Enabling Compiler
Transformations for pSather 1.1

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TR-95-040
August 1995

Abstract
pSather 1.1 [2] is a parallel extension of the object-oriented sequential programming
language Sather 1.1 [1]. A compiler for sequential Sather is available which is written
in Sather. This document describes the basic ideas of the extensions of the sequential
Sather compiler to handle pSather programs and is thus a high-level documentation
of parts of the pSather compiler. Most of the transformations are presented in form
of a transformation from pSather to Sather.

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1 Introduction

Throughout this document we assume that the reader is familiar with the language definitions of sequential Sather 1.1 [1] and the parallel extension pSather 1.1 [2].

Conceptually, the transformation of pSather to Sather is organized in phases, each of which deals with a separate problem of the translation. The document’s organization reflects these phases. Note however, that a phase does not correspond with a pass of compilation. Instead the implementation achieves all transformations in a single pass.

**Phase I.** The first phase of the transformation focuses on pSather’s memory consistency model. The memory consistency model of pSather offers a shared address space to the programmer. But it is not a sequentially consistent shared memory model because changes to object attributes are in general not immediately visible to all threads. The language specification associates *import* and *export* operations with various language constructs and operations.

The goal of the first phase of the transformation of pSather’s memory consistency model is to make these operations explicit, i.e., instead of associating import and export operations with language constructs and operations, functions of the SYS class are called explicitly.

The transformations of the first phase are described in section 2.

**Phase II.** In the second phase threads are transformed into routines or functions. This is relevant for all pSather implementations since most available thread packages require a correspondence between threads and functions. Local variables which are visible at the point of thread creation in pSather must be made accessible in the resulting routine. We decided to pass these local variables into the new routine by use of newly created objects, so called helper objects.

The transformations of the second phase are described in sections 3 to 5.

In this part of the document, we assume that the Sather compiler targets a run-time system that offers threads and mechanisms for blocking and synchronization. Hence, we rely on a mechanism for starting routines concurrently that are implemented in sequential Sather.

**Phase III.** In section 6 we focus on the declaration of helper objects and discuss the access to attributes of these helper objects. The transformation is context sensitive and behaves differently for different nestings of *par*, *fork*, and *attach* statements. The declaration of helper objects, their packing and unpacking, and the update of attributes is described in detail in section 6.

Finally, section 7 discusses a pSather implementation of the producer-consumer problem and presents the result of all transformation phases.
2 Transformation of pSather’s Memory Consistency Model

The first phase of the transformation focuses on pSather’s memory consistency model. The memory consistency model of pSather offers a shared address space to the programmer. But it is not a sequentially consistent shared memory model because changes to object attributes are in general not immediately visible to all threads. The language specification associates import and export operations with various language constructs and operations.

The goal of the memory model transformation is to make these operations explicit, i.e., instead of associating import and export operations with language constructs and operations, functions of the SYS class are called explicitly. In the remainder of this section we describe transformation templates that implement pSather’s memory consistency model.

Let us first look at the import and export rules as defined in the pSather language specification. An import occurs:

<table>
<thead>
<tr>
<th>Rule</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imp1</td>
<td>in a newly created thread,</td>
</tr>
<tr>
<td>Imp2</td>
<td>on exiting a par statement (children have terminated),</td>
</tr>
<tr>
<td>Imp3</td>
<td>on entering one of the branches of a lock statement,</td>
</tr>
<tr>
<td>Imp4</td>
<td>on exiting exclusive GATE and GATE{T} operations, and</td>
</tr>
<tr>
<td>Imp5</td>
<td>on completion of a sync statement.</td>
</tr>
</tbody>
</table>

An export occurs:

<table>
<thead>
<tr>
<th>Rule</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp1</td>
<td>in a parent thread when a child thread is forked,</td>
</tr>
<tr>
<td>Exp2</td>
<td>by a thread on termination,</td>
</tr>
<tr>
<td>Exp3</td>
<td>on exiting a lock statement,</td>
</tr>
<tr>
<td>Exp4</td>
<td>on entering an unlock statement,</td>
</tr>
<tr>
<td>Exp5</td>
<td>on entering exclusive GATE and GATE{T} operations, and</td>
</tr>
<tr>
<td>Exp6</td>
<td>on initiation of a sync statement.</td>
</tr>
</tbody>
</table>

In the remainder of this section we present transformation templates for all relevant constructs of pSather.

