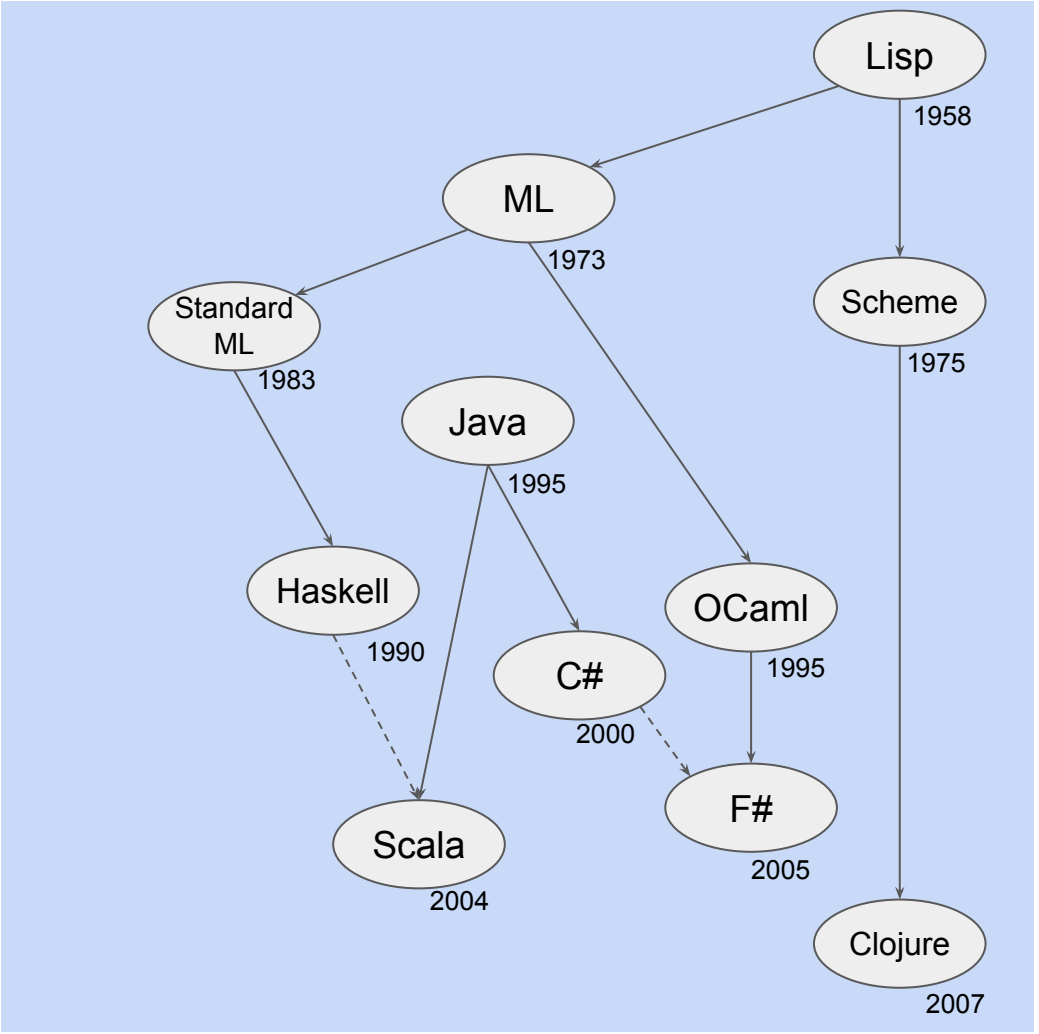
Julian Hyde (Google) @julianhyde

https://github.com/hydromatic/morel @morel_lang

https://calcite.apache.org @ApacheCalcite

Extra slides

Evolution of functional languages



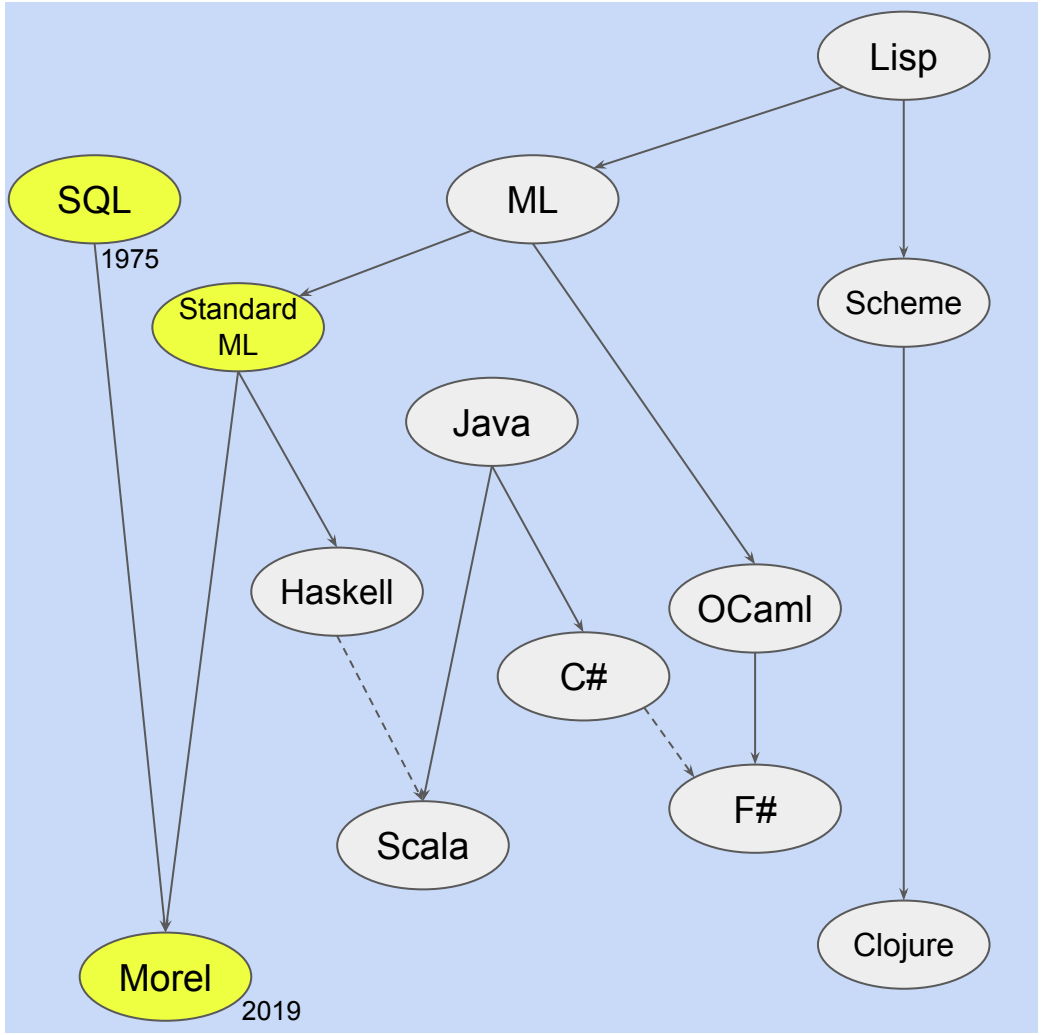
Extend Standard ML

Standard ML is strongly statically typed, and can very frequently deduce every type in a program.

Standard ML has record types. (These are important for queries.)

Haven't decided whether Morel is eager (like Standard ML) or lazy (like Haskell and SQL)

Haskell's type system is more powerful. So, Haskell programs often have explicit types.



Other operators

from in

where

yield

order … desc

group … compute

count max min sum

intersect union except

exists notExists elem notElem only

Compared to other languages

Haskell – Haskell comprehensions are more general (monads vs lists). Morel is focused on relational algebra and probably benefits from a simpler type system.

Builder APIs (e.g. LINQ, FlumeJava, Cascading, Apache Spark) – Builder APIs are two languages. E.g. Apache Spark programs are Scala that builds an algebraic expression. Scala code (especially lambdas) is sprinkled throughout the algebra. Scala compilation is not integrated with algebra optimization.

SQL – SQL's type system does not have parameterized types, so higher order functions are awkward. Tables and columns have separate namespaces, which complicates handling of nested collections. Functions and temporary variables cannot be defined inside queries, so queries are not Turing-complete (unless you use recursive query gymnastics).

