Flattening Nested Database Queries

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Nested array representation

```
arr    = [[1 2] [3 4 5] [] [6]]

segd   = [2 3 0 1]
data   = [1 2 3 4 5 6]
```

Flat vs Nested Data Parallelism

- Flat Parallelism: Worker function is sequential.

```
thingo xs
  = mapP (\x. x + 1) xs
```

- Nested Parallelism: Worker function is parallel.

```
thingo xss
  = mapP (\xs. zipWithP g xs ys) xss
```

- The Flattening / Vectorisation transform converts nested parallelism into flat parallelism.

The Flattening Transform

```
f :: Int -> Int
f x = x + 1

g :: Array Int -> Array Int
g ys = mapP f ys
```

The Flattening Transform

```
f :: Int -> Int
f x = x + 1

g :: Array Int -> Array Int
g ys = mapP f ys
```

```
fL :: Array Int -> Array Int
fL xs = xs +L (replicate n 1)
 where n = length xs

g :: Array Int -> Array Int
g ys = fL ys
```

The Flattening Transform

```
f :: Int -> Int
f x = x + 1

g :: Array Int -> Array Int
g ys = mapP f ys
```

```
fL :: Array Int -> Array Int
fL xs = zipWithP (+) xs (replicate n 1)
 where n = length xs

g :: Array Int -> Array Int
g ys = fL ys
```

The Flattening Transform

```
f :: Int -> Int
f x = x + 1

g :: Array Int -> Array Int
g ys = mapP f ys

h :: Array (Array Int) -> Array (Array Int)
h zss = mapP g zss
```

The Flattening Transform

```
f :: Int -> Int
f x = x + 1

g :: Array Int -> Array Int
g ys = mapP f ys

h :: Array (Array Int) -> Array (Array Int)
h zss = mapP g zss
```

```
g :: Array Int -> Array Int
g ys = fL ys

gL :: Array (Array Int) -> Array (Array Int)
gL yss = fLL yss
```

The Flattening Transform

```
f :: Int -> Int
f x = x + 1

g :: Array Int -> Array Int
g ys = mapP f ys

h :: Array (Array Int) -> Array (Array Int)
h zss = mapP g zss
```

```
g :: Array Int -> Array Int
g ys = fL ys

gL :: Array (Array Int) -> Array (Array Int)
gL yss = unconcatP yss (fL (concatP yss))
```

Nested array representation

```
arr    = [[1 2] [3 4 5] [] [6]]

segd   = [2 3 0 1]
data   = [1 2 3 4 5 1]
```

Relational Algebra: Mother Tongue—XQuery: Fluent

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ABSTRACT

This work may be seen as a further proof of the versatility of the relational database model. Here, we add XQuery to the catalog of languages which RDBMSs are able to "speak" fluently.

Given suitable relational encodings of sequences and ordered, unranked trees—the two data structures that form the backbone of the XML and XQuery data models—we describe a compiler that translates XQuery expressions into a simple and quite standard relational algebra which we expect to be efficiently implementable on top of any relational query engine. The compilation procedure is fully compositional and emits algebraic code that strictly adheres to the XQuery language semantics: document and sequence order as well as node identity are obeyed. We exercise special care in translating arbitrarily nested XQuery `FLWOR` iteration constructs into equi-joins, an operation which RDBMSs can perform particularly fast. The resulting purely relational XQuery processor shows promising performance figures in experiments.

types onto tables. Such encodings have also been proposed for *ordered, unranked trees*, the data type that forms the backbone of the XML data model. These mappings turn RDBMSs into *relational XML processors*. Furthermore, if the tree encoding is designed such that core operations on trees—XPath axis traversals—lead to efficient table operations, this can result in high-performance *relational XPath* implementations [8, 10].

In this work we extend the relational XML processing stack and propose the fully relational evaluation of XQuery [1] expressions. We give a compositional set of translation rules that compile XQuery expressions into a standard, quite primitive relational algebra. We expect any relational query engine to be able to efficiently implement the operators of this algebra. The operators were, in fact, designed to match the capabilities of modern SQL-based relational database systems (*e.g.*, the row numbering operator ϱ exactly mirrors SQL:1999 OLAP ranking functionality) [9].

