Set-Oriented Query Processing

Motivation

During query processing, the DBMS tries to process whole *sets of data items* at a time

- "manual" programming is usually record oriented
- e.g., compare two records
- easy to understand, but this does not scale

Consider: intersecting two lists

- breaking it down into record-level operators is inefficient
- compares each record with each other record
- $O(n^2)$
- considering the complete lists in one step is more efficient
- $O(n \log n)$

Motivation (2)

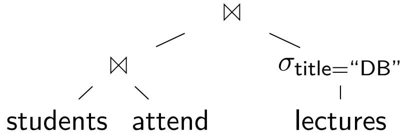
Set-oriented processing has several advantages

- data can be pre-processed before processing
- sorting/hashing/index structures etc.
- amortizes over the set
- leads to more efficient algorithms
- easier to cope with memory limitations etc.
- easier parallelism
- ...

Algorithms tend to become more scalable, but also more involved.

The Algebraic Model

Query processing is usually expressed by relational algebra



- operators consumes zero or more relations, and produce one output relation
- inherently set (or rather: bag) oriented

Implementing the Algebraic Model

Operators are specified in a query agnostic manner:

- intersect
  - left
  - right
  - compare

Operator does not understand the query semantic. It only knows:

- *left* will produce a result set
- *right* will produce a result set
- *compare* compares two elements

Note: a scalable implementation will need more (e.g., *hashLeft*,*hashRight*), we ignore this for now.

Implementing the Algebraic Model (2)

The algebraic operators define the **abstract logic** of query processing primitives. The query specific parts are hidden in **subscripts**.

In particular:

- operators do not "know" the data types or byte size of input tuples
- they do not "understand" the content of a tuple
- they only specify the data flow and the control flow
- all query dependent operations are delegated to helper subscripts
- keeps the operator itself very generic

Note: sometimes operators are hinted with query specific info (e..g, a fixed tuple size) for performance reasons, but this is only a minor variation.

Implementing the Algebraic Model (3)

Example: intersectSorted(left,right,compare)

t_1=next tuple from *left*
n=*right*
while input is not exhausted
  if n=*left*
    t_1=next tuple from *left* **else**
    t_2=next tuple from *right*
  c=*compare*(t_1,t_2)
  if $c = 0$
    store t_1 as result
  else if $c < 0$
    n=*left*
  else
    n=*right*

The code is independent from the concrete query.

Operator Composition

- each operator produces a set (bag/stream) of result tuples
- operators consume zero or more input sets
- usually assume nothing about their input
- therefore can be combined in an arbitrary manner
- very flexible

Operator Interface

Option 1: Full Materialization

Every operator materializes its output. The input is always read from a materialized state.

Advantages:

- easy to implement
- can handle surprises concerning intermediate result sizes (dynamic plans)
- advanced techniques like parallelization, result sharing, etc. are simple

Disadvantages:

- materialization is expensive
- in particular if data is larger than main memory

Few systems use this approach, but some do (MonetDB).

Operator Interface (2)

Option 2: Iterator Model

Each operator produces a tuple stream on demand. The input is iterated over.

Advantages:

- data is pipelined between operators
- avoids unnecessary materialization
- flexible control flow
- easy to implement

Disadvantages:

- millions of virtual function calls
- poor locality

The standard model. Widely used.

Operator Interface (3)

The iterator model usually offers the following interface:

- open
- next
- close

Repeated calls to *next* produce the output stream.

Internally, operators maintain a complex state to offer the iterator interface.

Operator Interface (4)

How to pass data from one operator to the other?

- the data itself is opaque
- as a consequence, it cannot be passed (easily) by value

Alternative 1: pass tuple pointers

- the real data resides on a page/in the buffer
- operators are only passed pointers to the data

Alternative 2: not at all

- there is a global data space ("registers")
- subscript functions operate on these registers
- the operators never touch the data directly

Alternative 2 is more generic, and can cope better with computed columns.

Operator Interface (5)

Option 3: blockwise processing
Each operator produces a tuple stream, but not tuple-by-tuple but as a stream of larger chunks.