The transformation templates map pSather programs into pSather programs, since SYS::import and SYS::export are legitimate pSather statements. Moreover, because repetitions of one of these calls are semantically equivalent to a single call, the semantics of a given pSather program is not changed by adding these calls explicitly where implicit import or export operations are defined by the language.

For notational purposes, we define a new language pSather_{ie}, which is pSather without the association of import and export to constructs and operations. Therefore, if in pSather_{ie} a thread changes an attribute of an object, another thread is only guaranteed to observe this change, if (1) the first thread has executed an explicit export operation, if (2) the second thread has executed an explicit import operation, and if (3) export and import have occurred in this temporal order.

In the code fragments shown below the left hand side shows the given pSather code. The right hand side shows pSather_{ie} code which is the result of the transformation. The explanations of the transformation use the rule identifiers given in the above tables.
2.1 Constructs Dealing with Threads

2.1.1 Memory Model Transformation of \texttt{par} Statements

\[
\text{par} \quad \rightarrow \quad \text{par}\_\text{re}
\]

\[
\begin{array}{ll}
\text{par} & \text{SYS}::\text{export}; \\
\text{stmts}_1 & \text{SYS}::\text{import}; \\
\text{end} & \text{SYS}::\text{export}; \\
\end{array}
\]

The language specification defines that the body of a \texttt{par} statement is (conceptually) executed by a new thread. Therefore, rule \texttt{Exp1} requires an export immediately before the \texttt{par} statement (line 1). Analogously, rule \texttt{Imp1} results in an import at the beginning of the body (line 3). Due to rule \texttt{Exp2}, the new thread must export changes before termination (line 5). These changes must be imported after the \texttt{par} in line 7 because of rule \texttt{Imp2}.

Note that the new thread cannot legally terminate inside of \texttt{stmts}_1 since the use of \texttt{return}, \texttt{yield}, and \texttt{quit} is not allowed inside the body of a \texttt{par} statement. Moreover, iters can only be called inside the body of the \texttt{par} statement if the enclosing \texttt{loop} statement is as well inside the body of the \texttt{par} statement. Exceptions are not an issue with respect to thread termination. If the programmer does not catch exceptions with explicit \texttt{protect} statements in the body of the \texttt{par} (and hence before the termination of the thread) these exceptions are considered to be fatal errors. Since the program is terminated in presence of such exceptions, no export operation must be called.

Other than the mentioned rules \texttt{Imp1}, \texttt{Imp2}, \texttt{Exp1}, and \texttt{Exp2}, no memory consistency model rules must be applied when transforming a \texttt{par} statement.

2.1.2 Memory Model Transformation of \texttt{fork} Statements

\[
\text{fork} \quad \rightarrow \quad \text{fork}\_\text{re}
\]

\[
\begin{array}{ll}
\text{fork} & \text{SYS}::\text{export}; \\
\text{stmts}_1 & \text{SYS}::\text{import}; \\
\text{end} & \text{SYS}::\text{export}; \\
\end{array}
\]

The memory model transformation of the \texttt{fork} statement results from the same rules \texttt{Imp1}, \texttt{Exp1}, and \texttt{Exp2} as the memory model transformation of the \texttt{par} statement shown above.

The difference is that after the \texttt{fork} statement no import is required. Hence, unless caused by other import or export rules that might be hidden in \texttt{stmts}_1, there is no specific point in the program at which the thread that executes the \texttt{fork} statement will become aware of changes made by the forked thread. However, since \texttt{fork} statements may only occur inside the body of a \texttt{par} statement, the closing import caused by the \texttt{par} statement makes sure that these changes are seen by the originating thread.

Note again, that the new thread cannot legally terminate inside of \texttt{stmts}_1 since the use of \texttt{return}, \texttt{yield}, and \texttt{quit} is not allowed inside the body of a \texttt{fork} statement. Again, iters can only be called inside the body of the \texttt{fork} statement if the enclosing \texttt{loop} statement is as well inside the
body of the fork statement. Because of the same reasons given for the par statement, exceptions are not an issue with respect to thread termination inside of the body of the fork.