By design, we only have minimalistic assumptions on the underlying tree encoding, met by several XML encoding schemes [4, 13]. Our algebra can be easily modified to oper-

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Nested XQueries

$$
s \left\{
\begin{array}{l}
\texttt{for } \$v_0 \texttt{ in (1,2) return} \\
\qquad s_0 \left\{
\begin{array}{l}
\texttt{(} \$v_0 \texttt{ ,} \\
\quad \texttt{for } \$v_{0\cdot 0} \texttt{ in (10,20) return} \\
\qquad s_{0\cdot 0} \left\{ \texttt{(}\$v_0 \texttt{,} \$v_{0\cdot 0}\texttt{)} \right. \\
\texttt{)}
\end{array}
\right.
\end{array}
\right.
$$

Nested XQueries

```
s { for $v0 in (1,2) return
       s0 { ( $v0 ,
              for $v0·0 in (10,20) return
                 s0·0 { ($v0,$v0·0)
            )
```

iter	*pos*	*item*
1	1	"1"
1	2	"10"
2	1	"1"
2	2	"20"
3	1	"2"
3	2	"10"
4	1	"2"
4	2	"20"

(a) Intermediate result in $s_{0 \cdot 0}$.

iter	*pos*	*item*
1	1	"1"
1	2	"10"
1	3	"1"
1	4	"20"
2	1	"2"
2	2	"10"
2	3	"2"
2	4	"20"

(b) Intermediate result in s_0.

iter	*pos*	*item*
1	1	"1"
1	2	"1"
1	3	"10"
1	4	"1"
1	5	"20"
1	6	"2"
1	7	"2"
1	8	"10"
1	9	"2"
1	10	"20"

(c) Final result in top-level scope.

Nested array representation

```
arr    = [[1 2] [3 4 5] [] [6]]

segd   = [2 3 0 1]
data   = [1 2 3 4 5 1]
```

Nested array representation

```
arr     = [[1 2] [3 4 5] [] [6]]

segd    = [2 3 0 1]
data    = [1 2 3 4 5 1]

segdA’ = [0 0 1 1 1 3]
segdB’ = [0 1 0 1 2 0]
```

$e ::=$	c	atomic constants
$\mid$	$\$v$	variables
$\mid$	(e,e)	sequence construction
$\mid$	$e/\alpha::n$	loc. step (axis α, node test n)
$\mid$	$\texttt{element}\ t\ \{e\}$	element constructor (tag t)
$\mid$	$\texttt{for}\ \$v\ \texttt{in}\ e\ \texttt{return}\ e$	iteration
$\mid$	$\texttt{let}\ \$v\ \texttt{:=}\ e\ \texttt{return}\ e$	let binding
$\mid$	$e+e$	addition

$e ::=$	c	atomic constants
$\mid$	`$`v	variables
$\mid$	`(`e`,`e`)`	sequence construction
$\mid$	e`/`α`::`n	loc. step (axis α, node test n)
$\mid$	**`element`** t `{`e`}`	element constructor (tag t)
$\mid$	**`for`** `$`v **`in`** e **`return`** e	iteration
$\mid$	**`let`** `$`v `:=` e **`return`** e	let binding
$\mid$	e`+`e	addition

$\pi_{a_1:b_1,\ldots,a_n:b_n}$	projection (and renaming)
σ_a	selection
$\dot{\cup}$	disjoint union
$\times$	cartesian product
$\bowtie_{a=b}$	equi-join
$\varrho_{b:\langle a_1,\ldots,a_n\rangle/p}$	row numbering
$⊿_{\alpha,n}$	XPath axis join (axis α, node test n)
ε	element construction
$\circledast_{b:\langle a_1,\ldots,a_n\rangle}$	n-ary arithmetic/comparison operator $*$
$\underline{a\,\vert\,b}$	literal table