Standard ML: types

	Type	Example

Primitive types	`bool`
	`char`
	`int`
	`real`
	`string`
	`unit`
		`true: bool`
		`#"a": char`
		`~1: int`
		`3.14: real`
		`"foo": string`
		`(): unit`

Function types	`string -> int` `int * int -> int`	`String.size` `fn (x, y) => x + y * y`
Tuple types	`int * string`	`(10, "Fred")`
Record types	`{empno:int, name:string}`	`{empno=10, name="Fred"}`
Collection types	`int list` `(bool * (int -> int)) list`	`[1, 2, 3]` `[(true, fn i => i + 1)]`
Type variables	`'a`	`List.length: 'a list -> int`

Algebraic data types, `case`, and recursion

`datatype` declares an algebraic data type. **`'a`** Is a type variable and therefore **`'a tree`** is a polymorphic type.

```
datatype 'a tree =
=     EMPTY
=   | LEAF of 'a
=   | NODE of ('a * 'a tree * 'a tree);
```

Algebraic data types, `case`, and recursion

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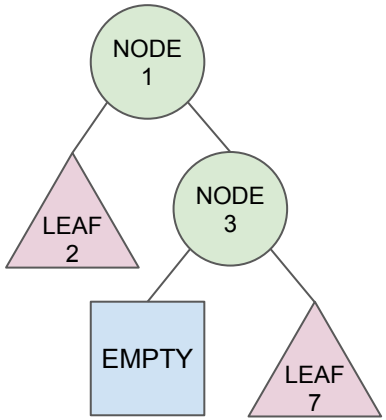
```
- datatype 'a tree =
=     EMPTY
=   | LEAF of 'a
=   | NODE of ('a * 'a tree * 'a tree);

- val t =
=   NODE (1, LEAF 2, NODE (3, EMPTY, LEAF 7));
```

Define an instance of **`tree`** using its constructors **`NODE`**, **`LEAF`** and **`EMPTY`**.



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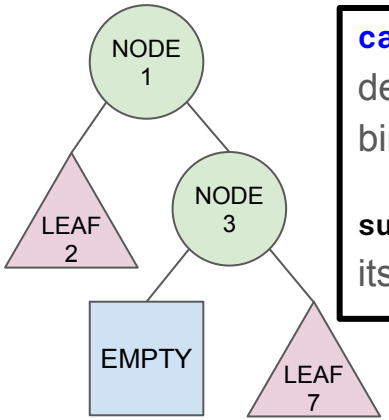


`case` matches patterns, deconstructing data types, and binding variables as it goes.

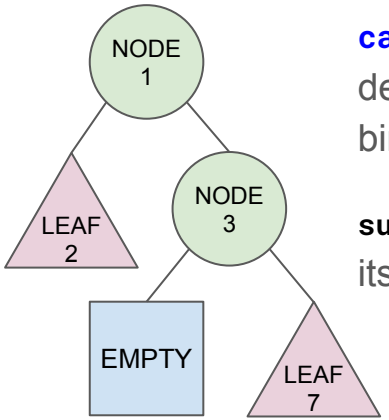
`sumTree` use **`case`** and calls itself recursively.

```
- datatype 'a tree =
=     EMPTY
=   | LEAF of 'a
=   | NODE of ('a * 'a tree * 'a tree);

- val t =
=   NODE (1, LEAF 2, NODE (3, EMPTY, LEAF 7));

- val rec sumTree = fn t =>
=   case t of EMPTY => 0
=     | LEAF i => i
=     | NODE (i, l, r) =>
=         i + sumTree l + sumTree r;
val sumTree = fn : int tree -> int

- sumTree t;
val it = 13 : int
```

Algebraic data types, `case`, and recursion

`datatype` declares an algebraic data type. **`'a`** Is a type variable and therefore **`'a tree`** is a polymorphic type.

Define an instance of **`tree`** using its constructors **`NODE`**, **`LEAF`** and **`EMPTY`**.



`case` matches patterns, deconstructing data types, and binding variables as it goes.

`sumTree` use **`case`** and calls itself recursively.

