Module 4

Implementation of XQuery

Part 1: Overview of Compiler, Runtime System

Now let us talk XQuery

- Compile Time + Optimizations
  - Operator Models
  - Query Rewrite
  - Runtime + Query Execution
- XML Data Representation
  - XML Storage
  - XML Indexes
  - Compression + Binary XML

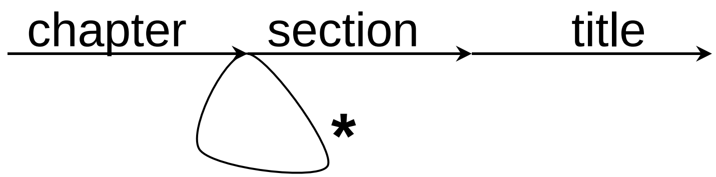
Code representation

- For SQL, relational algebra
  - e.g., joins, scan, group-by, sort, …
  - logical and physical operators
- For XQuery, many proposals exist:
  - algebra (operators) vs expressions vs automata
  - standard algebra for XQuery (-> XQuery Formal Sem.)
  - logical vs. physical algebra
  - redundant algebra or not
    - SQL is redundant at the physical not logical level (!)
  - additional structures: dataflow, dependency graphs

Automata representation

[YFilter'03, Gupta'03, etc]

$x/chapter//section/title




```
<book>
   <chapter>
      <section>
         <title/>
      </section>
   </chapter>
</book>
```

begin book
begin chapter
begin section
begin title
end title
end section
end chapter
end book

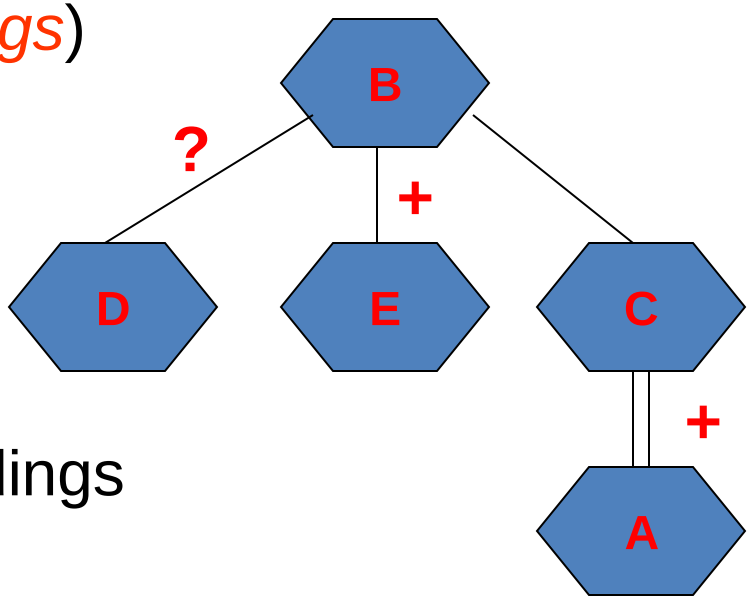
- Many variants
  - one path vs. a set of paths
  - NFAs vs DFAs
- Limitations
  - not extensible to full XQuery
  - better suited for push execution, pull is harder
  - lazy evaluation is hard

TLC Algebra

(Jagadish et al. 2004)

- XML Query tree patterns (called *twigs*)
- Annotated with predicates
- Tree matching as basic operation
  - Logical and physical operation

- Tree pattern matching => tuple bindings (i.e. relations)
- Tuples combined via classical relational algebra
  - Select, project, join, duplicate-elim., …