$$\boxed{\Gamma; \mathsf{loop}; \Delta \vdash e \Mapsto (q, \Delta')}$$

$$\frac{}{\Gamma; \mathsf{loop}; \Delta \vdash c \Mapsto \left(\mathsf{loop} \times \begin{array}{c|c} pos & item \\ \hline 1 & c \end{array}, \Delta\right)} \; . \qquad \text{(Const)}$$

```
Ln[ c ] = replicate n c
```

$$\boxed{\Gamma; \mathsf{loop}; \Delta \vdash e \Mapsto (q, \Delta')}$$

$$\frac{\Gamma; \mathsf{loop}; \Delta \vdash e_1 \Mapsto (q_1, \Delta_1) \qquad \Gamma; \mathsf{loop}; \Delta_1 \vdash e_2 \Mapsto (q_2, \Delta_2)}{\Gamma; \mathsf{loop}; \Delta \vdash e_1 \;\mathsf{+}\; e_2 \Mapsto \left(\pi_{iter,pos,item:res} \left(\oplus_{res:\langle item,item' \rangle}(q_1 \Join_{iter=iter'} \left(\pi_{iter':iter,item':item} q_2\right)\right)\right), \Delta_2\right)}$$

$$\boxed{\Gamma; \mathsf{loop}; \Delta \vdash e \Mapsto (q, \Delta')}$$

$$\frac{\Gamma; \mathsf{loop}; \Delta \vdash e_1 \Mapsto (q_1, \Delta_1) \qquad \Gamma; \mathsf{loop}; \Delta_1 \vdash e_2 \Mapsto (q_2, \Delta_2)}{\Gamma; \mathsf{loop}; \Delta \vdash e_1 \text{ + } e_2 \Mapsto \left(\pi_{iter,pos,item:res}\left(\oplus_{res:\langle item,item' \rangle}(q_1 \bowtie_{iter=iter'} (\pi_{iter':iter,item':item} q_2))\right), \Delta_2\right)}$$

iter	*pos*	*item*
1	1	"1"
1	2	"10"
2	1	"1"
2	2	"20"
3	1	"2"
3	2	"10"
4	1	"2"
4	2	"20"

(a) Intermediate result in $s_{0.0}$.

iter	*pos*	*item*
1	1	"1"
1	2	"10"
1	3	"1"
1	4	"20"
2	1	"2"
2	2	"10"
2	3	"2"
2	4	"20"

(b) Intermediate result in s_0.

iter	*pos*	*item*
1	1	"1"
1	2	"1"
1	3	"10"
1	4	"1"
1	5	"20"
1	6	"2"
1	7	"2"
1	8	"10"
1	9	"2"
1	10	"20"

(c) Final result in top-level scope.

$$\Gamma; \mathsf{loop}; \Delta \vdash e \Mapsto (q, \Delta')$$

$$\frac{\Gamma; \mathsf{loop}; \Delta \vdash e_1 \Mapsto (q_1, \Delta_1) \qquad \Gamma; \mathsf{loop}; \Delta_1 \vdash e_2 \Mapsto (q_2, \Delta_2)}{\Gamma; \mathsf{loop}; \Delta \vdash e_1 \texttt{ + } e_2 \Mapsto \left(\pi_{iter,pos,item:res}\left(\oplus_{res:\langle item,item'\rangle}(q_1 \bowtie_{iter=iter'} (\pi_{iter':iter,item':item}\, q_2))\right), \Delta_2\right)}$$

iter	*pos*	*item*
1	1	"1"
1	2	"10"
2	1	"1"
2	2	"20"
3	1	"2"
3	2	"10"
4	1	"2"
4	2	"20"

(a) Intermediate result in $s_{0.0}$.

iter	*pos*	*item*
1	1	"1"
1	2	"10"
1	3	"1"
1	4	"20"
2	1	"2"
2	2	"10"
2	3	"2"
2	4	"20"

(b) Intermediate result in s_0.

iter	*pos*	*item*
1	1	"1"
1	2	"1"
1	3	"10"
1	4	"1"
1	5	"20"
1	6	"2"
1	7	"2"
1	8	"10"
1	9	"2"
1	10	"20"

(c) Final result in top-level scope.