`fun` is a shorthand for **`case`** and **`val rec`**.

```
- datatype 'a tree =
=     EMPTY
=   | LEAF of 'a
=   | NODE of ('a * 'a tree * 'a tree);

- val t =
=   NODE (1, LEAF 2, NODE (3, EMPTY, LEAF 7));

- val rec sumTree = fn t =>
=   case t of EMPTY => 0
=     | LEAF i => i
=     | NODE (i, l, r) =>
=         i + sumTree l + sumTree r;
val sumTree = fn : int tree -> int

- sumTree t;
val it = 13 : int

- fun sumTree EMPTY = 0
=   | sumTree (LEAF i) = i
=   | sumTree (NODE (i, l, r)) =
=         i + sumTree l + sumTree r;
val sumTree = fn : int tree -> int
```

Functional programming ↔ relational programming

Functional programming in-the-small

```
- fun squareList [] = []
=   | squareList (x :: xs) = x * x :: squareList xs;
val squareList = fn : int list -> int list

- squareList [1, 2, 3];
val it = [1,4,9] : int list
```

Functional programming in-the-large

```
- fun squareList xs = List.map (fn x => x * x) xs;
val squareList = fn : int list -> int list

- squareList [1, 2, 3];
val it = [1,4,9] : int list
```

Relational programming

```
- fun squareList xs =
=   from x in xs
=     yield x * x;

- squareList [1, 2, 3];
val it = [1,4,9] : int list
```

Implementing Join using higher-order functions

`List.map` function is equivalent to Project relational operator (SQL **`SELECT`**)

We also define a **`flatMap`** function.

Equivalent SQL

```
SELECT d.deptno, e.name
FROM emps AS e,
  depts AS d
WHERE d.deptno = e.deptno
```

```
- val depts = [
=   {deptno = 10, name = "Sales"},
=   {deptno = 20, name = "Marketing"},
=   {deptno = 30, name = "R&D"}];

- fun flatMap f xs = List.concat (List.map f xs);
val flatMap =
  fn : ('a -> 'b list) -> 'a list -> 'b list

- List.map
=   (fn (d, e) => {deptno = #deptno d, name = #name e})
=   (List.filter
=     (fn (d, e) => #deptno d = #deptno e)
=     (flatMap
=       (fn e => (List.map (fn d => (d, e)) depts))
=       emps));
val it =
  [{deptno=10,name="Fred"}, {deptno=20,name="Velma"},
   {deptno=30,name="Shaggy"}, {deptno=30,name="Scooby"}]
 : {deptno:int, name:string} list
```

wordCount again

wordCount in-the-small

```
- fun wordCount list = ...;
val wordCount = fn : string list -> {count:int, word:string} list
```

wordCount in-the-large using **mapReduce**

```
- fun mapReduce mapper reducer list = ...;
val mapReduce = fn : ('a -> ('b * 'c) list) ->
    ('b * 'c list -> 'd) -> 'a list -> ('b * 'd) list

- fun wc_mapper line =
=   List.map (fn w => (w, 1)) (split line);
val wc_mapper = fn : string -> (string * int) list

- fun wc_reducer (key, values) =
=   List.foldl (fn (x, y) => x + y) 0 values;
val wc_reducer = fn : 'a * int list -> int

- fun wordCount list = mapReduce wc_mapper wc_reducer list;
val wordCount = fn : string list -> {count:int, word:string} list
```

Relational implementation of **mapReduce**

```
- fun mapReduce mapper reducer list =
=   from e in list,
=       (k, v) in mapper e
=     group k compute c = (fn vs => reducer (k, vs)) of v;
```

group .... compute

```
- fun median reals = ...;
val median = fn : real list -> real

- from e in emps
=   group x = e.deptno mod 3,
=         e.job
=   compute c = count,
=     sum of e.sal,
=     m = median of e.sal + e.comm;
val it = {c:int, job:string, m:real, sum:real, x.int} list
```

Two ways to define a relation

```
# Morel

# Relation defined using algebra
fun clerks () =
  from e in emps
    where e.job = "CLERK";

# Query uses regular iteration
from e in clerks,
    d in depts
  where d.deptno = e.deptno
  andalso d.loc = "DALLAS"
  yield e.name;
[“SMITH”, “ADAMS”];
```

```
# Morel

# Relation defined using a predicate
fun isClerk e =
  e.job = "CLERK";

# Query uses a mixture of constrained
# and regular iteration
from e suchthat isClerk e,
    d in depts
  where d.deptno = e.deptno
  andalso d.loc = "DALLAS"
  yield e.name;
[“SMITH”, “ADAMS”];
```