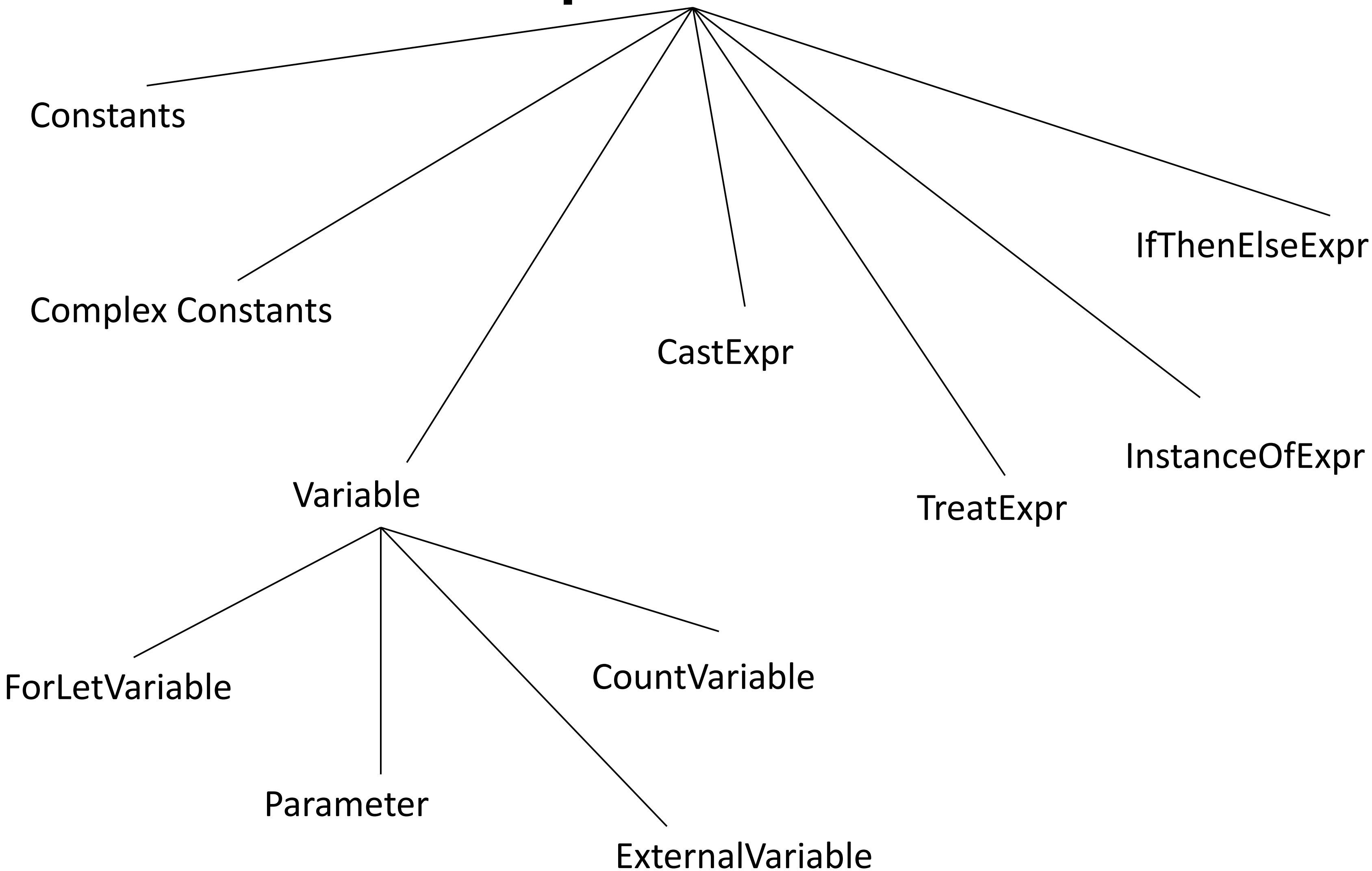


XQuery Expressions