$$L_n[\ e_1 + e_2\ ] = Ln[\ e_1\ ] +L\ Ln[\ e_2\ ]$$

$$\dfrac{\begin{array}{ll}\{\ldots, \$v_i \mapsto q_{v_i}, \ldots\}; \mathsf{loop}; \Delta \vdash e_1 \mapsto (q_1, \Delta_1) & q_v \equiv \frac{pos}{1} \times \pi_{iter:inner,item}\left(\varrho_{inner:\langle iter,pos\rangle} q_1\right) \\ \mathsf{loop}_v \equiv \pi_{iter} q_v & \mathsf{map} \equiv \pi_{outer:iter,inner}\left(\varrho_{inner:\langle iter,pos\rangle} q_1\right) \\ \multicolumn{2}{l}{\{\ldots, \$v_i \mapsto \pi_{iter:inner,pos,item}\left(q_{v_i} \bowtie_{iter=outer} \mathsf{map}\right), \ldots\} + \{\$v \mapsto q_v\}; \mathsf{loop}_v; \Delta_1 \vdash e_2 \mapsto (q_2, \Delta_2)}\end{array}}{\begin{array}{c}\{\ldots, \$v_i \mapsto q_{v_i}, \ldots\}; \mathsf{loop}; \Delta \vdash \texttt{for } \$v \texttt{ in } e_1 \texttt{ return } e_2 \mapsto \\ \left(\pi_{iter:outer,pos:pos_1,item}\left(\varrho_{pos_1:\langle iter,pos\rangle / outer}\left(q_2 \bowtie_{iter=inner} \mathsf{map}\right)\right), \Delta_2\right)\end{array}}$$

(FOR)

Purely Relational FLWORs

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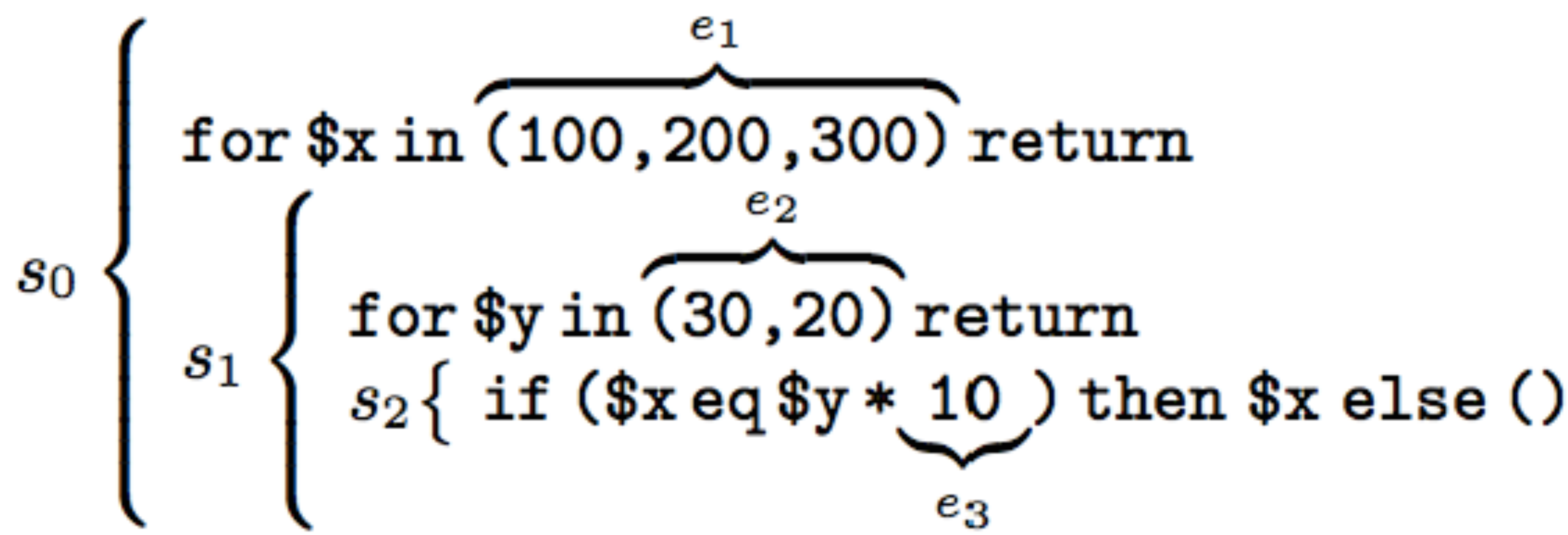
ABSTRACT