Advantages:

- far fewer function calls
- better code and data locality

Disadvantages:

- additional materialization overhead
- consumes memory bandwidth
- control flow not as flexible

Operator Interface (6)

Option 4: pushing tuples up
Each operator pushes produced tuples towards the consuming operators.

Advantages:

- operator logic is concentrated in a few loops
- good code and data locality
- pipelining etc. still possible
- support for DAG-structured plans

Disadvantages:

- some restrictions in control flow
- code generation more involved

Examples - Full Materialization

```
scan(R)
   // no-op, all operators read their input
   return R
select(R,p)
   R'=new temporary relation
   for each t ∈ R
      if p(t)
         append t to R'
   return R'
cross(R1,R2)
   R'=new temporary relation
   for each t1 ∈ R1
      for each t2 ∈ R2
         append t1 ∘ t2 to R'
   return R'
```

Examples - Iterator Model

class Scan
  in,*tid*,*limit*

Scan::open(R)
  in=R
  tid=0
  $limit$=$|R|$

Scan::next()
  if $tid \geq limit$
    return false
  load tuple t from *in* at position *tid*
  tid=tid+1
  return true

Examples - Iterator Model (2)

class Select
  in,*p*

Select::open(*in*,*p*)
  this.*in*=*in*
  this.*p*=*p*

Select::next(in,*p*)
  while *in*.next()
    if *p*()
      return true
  return false

Examples - Iterator Model (3)

```
class Cross
   left,right,step
Cross::open(left,right)
   this.left=left
   this.right=right
   step=true
Cross.next()
   while true
      if step
         if not left.next()
            return false
         right.open()
         step=false
      if right.next()
         return true
      step=true
```

Examples - Blockwise Processing

class Scan
  in,*tid*,*limit*

Scan::open(R)
  in=R
  tid=0
  $limit$=$|R|$

Scan::next()
  C=min($limit$-tid,1000)
  R'=tuple array of size C
  for i=0...$C-1$
    load tuple $R'[i]$ from *in* at position tid+i
  tid=tid+C
  return R'

Examples - Blockwise Processing (2)

class Select
  in,*p*
Select::open(*in*,*p*)
  this.in=in, **this**.p=p
Select::next(in,*p*)
  while true
    R'=in.next()
    if $|R'| = 0$
      return R'
    w=0
    for i=0...$|R'| - 1$
      $R'[w] = R'[i]$
      $w = w + p(R'[w])$
    R'.length=w
    if $|R'| > 0$
      return R'

Examples - Blockwise Processing (3)

class Cross
  $left, right, c_L, l_L, R_L, c_R, l_R, R_R$

Cross::open($left$,$right$)
  this.$left$=$left$
  this.$right$=$right$
  $step$=**true**
  $c_L = l_L = c_R = r_R = 0$

Cross.next()
  R'=tuple array of size 1000, w=0

Examples - Blockwise Processing (4)

while true

  while $c_R = l_R$

    if $c_L \geq l_L$

      $R_R = \mathit{right}.\text{next}()$

      if $|R_R| = 0$

        $R_L = \mathit{left}.\text{next}()$

        if $|R_L| = 0$

          $R'.\text{length}{=}w$, **return** R'

        $\mathit{right}.\text{rewind}()$, $R_R = \mathit{right}.\text{next}()$

      $c_L = 0$, $l_L = |R_L|$

    else $c_L = c_L + 1$

    $c_R = 0$, $l_R = |R_R|$

  $R'[w] = R_L[c_L] \circ R_R[c_R]$

  $c_R = c_R + 1$, $w = w + 1$

  if $w = |R'|$

    return R'

Examples - Push

class Scan
  consumer, *R*

Scan::open(*consumer*, *R*)
  this.*consumer*=consumer
  this.*R*=*R*

Scan::produce()
  for each *t* in *R*
    consumer.consume(*t*)