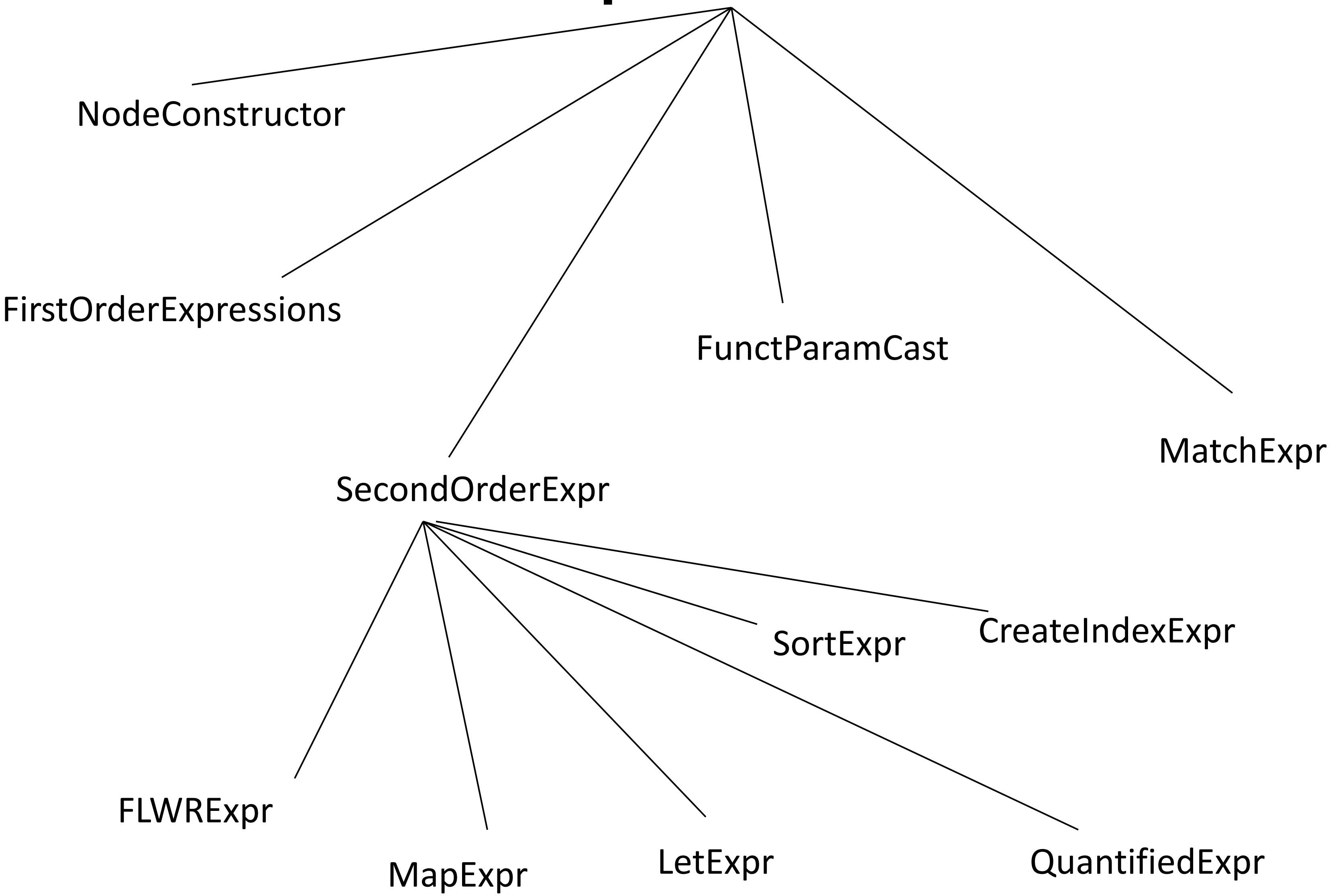
XQRL/BEA/Oracle, XL, MXQuery, Zorba / Sausalito