2.1.3 Memory Model Transformation of attach Statements

Although the right hand side of an attach statement can be a complex expression, let us assume for now and without loss of generality that the right hand side is simply a function call.

The given transformation template is incomplete and only suggestive because such a definition of new routines induces additional problems due to local variables. Since this problem will be solved in section 3 we – for now – postpone the presentation of a complete transformation template.

\[ pSather \rightarrow pSather_{ie}, \text{ incomplete} \]

| expr1 :- operation; | SYS::export; \(1\) |
| expr1 :- operation’; -- ie | \(2\) |
| \(\text{operation’} = \) | \(101\) |
| SYS::import; | \(102\) |
| tmp := operation; | \(103\) |
| SYS::export; | \(104\) |
| return tmp; | \(105\) |

The memory model transformation of attach statements is slightly more complicated. Although the same rules Imp1, Exp1, and Exp2 apply to the attach statement as they do to the fork statement, the transformation requires more work since pSather allows only expressions on the right hand side of the attach statement. Hence, simply adding additional statements is not possible.

To circumvent this problem, we define a new routine operation’ that has the necessary import and export calls. Instead of attaching operation to the gate determined by evaluation of expr1, the new routine operation’ is attached.

Note, that there is no explicit import operation after the asynchronous call of operation’ in line 2. The reason is, that the originating thread proceeds without waiting for the newly created thread. The two threads synchronize, when the originating thread uses an exclusive gate operation to access the result of operation’ which is stored in the gate. See section 2.3 for the transformation templates used to implement rules Exp4 and Imp4 of pSather’s memory consistency model.

2.2 Constructs Dealing with Locks

2.2.1 Memory Model Transformation of lock Statements

Rule Imp3 requires an import when entering a branch of a lock statement. This is implemented in lines 3, 7, and 11 of the following (incomplete and only suggestive) transformation template. Rule Exp3 results in export in lines 5, 9, and 13 at the end of the branches of the lock statement.

Other than the mentioned rules Imp3 and Exp3, no memory consistency model rules must be applied when transforming the lock statement.
\[ pSather \rightarrow pSather_{\text{c}}, \text{ incomplete} \]

```plaintext
lock
  guard <expr> when <lck\_list_1> then
    stmts_1
  when <lck\_list_2> then
    stmts_2
  else
    stmts_3
end
```

However, simply inserting an export call as the last statement of all branches of the `lock` statement is often incorrect. The export must occur whenever the body can be left by the control flow.

This is the case for `return`, `quit` and `raise` statements. (The `yield` statement is not allowed in the `lock` statement.) Moreover, the control flow can leave the `lock` statement if an `iter` is called inside the `lock` statement but the enclosing `loop` is outside the `lock` statement. To implement this requirement, the statement list `stmts_1`, `stmts_2`, and `stmts_3` must be processed as shown in the following pseudo code:

\[ pSather_{\text{c}} \rightarrow \text{ Transformation Algorithm append\textunderscore export:} \]

```plaintext
append\_export(stmt\_list.mode) is
  -- process all statements in stmt\_list sequentially
  s:=stmt\_list.first.stmt;
  loop
    if is\_in\_loop\_and\_contains\_iter\_call(s) then
      insert\_export\_stmt\_before(s);
    end;
    typecase $
      when RETURN\_STMT, QUIT\_STMT, RAISE\_STMT then
        insert\_export\_stmt\_before(s);
      when STMT\_WITH\_BODIES then
        loop append\_export(s.bodies!, on\_exit\_only) end;
    end;
    until!(void(s.next)); s:=s.next;
  end;
  -- work on last statement of stmt\_list
  if mode /= on\_exit\_only then
    typecase $
      when RETURN\_STMT, QUIT\_STMT, RAISE\_STMT then -- done
      else
        insert\_export\_after(s);
      end
    end;
  end;
end;
```
Algorithm Description. The \texttt{loop} in lines 4 to 15 processes the statements in \texttt{stmt_list}. If the current statement (s) contains an iter call we add a (speculative) export in front of this statement. See lines 5 to 7. This export is only required by rule \texttt{Exp3} if the control flow really leaves the \texttt{lock} statement. However, since we cannot know this during the transformation, we add a potentially unnecessary export. The \texttt{typecase} statement in lines 8 to 13 handles all other statements that might result in leaving the \texttt{lock} statement. In front of \texttt{return}, \texttt{quit}, and \texttt{raise} statements an export is added (lines 9 and 10). For statements that have bodies of their own, for example the \texttt{if} statement, all their bodies are processed recursively. The difference is that their bodies are processed in \texttt{on_exit_only} mode. In this mode, only the transformation described so far is applied to the statement list.