We report on a compilation procedure that derives relational algebra plans from arbitrarily nested XQuery FLWOR blocks. While recent research was able to develop relational encodings of trees which may turn RDBMSs into highly efficient XPath and XML Schema processors, here we describe *relational encodings of nested iteration*, *variables*, and the *item sequences* to which variables are bound. The developed techniques are *purely relational* in more than one sense: (a) we rely on a standard (or rather: classical) algebra that is readily supported by relational engines, and (b) we use re-

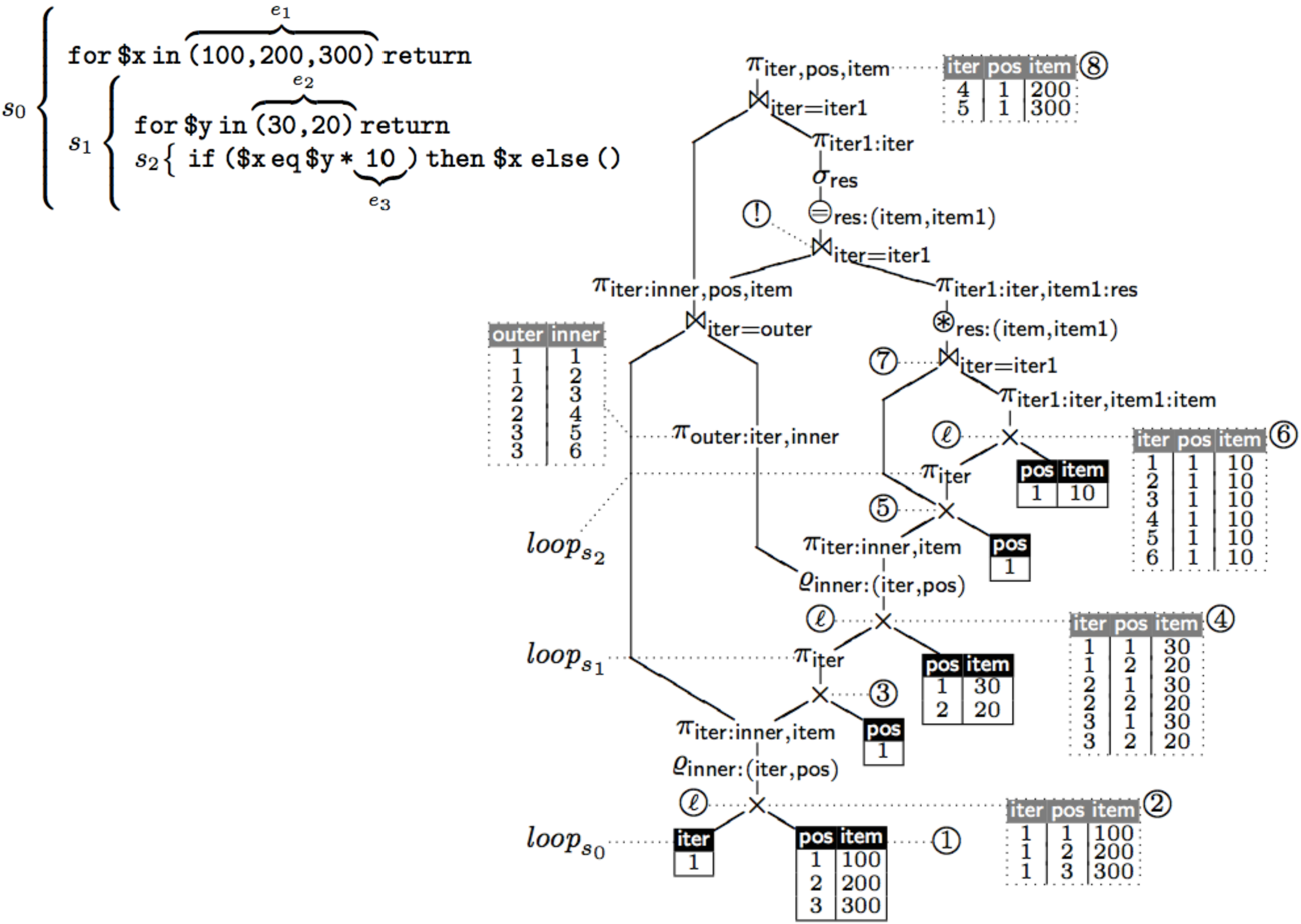
other benefits, the resulting systems inherit the scalability of the underlying relational back-ends [3]. It is legitimate to hope that this technology may be developed into full-fledged XQuery implementations, given that we can find relational ways to also express XQuery concepts beyond XPath axis traversals.