- “Expressions” built during parsing
- (almost) 1-1 mapping between XQuery expressions and internal expressions
  - exception: Match(expr, NodeTest) for path expressions
- Annotated expressions
  - *E.g. unordered* is an annotation
  - Annotations exploited during optimization
- Redundant algebra
  - general FLWR, but also LET and MAP
  - typeswitch, but also instanceof and conditionals
  - many different versions of constructor
    - streaming vs. blocking; recycling of constructed nodes; node ids
- Support for dataflow analysis is fundamental

Expressions



Expressions



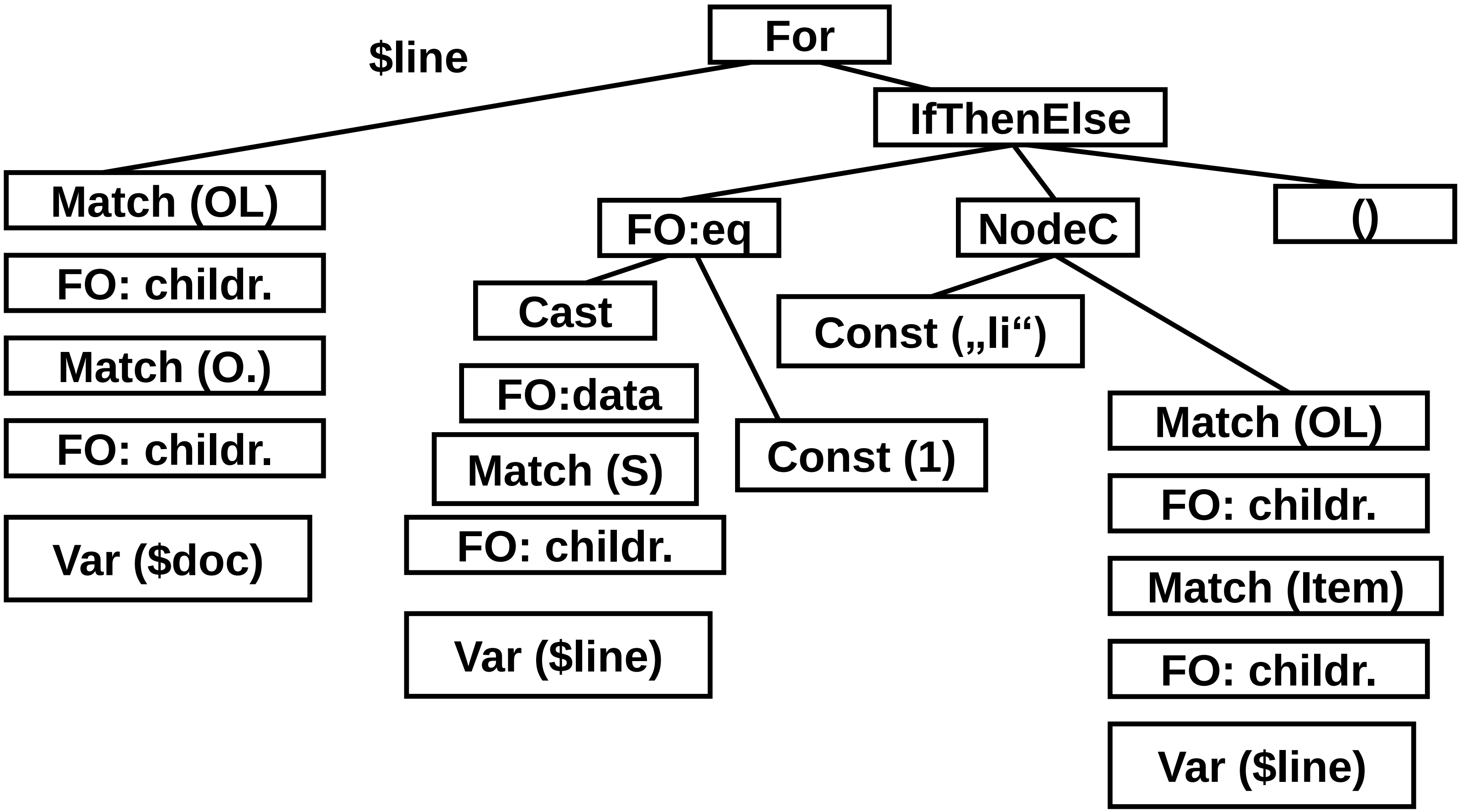
Expression representation example

- First „normalize“ query – make implicit operations explicit

```
for $line in $doc/Order/OrderLine
   where $line/SellersID eq 1
   return <lineItem>{$line/Item/ID}</lineItem>
```

```
for $line in $doc/Order/OrderLine
      where xs:integer(fn:data($line/SellersID)) eq 1
      return <lineItem>{$line/Item/ID}</lineItem>
```

Translation to expression tree



- Optimization: Transformations on expression tree
- Code gen: Select physical implementation for each expr.

Dataflow Analysis

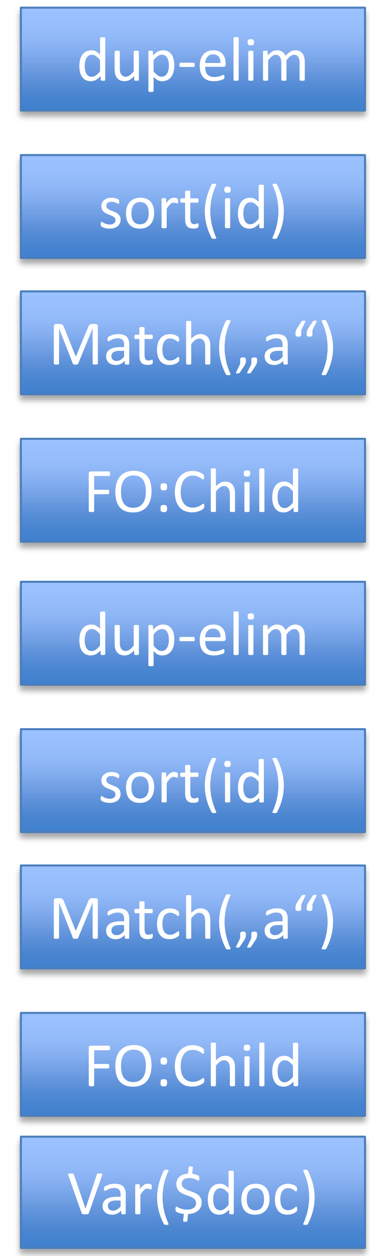
- Annotate each operator (attribute grammars)
  - Type of output (e.g., BookType*)
  - Is output sorted? Does it contain duplicates?
  - Has output node ids? Are node ids needed?
- Annotations computed in walks through plan
  - Instrinsic: e.g., preserves sorting
  - Synthetic: e.g., type, sorted
  - Inherited: e.g., node ids are required
- Optimizations based on annotations
  - Eliminate redundant sort operators
  - Avoid generation of node ids in streaming apps

Dataflow Analysis: Static Type

Match(„book“)	elem book of BookType
FO:child	elem book of BookType or elem thesis of BookType
FO:child	elem bib of BibType
validate as „bib.xsd“	doc of BibType
doc(„bib.xml“)	item*

Order, Duplicate Annotations

- Program: $doc/a/b
- Implicit operators of Xpath
  - sort in document order
  - eliminate duplicates
- Very expensive operations
  - do not do them if unnecessary
  - do not worry about node-ids if no necessary
- Example also shows need for different implementations, algebraic properties of operators
  - dup-elim before / after sort???