Examples - Push (2)

class Select
  in, *consumer*, *p*

Select::open(*in*, *consumer*, *p*)
  this.*in*=*in*, **this**.*consumer*=*consumer*, **this**.*p*=*p*

Select::produce()
  in.produce()

Select::consume(*t*)
  if *p*(*t*)
    consumer.consume(*p*)

Examples - Push (3)

class Cross
  left,*right*,*consumer*,t_L

Cross::open(*left*,*right*,*consumer*)
  this.*left*=*left*, **this**.*right*=*right*, **this**.*consumer*=*consumer*

Cross::produce()
  left.produce()

Cross::consumeFromLeft(t)
  $t_L = t$
  right.produce()

Cross::consumeFromRight(t)
  consumer.consume($t_L \circ t$)

Additional Functionality

We ignored the *close* function so far

- releases allocated resources

Other functionality implemented or used by operators:

- rewind/rebind
- memory management
- spooling intermediate results

Implementing Subscripts

The operators are query independent, but the subscripts are not

- cover the query-specific parts of the query
- attribute access (e.g., `x.a`)
- predicates (e.g., `a=b`)
- computations (e.g., `sum(amount*(1+tax))`)
- ...

Must be implemented, too

- different for every query
- but usually relatively simple
- complexity much lower than for operators

Implementing Subscripts (2)

Option 1: interpreter objects

Subscripts are assembled from interpreter objects.

- very flexible
- easy to implement
- widely used
- but: many virtual function calls

```
Val AccessInt::eval(char* ptr)
  return *((int*)(ptr+ofs));

Val CompareEqInt::eval(char* ptr)
  return left->eval(ptr).intValue==right->eval(ptr).intValue
```

Implementing Subscripts (3)

Option 2: virtual machines

Subscripts are compiled into instructions for a virtual machine.

- more efficient than interpreter objects
- but also more complex
- requires a compiler to byte code

```
while (true) switch ((++op)->cmd) {
  case Cmd::AccessInt:
    reg[op->out]=*((*int)(ptr+op->val);
    break;
  case Cmd::CompareEqInt:
    reg[op->out]=reg[op->in1].intValue==reg[op->in2].intValue;
    break;
  ...
}
```

Implementing Subscripts (4)

Option 3: pre-compiled fragments

Subscripts are expressed as combination of pre-compiled fragments.

- each fragment performs a number of operations
- quite efficient (vectorization)
- but usually only applicable for column stores

```
CompareEqInt(unsigned len,int* col1,int* col2,bool* result)
  for (unsigned index=0;index!=len;++index)
    result[index]=col1[index]==col2[index]
```

Implementing Subscripts (5)

Option 4: generated machine code

Subscripts are at runtime compiled into native machine code.

- the most efficient alternative
- but also the most difficulty
- portability is an issue
- we will look at this in the Section Code Generation

```
...
movq  72(%rsp), %rax
movl  (%rax,%r12,4), %r13d
movq  120(%rsp), %rax
movl  (%rax,%r12,4), %edi
cmpl  %r13d,%edi
...
```

Pipelining

As mentioned, most approaches try to avoid copying data between operators

- this is called *pipelining*
- operators that do materialize their input are called *pipeline breakers*
- operators are consume their input completely before processing are called *full pipeline breakers*
- some binary operators are pipeline breakers on only one side

This behavior has implications regarding other operators.

Pipelining (2)

Some effects of different pipeline behavior

- if a pipeline break is between source and sink the original data is no longer accessible
  - relevant for lazy attribute access/TID join/string representations etc.
  - the system must plan defensively
- if a full pipeline breaker is between two operators both are decoupled
  - the full pipeline break breaks the plan into fragments
  - can be executed independent from each other
  - relevant for scheduling
- ...

The code generation must know the pipeline behavior of operators.

Parallelization

How can we exploit multiple cores during query processing?

- inter-query parallelism is simple
- intra-query parallelism is much harder
- independent parts of the query can be executed in parallel (see: full pipeline breaker)
- parallelizing individual operators is more difficult
- usual strategy: partition the input

We will discuss this later in more detail.