Code Generation

Motivation

For good performance, the operator subscripts have to be compiled

- to byte code
- to C code
- or to machine code.

Generating machine code is more difficult but also more efficient (both in terms of compile and runtime).

Machine code has portability problems

- code generation frameworks hide these
- some well known kits: LLVM, libjit, GNU lightning, ...
- greatly simplify code generation, often offer optimizations

LLVM is one of the more mature choices.

LLVM Intermediate Representation

- unbounded number of registers
- SSA form
- strongly typed values

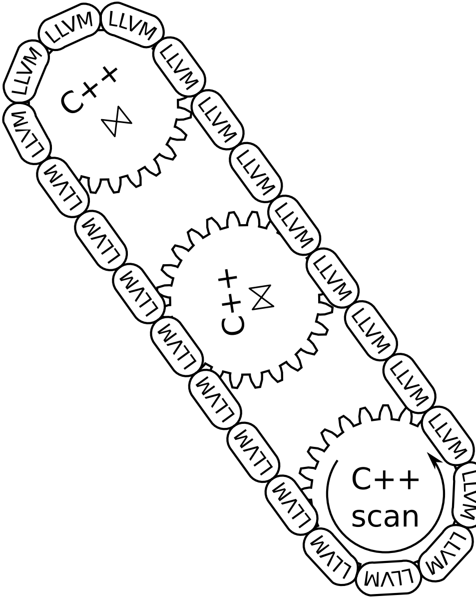
```
define i32 @fak(i32 %x) {
     %1 = icmp ugt i32 %x, 1
     br i1 %1, label %L1, label %L2
L1:  %2 = sub i32 %x, 1
     %3 = call i32 @fak(i32 %2)
     %4 = mul i32 %x, %3
     br label %L3
L2:  br label %L3
L3:  %5 = phi i32 [ %4, %L1 ], [ 1, %L2 ]
     ret i32 %5
}
```

Has different backends for compiling to different machine languages (AMD64/Intel64, x86, ARM, PowerPC, and more)

LLVM (2)

Not everything needs to be LLVM code

- many complex code pieces remain unchanged
- e.g., spooling to disk
- much more reasonable to implement it in C++
- only the hot path is performance critical
- executed for millions of tuples, but relative simple
- implemented in LLVM code
- keeps the amount of runtime code down



Compiling Scalar Expressions

- all scalar values are kept in LLVM registers
- additional register for NULL indicator if needed
- most scalar operations (=, +, -, etc.) compile to a few LLVM instructions
- C++ code can be called for complex operations (`like` etc.)
- goal: minimize branching, minimize function calls

The real challenge is integrating these into set-oriented processing.

Data-Centric Query Execution

Why does the iterator model (and its variants) use the operator structure for execution?

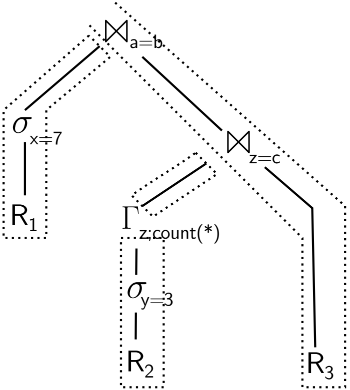
- it is convenient, and feels natural
- the operator structure is there anyway
- but otherwise the operators only describe the data flow
- in particular operator boundaries are somewhat arbitrary

What we really want is **data centric** query execution

- data should be read/written as rarely as possible
- data should be kept in CPU registers as much as possible
- the code should center around the data,
  not the data move according to the code
- increase locality, reduce branching

Data-Centric Query Execution (2)

Example plan with visible pipeline boundaries:



- data is always taken out of a pipeline breaker and materialized into the next
- operators in between are passed through
- the relevant chunks are the pipeline fragments
- instead of iterating, we can push up the pipeline

Data-Centric Query Execution (3)

Corresponding code fragments:

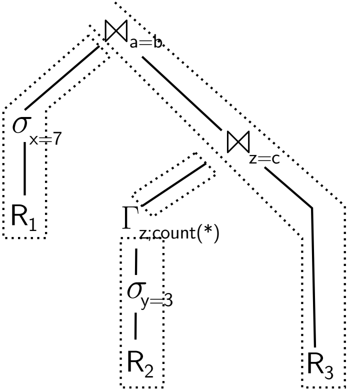
initialize memory of $\bowtie_{a=b}$, $\bowtie_{c=z}$, and Γ_z

for each tuple t in R_1
  if $t.x = 7$
    materialize t in hash table of $\bowtie_{a=b}$

for each tuple t in R_2
  if $t.y = 3$
    aggregate t in hash table of Γ_z

for each tuple t in Γ_z
  materialize t in hash table of $\bowtie_{z=c}$

for each tuple t_3 in R_3
  for each match t_2 in $\bowtie_{z=c}[t_3.c]$
    for each match t_1 in $\bowtie_{a=b}[t_3.b]$
      output $t_1 \circ t_2 \circ t_3$