Order, Duplicate Annotations: $doc/a/b

dup-elim

sort(id)

Match(„a“)

FO:Child

dup-elim

sort(id)

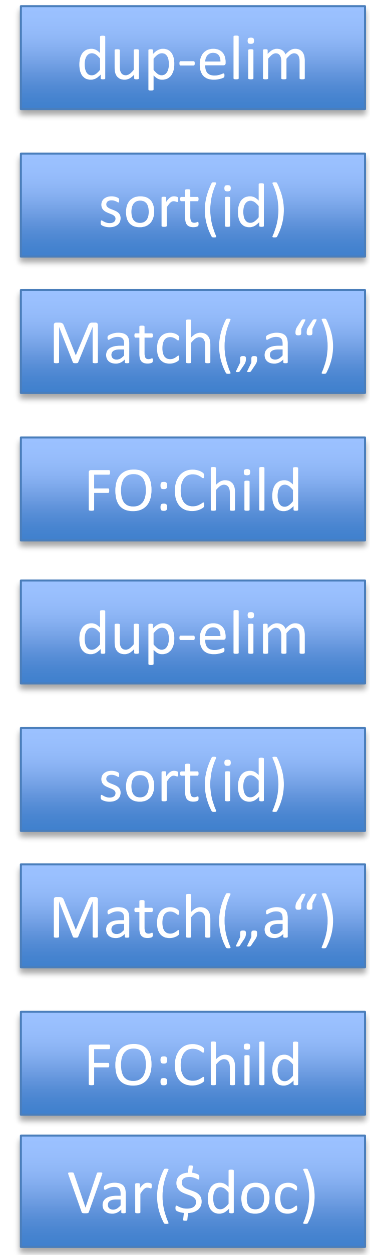
Match(„a“)

FO:Child

Var($doc)

Order = ?, Duplicates = no

Order, Duplicate Annotations: $doc/a/b



Order = ?, Duplicates = no

Order = ?, Duplicates = no

Order, Duplicate Annotations: $doc/a/b

dup-elim

sort(id)

Match(„a“)

FO:Child

dup-elim

sort(id)

Order = ?, Duplicates = no — Match(„a“)

Order = ?, Duplicates = no — FO:Child

Order = ?, Duplicates = no — Var($doc)

Order, Duplicate Annotations: $doc/a/b

dup-elim

sort(id)

Match(„a“)

FO:Child

dup-elim

Order = yes, Duplicates = no sort(id)

Order = ?, Duplicates = no Match(„a“)

Order = ?, Duplicates = no FO:Child

Order = ?, Duplicates = no Var($doc)

Order, Duplicate Annotations: $doc/a/b

	dup-elim
	sort(id)
	Match(„a“)
	FO:Child
Order = yes, Duplicates = no	dup-elim
Order = yes, Duplicates = no	sort(id)
Order = ?, Duplicates = no	Match(„a“)
Order = ?, Duplicates = no	FO:Child
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Order, Duplicate Annotations: $doc/a/b

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Order, Duplicate Annotations: $doc/a/b

Order = yes, Duplicates = no — dup-elim

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Order = ?, Duplicates = no — Match(„a“)

Order = ?, Duplicates = no — FO:Child

Order = ?, Duplicates = no — Var($doc)