For the top level statement list of the \texttt{lock} statement however, \texttt{append_export} is called in \texttt{with_final_export} mode. This mode makes sure, that at least one export is called at the end of the branch of the \texttt{lock} statement. See lines 17 to 23. The final export is only added if the last statement of the list does not cause an export itself. Moreover, the semantics of sequential Sather prohibits the existence of statements after \texttt{return} and \texttt{raise}.

Implementation Restriction.

Although pSather requires that the export occurs immediately upon leaving the \texttt{lock} statement, the statement based transformation might cause some problems. Imagine a \texttt{return} statement that returns a value. However, let this value be provided by a function call that itself changes some global state. The transformation presented above will not export these changes because the export is called before the return statement. This could be corrected by evaluating the expression of the \texttt{return} statement into a newly introduced temporary variable first, i.e. before the export operation. The return statement then would return the new temporary variable. Similar effects might occur in statements that accomplish work before calling an iter. Again, since the export is already done the current implementation will not export the accomplished work. Similar to the return statement, the transformation could easily be extended to cover this case correctly.

Now we are equipped to present the complete transformation template for the \texttt{lock} statement. In line 4 the statement list \texttt{stmts_1} is transformed by the algorithm we have just described. The recursive algorithm is called in \texttt{with_final_export} mode to make sure that there is at least one export after the statements in \texttt{stmts_1} unless the type of last statement prohibits this. The same transformation algorithm is called for \texttt{stmts_2} (in line 7) and \texttt{stmts_3} (in line 10).

\[
pSather \rightarrow pSather_{re}
\]

\begin{verbatim}
lock
guard <expr> when <lck_list_1> then
stmts_1
when <lck_list_2> then
stmts_2
else
stmts_3
end

lock
guide <expr> when <lck_list_1> then
SYS::import;
append_export(stmts_1 with final_export);
when <lck_list_2> then
SYS::import;
append_export(stmts_2 with final_export);
else
SYS::import;
append_export(stmts_3 with final_export);
end;
\end{verbatim}
2.2.2 Memory Model Transformation of unlock Statements

\[
pSather \rightarrow pSather_{ie}
\]

<table>
<thead>
<tr>
<th>unlock &lt;lck&gt;;</th>
<th>SYS::export;</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>unlock &lt;lck&gt;;</td>
<td>SYS::import;</td>
<td>2</td>
</tr>
</tbody>
</table>

Only rule Exp4 is applicable to the unlock statement. Before executing an unlock statement, an export must occur.

2.2.3 Memory Model Transformation of sync Statements

\[
pSather \rightarrow pSather_{ie}
\]

| sync; | SYS::export; | 1 |
| sync; | SYS::import; | 3 |

Rule Imp5 causes an import in front of the sync statement. Similarly, rule Exp6 is applicable and causes the export operation immediately after the sync operation in pSather_{ie}.

2.3 Exclusive Gate Operations

Rules Imp4 and Exp5 require that exclusive gate operations are surrounded by export and import operations. Exclusive gate operations are operations that work on the queue of a gate (set, get, enqueue, and dequeue).

To implement the requirement that exclusive gate operations are immediately surrounded by export and import, expressions must be broken up into sequences of individual statements with temporary variables, isolating the gate operation. After the isolation of exclusive gate operations in individual statements, the statement containing the gate operation can easily be immediately surrounded by export and import.

**Implementation Restriction.**

Although pSather requires that these operations are immediately surrounded by export and import, the implemented transformation is slightly weaker. Instead of immediately surrounding exclusive gate operations, we surround the statement that contains the exclusive gate operation.

The difference only becomes visible if a program relies on the order of execution of expressions. For example, in cases like g.get + x, where x is changed by a different thread and the import caused by get is essential for the correct behavior of the program.