To this end, this paper does *not* talk about XPath evaluation at all but shifts focus to *the* central XQuery language feature, the `for-let-where-order by-return` (or FLWOR) block [2]. The presence of arbitrarily nested iteration as well as the possibility to bind and then refer to variables in

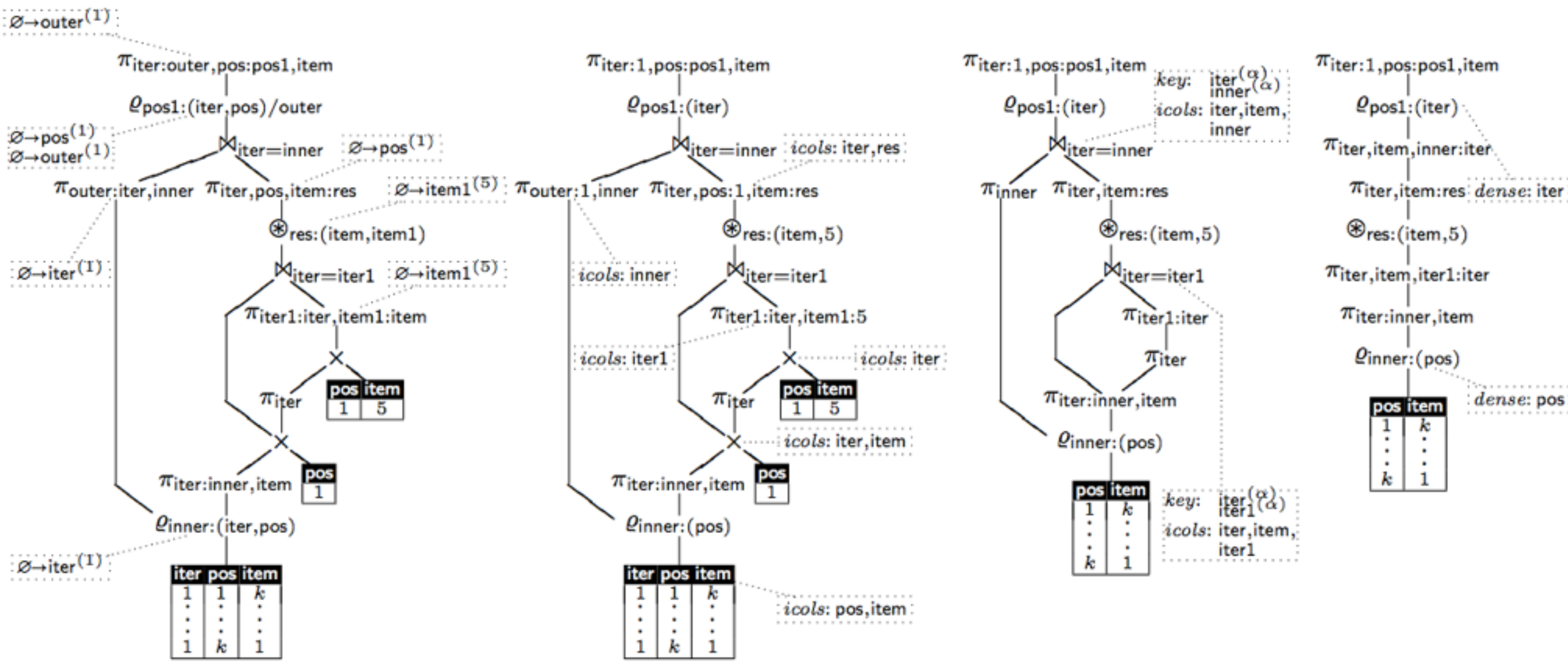
XIME-P 2005, June 16–17, Baltimore, Maryland.