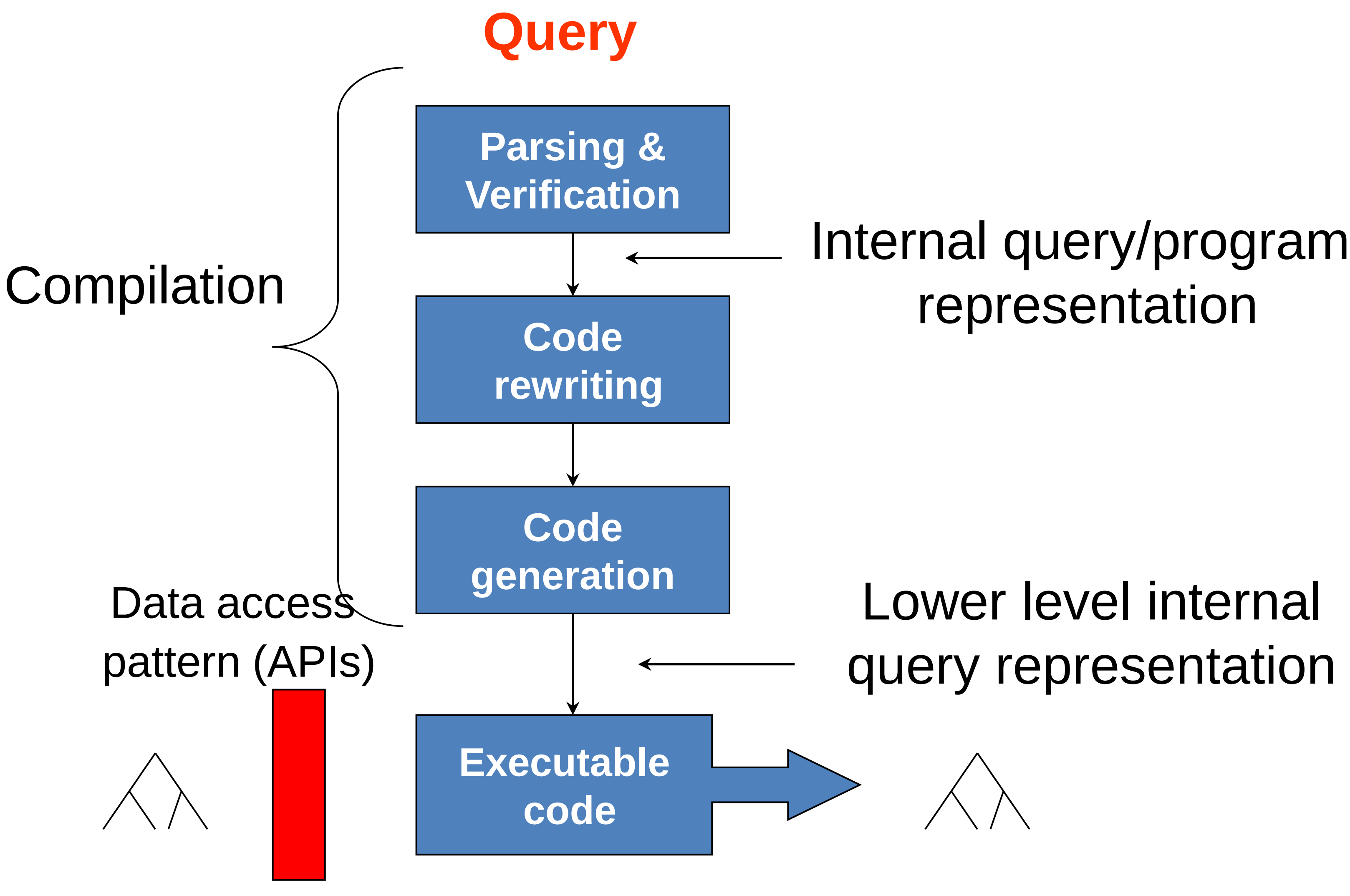
Optimizing: $doc/a/b

Order = yes, Duplicates = no	dup-elim
Order = yes, Duplicates = no	sort(id)
Order = yes, Duplicates = no	Match(„a“)
Order = yes, Duplicates = no	FO:Child
Order = yes, Duplicates = no	dup-elim
Order = yes, Duplicates = no	sort(id)
Order = ?, Duplicates = no	Match(„a“)
Order = ?, Duplicates = no	FO:Child
Order = ?, Duplicates = no	Var($doc)

How about $doc//a//b

- Does „//“ preserve order?
- Does „//“ generate duplicates?
- How would you implement „//“
  - under which circumstances can you stream it?
  - under which circumstances do you have to materialize?
- Properties of „//“ depend on
  - algorithm used to compute „//“
  - knowledge of the types

Architecture of XQuery Processor



Major compilation steps

1. Parsing
2. Normalization
3. Type checking
4. *Optimization*
   1. *Data access patterns agnostic optimization*
   2. Optimization that exploit the existing data access patterns
   3. *(Cost-based optimizations)*
5. Code Generation

XQuery Rewritings

- Algebraic properties of comparisons
- Algebraic properties of Boolean operators
- LET clause folding and unfolding
- Function inlining
- Constant folding
- Common sub-expressions factorization
- Type based rewritings
- Navigation based rewritings

Algebraic properties of comparisons

- General comparisons not reflexive, transitive
  - (1,3) = (1,2) *(but also !=, <, >, <=, >= !!!!!)*
  - Reasons
    - implicit existential quantification, dynamic casts

- Negation rule does not hold
  - fn:not($x = $y) is not equivalent to $x != $y

- Value comparisons are *almost* transitive
  - Exception:
    - xs:decimal due to the loss of precision

Impact on grouping, hashing, indexing, caching !!!

Properties of Boolean operators

- *And*, *Or* are commutative
- Short-circuiting is allowed
- Boolean operators are non-deterministic
  - surprise for programmers (lost satellites):

    ```
    If (($x castable as xs:integer) and
    (($x cast as xs:integer) eq 2) ) …
    ```

  - Is SQL deterministic? How can that happen in SQL?
- 2 value logic (unlike SQL!)
  - () is converted into fn:false() before use
- Conventional distributivity rules hold

LET clause folding

- Traditional rewriting

```
let $x := 3
return $x +2
```

```
3+2
```

- Not so easy!

```
let $x := <a/>
return ($x, $x )
```

```
(<a/>, <a/> )
```

NO. Side effects.
(Node identity)

```
declare namespace ns=“uri1”
let $x := <ns:a/>
return <b xmlns:ns=“uri2”>{$x}</b>
```

NO. Context sensitive
namespace processing.

```
declare namespace ns =“uri1”
<b xmlns:ns=“uri2”>{<ns:a/>}</b>
```

LET clause folding (cont.)