This implementation restriction requires a special treatment of the if statement which is presented in section 2.3.2.

2.3.1 Memory Model Transformation of Exclusive Gate Operations

\[
pSather \rightarrow pSather_{ie}
\]

| stmt_with_exclusive_gate_op; | SYS::export; | 1 |
| stmt_with_exclusive_gate_op; | SYS::import; | 3 |
Rule \textbf{Exp5} requires that before the statement with the exclusive gate operation an export is added to the code. Rule \textbf{Imp4} results in an import after that statement.

Similar to the special treatment of the \texttt{return} and \texttt{raise} statement in the transformation algorithm \texttt{append\_export}, the import is not necessary if the statement with the exclusive gate operation is a \texttt{return} or \texttt{raise} statement. Moreover, the semantics of sequential Sather in that case prohibit the added call of \texttt{SYS:import}. The specific transformation templates are given below:

\[
p\text{Sather} \longrightarrow p\text{Sather}_{\text{re}}
\]

<table>
<thead>
<tr>
<th>\text{Return Statement}</th>
<th>\text{Transformed Statement}</th>
<th>\text{Line}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{return expr_with_exclusive_gate_op;}</td>
<td>\text{SYS:export;}</td>
<td>1</td>
</tr>
<tr>
<td>\text{return expr_with_exclusive_gate_op;}</td>
<td>\text{SYS:export;}</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>\text{Raise Statement}</th>
<th>\text{Transformed Statement}</th>
<th>\text{Line}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{raise expr_with_exclusive_gate_op;}</td>
<td>\text{SYS:export;}</td>
<td>1</td>
</tr>
<tr>
<td>\text{raise expr_with_exclusive_gate_op;}</td>
<td>\text{SYS:export;}</td>
<td>2</td>
</tr>
</tbody>
</table>

2.3.2 Exclusive Gate Operations in if Statements

Without isolation of the exclusive gate operation in a separate statement, the if statement needs a special treatment\(^1\). Otherwise the effects of the evaluation of a condition with an exclusive gate operation might be invisible in the branches of the if statement.

\[
p\text{Sather} \longrightarrow p\text{Sather}_{\text{re}}
\]

<table>
<thead>
<tr>
<th>\text{If with Exclusive Gate}</th>
<th>\text{Transformed Statement}</th>
<th>\text{Line}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{end;}</td>
<td>\text{SYS:export;}</td>
<td>1</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>2</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>3</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>4</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>5</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>6</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:export;}</td>
<td>1</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>2</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>3</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>4</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>5</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>6</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>7</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>8</td>
</tr>
</tbody>
</table>

Export rule \textbf{Exp5} results in the leading export in line 1. The import operation required by rule \textbf{Imp4} results in the two imports. An import occurs before the statements of the then part (line 3). If there is no else part, then an additional import must occur after the if statement (line 6).

\[
p\text{Sather} \longrightarrow p\text{Sather}_{\text{re}}
\]

<table>
<thead>
<tr>
<th>\text{If with Exclusive Gate}</th>
<th>\text{Transformed Statement}</th>
<th>\text{Line}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:export;}</td>
<td>1</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>2</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>3</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>4</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>5</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>6</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>7</td>
</tr>
<tr>
<td>\text{if cond_with_exclusive_gate_op then} \text{stmts_1;} \text{else} \text{stmts_2} \text{end;}</td>
<td>\text{SYS:import;}</td>
<td>8</td>
</tr>
</tbody>
</table>

If there is an else part then the second import occurs inside the else part (line 6) instead of after the if statement.

---

\(^1\)Since the case statement is syntactic sugar based on the if statement, we do not consider the case statement in more detail.
Transformation of pSather’s Threads

Threads can be created in pSather in three ways. One way is the attach statement, the second way is the par statement, and the third way is the fork statement. The basic idea of a transformation used in the pSather compiler is to replace these statements with sequential Sather statements: the attach statement, the par statement, and the fork statement are replaced with routines. This is necessary for most thread packages that can be used to implement a run-time system since only routines can be associated with run-time system threads in these packages.