s_0
e_1
for $x in (100,200,300) return
s_1
e_2
for $y in (30,20) return
s_2
if ($x eq $y * 10) then $x else ()
e_3



for $x in (100,200,300) return
for $y in (30,20) return
if ($x eq $y * 10) then $x else ()
e1
e2
e3
s0
s1
s2
π iter,pos,item
⋈ iter=iter1
π iter1:iter
σ res
= res:(item,item1)
!
⋈ iter=iter1
π iter:inner,pos,item
π iter1:iter,item1:res
⋈ iter=outer
* res:(item,item1)
⋈ iter=iter1
π iter1:iter,item1:item
π outer:iter,inner
π iter
ϱ inner:(iter,pos)
π iter:inner,item
π iter
π iter:inner,item
ϱ inner:(iter,pos)
loop s2
loop s1
loop s0
ℓ
1 2 3 4 5 6 7 8
iter pos item: 4 1 200; 5 1 300
outer inner: 1 1; 1 2; 2 3; 2 4; 3 5; 3 6
iter pos item: 1 1 10; 2 1 10; 3 1 10; 4 1 10; 5 1 10; 6 1 10
pos item: 1 10
pos: 1
iter pos item: 1 1 30; 1 2 20; 2 1 30; 2 2 20; 3 1 30; 3 2 20
pos item: 1 30; 2 20
pos: 1
iter: 1
pos item: 1 100; 2 200; 3 300
iter pos item: 1 1 100; 1 2 200; 1 3 300


∅→outer(1)
πiter:outer,pos:pos1,item
ϱpos1:(iter,pos)/outer
∅→pos(1)
∅→outer(1)
⋈iter=inner
∅→pos(1)
πouter:iter,inner
πiter,pos,item:res
∅→item1(5)
⊛res:(item,item1)
∅→iter(1)
⋈iter=iter1
∅→item1(5)
πiter1:iter,item1:item
πiter
pos item
1 5
pos
1
πiter:inner,item
ϱinner:(iter,pos)
∅→iter(1)
iter pos item
πiter:1,pos:pos1,item
ϱpos1:(iter)
⋈iter=inner
icols: iter,res
πouter:1,inner
πiter,pos:1,item:res
⊛res:(item,5)
icols: inner
⋈iter=iter1
πiter1:iter,item1:5
icols: iter1
icols: iter
icols: iter,item
ϱinner:(pos)
icols: pos,item
key: iter(α) inner(α)
icols: iter,item, inner
πinner
πiter,item:res
πiter1:iter
key: iter(α) iter1(α)
icols: iter,item, iter1
πiter,item,inner:iter
dense: iter
πiter,item,iter1:iter
dense: pos

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FERRY — Database–Supported Program Execution