- Impact of unordered{..} /* context sensitive*/

let $x := ($y/a/b)[1]	the c's of a specific b parent
return unorderded { $x/c }	(in no particular order)

not equivalent to

unordered {($y/a/b)[1]/c }	the c's of "some" b
	(in no particular order)

LET Clause Folding

- Sufficient conditions for correct rewriting of … into …

(: before LET :)
let $x := expr1
(: after LET :)
return expr2

(: before LET :)
(: after LET :)
return expr2'

where expr2' is expr2
with substitution {$x => expr1}

- Expr1 does not generate new nodes
- OR $x is used
  a) only once and
  b) not part of a loop and
  c) not input to a recursive function
- Dataflow analysis required

Let Clause Unfolding

- Traditional rewriting

```
for $x := (1 to 10)
return ($input+2)+$x
```

```
let $y := ($input+2)
for $x in (1 to 10)
return  $y+$x
```

- Not so easy!
  - Same problems as beforee: side-effects, NS handling, unordered
  - Additional problem: *error handling*

```
for $x in (1 to 10)
return  if($x lt 1)
            then  ($input idiv 0)
            else  $x
```

```
let $y := ($input idiv 0)
for $x in (1 to 10)
return if ($x lt 1)
    then $y
        else  $x
```

Guaranteed only if runtime implements consistently lazy evaluation.

Otherwise dataflow analysis *and* error analysis required.

Function inlining

- Traditional FP rewriting technique

  define function f($x as xs:integer) as xs:integer 2+1

  {$x+1}

  f(2)

- Not always!
  - Same problems as for LET (NS handling, side-effects, unordered
  - Additional problems: *implicit operations (atomization, casts)*

  define function f($x as xs:double) as xs:boolean

  {$x instance of xs:double}

  f(2)

  (2 instance of xs:double) NO

- Make sure this rewriting is done *after* normalization

Constant folding

- Place constant values where the result can already be determined at compile time

```
for $x in  (1 to 10)
where $x eq 3
return $x+1
```

```
for  $x in (1 to 10)
where $x eq 3
 return (3+1)
```

Constant folding - counterexamples

```
for $x in $input/a
where $x eq 3
return <b>{$x}</b>
```

```
for $x in $input/a
where $x eq 3
return <b>{3}</b>
```

```
for $x in (1.0,2.0,3.0)
where $x eq 1
return ($x instance of xs:integer)
```

```
for $x in (1.0,2.0,3.0)
where $x eq 1
return (1 instance of xs:integer)
```

Common Sub-expressions

- Preliminary questions
  - *Same* expression ?
  - *Same* context ?
  - *Error* "equivalence" ?
  - Create the same *new nodes*?

```
for $x in $input/a/b
where $x/c lt 3
return if ($x/c lt 2)
        then if ($x/c eq 1)
               then (1 idiv 0)
               else $x/c+1
        else   if($x/c eq 0)
                then (1 idiv 0)
                else $x/c+2
```

```
let $y := (1 idiv 0)
 for $x in $input/a/b
   where $x/c lt 3
     return if($x/c lt 2)
            then if ($x/c eq 1)
                   then $y
                   else $x/c+1
            else if($x/c eq 0)
                   then $y
                    else $x/c+2
```

FLWR unnesting

- Traditional database technique

```
for $x in (for $y in $input/a/b
              where $y/c eq 3
              return $y/d)
where $x/e eq 4
return $x
```

```
for $y in $input/a/b,
     $x in $y/d
where ($x/e eq 4) and ($y/c eq 3)
return $x
```

- Problem simpler than in OQL/ODMG
  - No nested collections in XML
- Order-by more complicated

FLWR unnesting (2)

- Another traditional database technique

```
for $x in $input/a/b
where $x/c eq 3
return (for $y in $x/d)
  ($y/c eq 3)
        where $x/e eq 4
         return $y)
```

```
for $x in $input/a/b,
    $y in $x/d
where ($x/e eq 4) and
return $y
```

Type-based rewritings

- Increase the advantages of lazy evaluation
  - `$input/a/b/c` → `((($input/a)[1]/b[1])/c)[1]`
- Eliminate the need for expensive operations (e.g.,sort)
  - `$input//a/b` → `$input/c/d/a/b`
- Static dispatch for overloaded built-in functions
  - e.g. min, max, avg, arithmetics, comparisons
  - Maximizes the use of indexes
- Elimination of no-operations
  - e.g. casts, atomization, effective boolean value
- Choice of various run-time implementations for certain logical operations

Dealing with backwards navigation

- Replace backwards navigation with forward axis

```
for $x in $input/a/b
return <c>{$x/.., $x/d}</c>
```

```
for $y in $input/a,
    $x in $y/b
return <c>{$y, $x/d}</c>
```

YES

```
for $x in $input/a/b
return <c>{$x//e/..}</c>
```

??