The target language of this second step of transformation is called pSather_{co-thread}. This language is pSather without par, fork, and attach statements and without cohort. Instead of these statements the language offers a macro THREAD with four arguments. The first argument is the name of a function to be called concurrently. The second argument is the helper object as defined below. The third argument denotes the gate to which the new thread is attached. Finally, the fourth argument of the macro is the cluster number which should be used to execute the new thread.

3 Transformation of attach Statements

3.1 Basic Transformation Principle

When presenting the pSather-to-pSather_{co} transformation for attach statements, we have already mentioned that a new routine is created. Here we complete the transformation template.

The following fragment shows pSather code. When routine r is executed, the running thread spawns a new thread in line 7 that executes the expression operation concurrently. On a parallel machine, operation is supposed to be evaluated on cluster p. The result of this evaluation is enqueued into the gate object resulting from the evaluation of expr1. The expression operation can be quite complex since it can contain routine calls and the use of local variables declared inside the routine r. The local variable local which is declared in line 3 is an example.

Original pSather Code:

```plaintext
class X is
    r is
        local : TYPE_OF_LOCAL := val;
        --
        -- some code
        --
        expr1 := operation @ p;
        --
        -- some code (2)
        --
        end; -- of r
        -- more class elements
    end; -- of class X
```

Moving the evaluation of operation into a new routine as required by the transformation to pSather_{co} requires that all the objects and variables which are visible at the point of the attach statement are passed into the new routine.
The transformation presented here achieves the visibility of locals in the new routine by use of helper objects. The attach statement is replaced by several statements, see lines 28 to 33.

First, the left hand side of the attach statement is transformed. In line 28, the expression expr is evaluated into a new gate object g of type GATE{T} whereby T is the resulting type of operation. In general, this is not necessary, if expr already is a gate. However, since expr could be a complex expression which might block during its evaluation, we choose to evaluate expr first, before we continue to transform the attach statement.

After creation of the gate, a new helper object is created in line 29, then all visible local variables declared inside the routine r (and all parameters of r if there were any) are copied into this helper object (lines 30 to 31). The Helper class is specific to the transformed attach statement. Transformation of other attach statements in general result in additional (and often different) helper classes and objects. The copy operations are called packing of the helper object. Due to the transformation to pSather, an explicit export operation is added in line 32.

Finally, THREAD is a macro that starts a new thread. The new thread concurrently executes the function fct(helper,g) at cluster p. In pSather semantics, the new thread is considered to be attached to gate g. If the p-expression and the cluster number are missing, the thread is supposed to run on the same cluster as the calling thread.

pSather thread Code after Transformation:

```plaintext
class X is
  r is
    local : TYPE_OF LOCAL := val;
    --
    -- some code
    --
    g : GATE{T} := expr;
    helper := #HELPER;
    helper.local := local;
    -- ...
    SYS: export;
    THREAD(fct.helper,g,p); -- concurrently executable
    --
    -- some code (2)
    --
  end; -- of r
  -- more class elements
private fct(helper.HELPER, g:GATE{T}) is
  local : TYPE_OF LOCAL;
  SYS: import;
  local := helper.local;
  tmp := operation;
  g.enqueue(tmp);
  -- maybe: helper.local := local;
  SYS: export;
end; -- of fct
end; -- of class X
```

In the routine fct (lines 39ff) the helper object is unpacked after an initial import operation, i.e., first local variables are declared that mirror the local variables which have been visible at the point of the original attach statement (line 40). Afterwards the helper object is unpacked, i.e., the newly
declared variables are filled (line 42). Then the expression operation is evaluated (line 43), the resulting value is enqueued into the gate g in line 44. Before the final export operation in line 46 which is required by the transformation to pSather, the affected local variables are copied back into the helper object. This is required in pSather 1.1 because of inout parameters. If operation would have had local as an inout argument, then the value of local could have changed. Rules for packing and unpacking of helper objects are discussed in more detail in section 3.2.

Note that the enqueue operation itself requires to be enclosed between export and import operations (see 2.3.1). Both operations however, can be omitted due to redundancy.