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```
let e = table Employees (id int, name string,
                         dept string, salary int)
        with keys ((id))
 in for x in e
    group by x.dept
    return (the (x.dept),
             take (2, for y in zip (x.name, x.salary)
                      order by y.2 descending
                      return y))
```


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Haskell Boards the Ferry

Database-Supported Program Execution for Haskell

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2010

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A study of the exact relationship between DPH and DSH still lies ahead. We conjecture that DSH's loop-lifting compilation strategy does have an equivalent formulation in terms of vectorisation or Blelloch's flattening transformation [4].

$$
\begin{array}{ll}
\mathit{fst}\hat{} & :: [:(a,b):] \rightarrow [:a:] \\
\mathit{snd}\hat{} & :: [:(a,b):] \rightarrow [:b:] \\
\mathit{bpermuteP} & :: [:a:] \rightarrow [:\mathit{Int}:] \rightarrow [:a:]
\end{array}
$$

$$
\begin{array}{l}
\textbf{let}\ sv = [:(1,0.1),(3,1.0),(4,0.0):] \\
\quad\ \ v\ = [:10,20,30,40,50:] \\
\textbf{in} \\
\quad \mathit{sumP}\ (\mathit{snd}\hat{}\ sv *\hat{}\ \mathit{bpermuteP}\ v\ (\mathit{fst}\hat{}\ sv))
\end{array}
$$

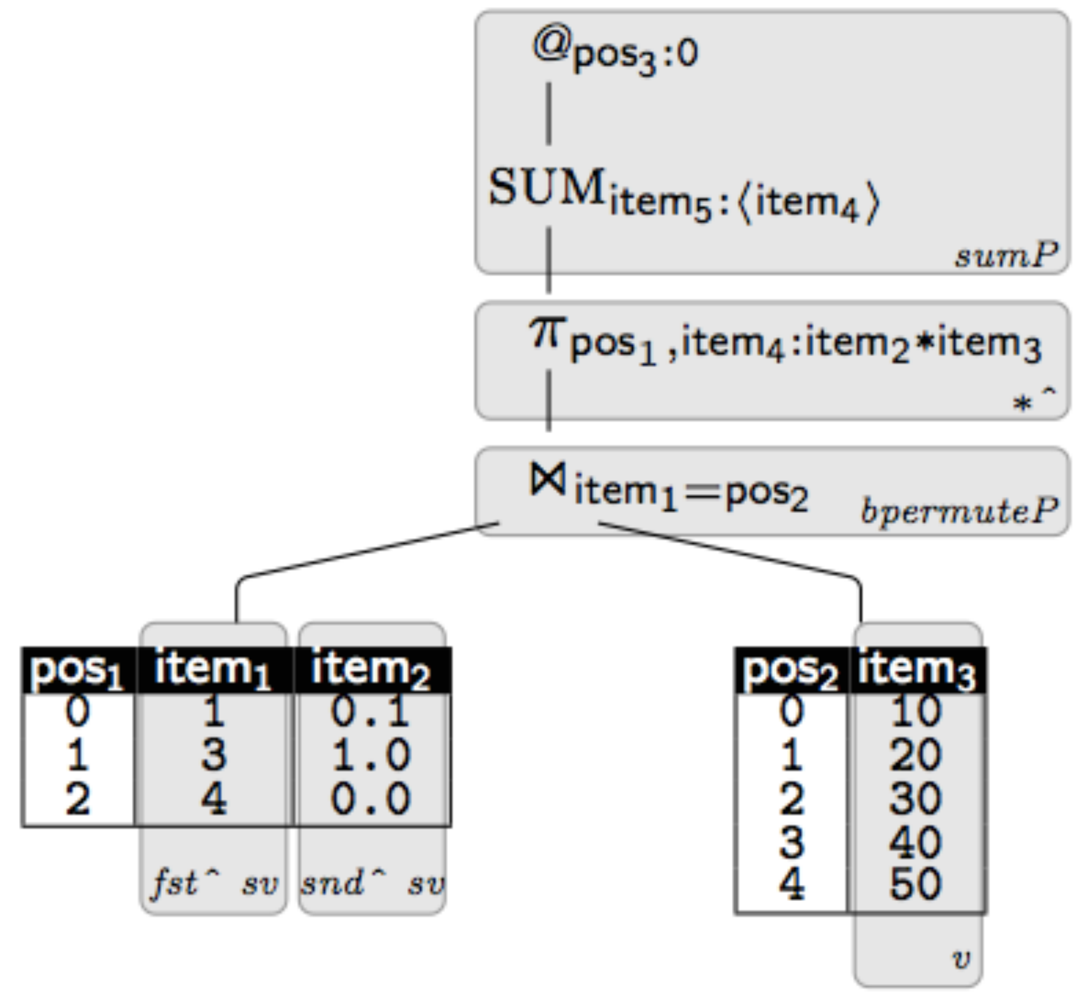

Fig. 6. Intermediate code generated for the sparse vector multiplication example of Fig. 5: DPH (left) *vs.* DSH (right).