- Enables streaming

More compiler support for efficient execution

- Streaming vs. data materialization
- Node identifiers handling
- Document order handling
- Scheduling for parallel execution

Detour/Background: Query Evaluation

- Hard to discuss special algorithms
  - Strongly depend on algebra
  - Strongly depends on the data storage, APIs and indexing

- Main issues:
  1. Streaming or materializing evaluations
  2. Lazy evaluation or not

Lazy Evaluation

- Compute expressions on demand
  - compute results only if they are needed
  - requires a **pull-based** interface (e.g. iterators)
- Example:

```
declare function endlessOnes() as integer*
  { (1, endlessOnes()) };
some $x in endlessOnes() satisfies $x eq 1
```

- The result of this program should be: `true`

Lazy Evaluation

- Lazy Evaluation also good for SQL
  - e.g., nested queries
- Particularly important for XQuery
  - existential, universal quantification (often implicit)
  - top N, positional predicates
  - recursive functions (non terminating functions)
  - if then else expressions
  - match
  - correctness of rewritings, …

Stream-based Processing

- Pipe input data through query operators
  - produce results before input is fully read
  - produce results incrementally
  - minimize the amount of memory required for the processing
- Stream-based processing
  - online query processing, continuous queries
  - particularly important for XML message routing
- Traditional in the database/SQL community

Stream based processing issues

- Streaming burning questions :
  - *push* or *pull* ?
  - Granularity of streaming ? Byte, event, item ?
  - Streaming with flexible granularity ?
- Pure streaming ?
  - Processing XQuery needs *some* data materialization
  - Compiler support to detect and minimize data materialization
- Notes:
  - Streaming + Lazy Evaluation possible
  - Partial Streaming possible/necessary

When should we materialize?

- Pipeline breakders operators (e.g. sort)
- Other conditions:
  - Whenever a variable is used multiple times
  - Whenever a variable is used as part of a loop
  - Whenever the content of a variable is given as input to a recursive function
  - In case of backwards navigation
- Those are the ONLY cases
- materialization can be *partial* and *lazy*
- Compiler can detect via dataflow analysis

How to minimize the use of node IDs?

- Node identifiers are required by the XQuery Data model but onerous (time, space)
- Solution:
  1. Decouple the node construction operation from the node id generation operation
  2. Generate node ids *only* if *really* needed
     - Only if the query contains (after optimization) operators that need node identifiers (e.g. sort by doc order, is, parent, <<) OR node identifiers are required for the result (e.g., XQuery Update Facility)
- Compiler support: dataflow analysis

How can we deal with Xpath?

- Sorting by document order and duplicate elimination required by the XQuery semantics but very expensive
- Semantic conditions
  - $document / a / b / c
    - Guaranteed to return results in doc order and not to have duplicates
  - $document / a // b
    - Guaranteed to return results in doc order and not to contain duplicates
  - $document // a / b
    - NOT guaranteed to return results in doc order but guaranteed not to contain duplicates
  - $document // a // b $document / a / .. / b
    - Nothing can be said in general

Parallel execution

```
ns1:WS1($input)+ns2:WS2($input)

for $x in (1 to 10)
return ns:WS($i)
```

- Certain expressions can be executed in parallel
  - Scheduling based on data dependency
- Parallelism *within* a single expression
  - Horizontal and vertical partitioning
- errors and paralellism is tricky
  - in particular for side-effecting expressions

XQuery expression analysis (1)

- How many times expression uses a variable?
  - potential for common subexpression factorization
- Does expression use variable in loop?
  - limits unfolding
- Is an expression a *map* on a certain variable?
  - great for parallelization
- Does expression return results in doc order?
  - eliminate unnecessary sorts
- Does expression return distinct nodes?
  - eliminate unnecessary duplicate-elims

XQuery expression analysis (2)

- Is an expression a “function”?
- Can the result of an expression contain newly created nodes ?
- Is the evaluation of an expression context-sensitive ?
- Can an expression raise user errors ?
- Is a sub expression of an expression guaranteed to be executed ?
- Etc.

Compiling XQuery vs. XSLT

- Empiric assertion : it depends on the entropy level in the data (*see M. Champion xml-dev*):
  - XSLT easier to use if the shape of the data is totally unknown (entropy *high*)
  - XQuery easier to use if the shape of the data is known (entropy *low*)
- Dataflow analysis possible in XQuery, much harder in XSLT
  - Static typing, error detection, lots of optimizations
- Conclusion: less entropy means more potential for optimization, unsurprisingly.