For the helper object a class must be defined that has an attribute for each local variable to be passed into the newly declared function.

```plaintext
class HELPER is
  attr local: TYPE OF LOCAL;
  -- ...
  create: SAME is
    return new;
  end: -- of create
end: -- of HELPER
```

The transformation of the right hand side expression of the attach relies on the fact that the pSather specification does not allow it to be called in the right hand side expression. Otherwise the transformation would result in an iter which is called in a routine without being textually enclosed in a loop statement.

Rationale for helper objects: The use of helper objects and the packing and unpacking of values seems to introduce more complexity than necessary. An alternative transformation could pass the locals as arguments into the new routine. However, there are several reasons for the introduction of helper objects. The first reason is the intended simplicity of the run-time system. Passing all locals via routine arguments would require that the thread creation mechanism of the run-time system could deal with an arbitrary number and worse, arbitrary type of arguments. By always passing a fixed number of arguments, i.e. routine name, helper object, gate, and cluster number, the interface is much simpler. A reason for unpacking is the intended simplicity of the transformation process: Instead of processing the original expression operation and replacing all accesses to local variables with accesses of attributes of the helper object, the expression operation can be copied textually into the body of the new routine. Another reason is efficiency: moving the whole helper object to the cluster that hosts the new thread and then working with local variables is in general much faster than always going through an additional level of indirection. The fourth reason, however, is orthogonality. Similar helper objects will be used in the transformation of both par and fork statements, where argument passing is insufficient as will be shown in sections 4 and 5.

Optimization: By data flow analysis the export of local variables could easily be optimized: Instead of passing all visible local variables and parameters through the helper object into the thread that implements the right hand side of the attach statement, only those must be copied that are used in the right hand side expression. However, for simplicity of both the presentation and the transformation we pass all local variables here.

3.2 Helper Objects in pSather’s Memory Consistency Model

As discussed in section 2 the memory consistency model of pSather requires that threads which use variables that are shared between threads import and export changes to these variables at certain points of the code. Every transformation must ensure a correct implementation of this memory consistency model.
By introducing explicit import and export operations into the code, the implementation of these routines must guarantee that changes to any objects will be observed correctly. The SYS routines however cannot guarantee correct import and export behavior between local variables and helper objects.

Therefore, the transformation from pSather\textsubscript{le} to pSather\textsubscript{le+thread} works in two steps, both of which have been applied above. In the first step, helper objects are created and threads are replaced by routines. However, the helper objects are neither packed nor unpacked.

In the second step, import and export operations which are either present in the original pSather program or might have resulted from the transformation to pSather\textsubscript{le} are expanded:

<table>
<thead>
<tr>
<th>Rule</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hlp1</td>
<td>Whenever an explicit import operation is encountered, immediately after this import operation the helper object is unpacked, i.e., the local variables are set according to the values of the helper object.</td>
</tr>
<tr>
<td>Hlp2</td>
<td>Whenever a routine is called which has an import operation in its transitive closure of calls, immediately after this routine call the helper object is unpacked.</td>
</tr>
<tr>
<td>Hlp3</td>
<td>Whenever a local variable is changed (either by an assignment to it or by using it as an inout argument) and this variable is also available in a helper object, immediately after this change the corresponding attribute of the helper object is updated.</td>
</tr>
<tr>
<td>Hlp4</td>
<td>If both Hlp2 and Hlp3 must be applied after a routine call, rule Hlp3 must be obeyed first.</td>
</tr>
</tbody>
</table>

In section 6 we will present in more detail what it means to pack/unpack/update helper objects in the general case, i.e., for arbitrary nestings of \texttt{par}, \texttt{fork}, and \texttt{attach} statements.

\textit{Implementation Restrictions:}

The same restrictions as for the requirement of immediately surrounding of exclusive gate operations by export and import apply here. The expansion is implemented on a per statement basis. For \texttt{if} (and hence \texttt{case}) statements the transformation is similar to the one shown in 2.3.2.