Data-Centric Query Execution (4)

Basic strategy:

1. the producing operator loops over all materialized tuples
2. the current tuple is loaded into CPU registers
3. all pipelining ancestor operators are applied
4. the tuple is materialized into the next pipeline breaker

- tries to maximize code and data locality
- a tight loops performs a number of operations
- memory access in minimized
- operator boundaries are blurred
- code centers on the data, not the operators

Producing the Code

Code generator mimics the produce/consume interface

- these methods do not really exist (at query execution time), they are conceptual constructs
- the *produce* logic generates the code to produce output tuples
- the *consume* logic generates the code to accept incoming tuples
- not clearly visible within the generated code

Producing the Code (2)

```
void HJTranslatorInner::produce(CodeGen& codegen,Context& context) const
{
  // Construct functions that will be be called from the C++ code
  {
    AddRequired addRequired(context,getCondition().getUsed().limitTo(left));
    produceLeft=codegen.derivePlanFunction(left,context);
  }
  {
    AddRequired addRequired(context,getCondition().getUsed().limitTo(right));
    produceRight=codegen.derivePlanFunction(right,context);
  }

  // Call the C++ code
  codegen.call(HashJoinInnerProxy::produce.getFunction(codegen),
    {context.getOperator(this)});
}
void HJTranslatorInner::consume(CodeGen& codegen,Context& context) const
{
  llvm::Value* opPtr=context.getOperator(this);
```

Producing the Code (3)

```
// Left side
if (source==left) {
  // Collect registers from the left side
  vector<ResultValue> materializedValues;
  matHelperLeft.collectValues(codegen,context,materializedValues);

  // Compute size and hash value
  llvm::Value* size=matHelperLeft.computeSize(codegen,materializedValues);
  llvm::Value* hash=matHelperLeft.computeHash(codegen,materializedValues);

  // Materialize in hash table, spools to disk if needed
  llvm::Value* ptr=codegen.callBase(HashJoinProxy::storeLeftInputTuple,
    {opPtr,size,hash});
  matHelperLeft.materialize(codegen,ptr,materializedValues);
```

Producing the Code (4)

```
    // Right side
    } else {
      // Collect registers from the right side
      vector<ResultValue> materializedValues;
      matHelperRight.collectValues(codegen,context,materializedValues);

      // Compute size and hash value
      llvm::Value* size=matHelperRight.computeSize(codegen,materializedValues);
      llvm::Value* hash=matHelperRight.computeHash(codegen,materializedValues);

      // Materialize in memory, spools to disk if needed, implicitly joins
      llvm::Value* ptr=codegen.callBase(HashJoinProxy::storeRightInputTuple,
        {opPtr,size});
      matHelperRight.materialize(codegen,ptr,materializedValues);
      codegen.call(HashJoinInnerProxy::storeRightInputTupleDone,{opPtr,hash});
    }
}
```

Producing the Code (5)

```
void HJTranslatorInner::join(CodeGen& codegen,Context& context) const
{
  llvm::Value* leftPtr=context.getLeftTuple(),*rightPtr=context.getLeftTuple();
  // Load into registers. Actual load may be delayed by optimizer
  vector<ResultValue> leftValues,rightValues;
  matHelperLeft.dematerialize(codegen,leftPtr,leftValues,context);
  matHelperRight.dematerialize(codegen,rightPtr,rightValues,context);

  // Check the join condition, return false for mismatches
  llvm::BasicBlock* returnFalseBB=constructReturnFalseBB(codegen);
  MaterializationHelper::testValues(codegen,leftValues,rightValues,
    joinPredicateIs,returnFalseBB);
  for (auto iter=residuals.begin(),limit=residuals.end();iter!=limit;++iter) {
    ResultValue v=codegen.deriveValue(**iter,context);
    CodeGen::If checkCondition(codegen,v,0,returnFalseBB);
  }
  // Found a match, propagate up
  getParent()->consume(codegen,context);
}
```