\textit{Optimization:} By data flow analysis the update of local variables due to Hlp3 could easily be optimized: Instead of updating a helper attribute immediately after the corresponding local variable has been changed, only the last of these changes preceding an export operation must be made visible in the helper object. Standard optimizations, e.g., loop invariant code motion could be used to improve run-time performance for locals that are written inside of a loop. However, for simplicity of both the presentation and the transformation we export all variables here.
4 Transformation of \texttt{par} Statements

The basic idea of the transformation of \texttt{pSather\_ie}'s \texttt{par} statement is its reduction to the \texttt{attach} statement. When a \texttt{par} statement is encountered, the semantics of \texttt{pSather} enforce that a new gate is created which is subsequently referred to as \texttt{cohort}. Then conceptually a new thread is started and attached to this gate which executes the body of the \texttt{par} statement. The original thread blocks and continues after the new thread has terminated.

\begin{verbatim}
\texttt{pSather\_ie Code:}
\end{verbatim}

\begin{verbatim}
class X is
  r is
    local : TYPE_OF\_LOCAL := val;
    -- some code
    -- SYS::export;
    par--ie
      SYS::import;
      -- some code (2)
      -- SYS::export;
    end;
    SYS::import;
    --
    -- some code (3)
    --
    end; -- of r
    -- more class elements
  end; -- of class X
\end{verbatim}

The following code shows the (still incomplete) result of the transformation which is very similar to the one applied to the \texttt{attach} statement. In line 35 a new gate is created. All accesses to \texttt{cohort} inside the body of the \texttt{par} statement are replaced by accesses to this new gate. Similar to the right hand side of the \texttt{attach} statement, the body of the \texttt{par} statement is moved into a newly created routine \texttt{fct} (lines 47 to 55). Again, parameters (if any) and visible variables which are declared locally inside the surrounding routine \texttt{r} are passed into the new routine by means of the helper object. Packing and unpacking of the helper object is not shown in detail.

\begin{verbatim}
\texttt{pSather\_ie+thread Code after Transformation, incomplete:}
\end{verbatim}

\begin{verbatim}
class HELPER is
  attr local:TYPE_OF\_LOCAL;
  -- ...
  create : SAME is
    return new;
  end; -- of create
end; -- of HELPER
class X is
  r is
    local : TYPE_OF\_LOCAL := val;
    --
\end{verbatim}
-- some code

new_cohort ::= # GATE;
helper ::= # HELPER;
-- pack helper (see section 6)
SYS::export;
THREAD(fct, helper, new_cohort, any); -- concurrently executable
lock when new_cohort.no_threads then end;
SYS::import;
-- unpack helper (see section 6)
--
-- some code (3)
--
end; -- of r

private fct(helper, HELPER, new_cohort, GATE) is
  local : TYPE_OF_LOCAL;
  SYS::import;
  -- unpack helper (see section 6)
  --
  -- some code (2); update helper object attributes
  --
  SYS::export;
end; -- of fct

-- more class elements
end; -- of class X

The lock statement in line 40 ensures that the original thread can only proceed when no more threads are attached to the new gate, i.e., if the thread that executes the body of the par statement has terminated. Later we will see that the same gate is used to attach threads that implement the bodies of fork statements. Therefore, all these threads have terminated as well, when the original thread succeeds in acquiring the lock. Note, that no additional import and export need to be introduced into the empty body of this lock statement.

Return values of any kind are not an issue. The definition of pSather does not allow any of the following statements to appear inside the body of the par statement: return, yield, quit.\(^2\)

\(^2\)The transformation could easily be extended to correctly handle return statements as well. For this purpose, a return statement in the body of the par must transport the return value (if any) to the original thread through the helper object. After the original thread succeeds in acquiring the lock it must check whether a return statement has been encountered - the helper object must provide a flag for this purpose - and then return this value.
5 Transformation of fork Statements

The basic idea of the transformation of pSather’s fork statement is very similar to the transformation applied to par statements. The semantics of pSather only allow fork statements to appear in the body of par statements, and hence in the bodies of routines implementing par statements according to the transformation presented in section 4. Therefore, we face the following situation during transformation.

\begin{verbatim}
class X is
    -- more class elements
private fct(helper,helper, new_cohort,GATE) is -- transformed par statement
    local : TYPE_OF_LOCAL;
    SYS::import;
    -- unpack helper
    --
    myLocal : TYPE_OF_LOCAL;
    --
    -- some code
    --
    SYS::export;
fork @ p; -- ie
    SYS::import;
    --
    -- some code (2)
    --
    SYS::export;
end;
    --
    -- some code (3), update helper object attributes
    --
    SYS::export;
end; -- of fct
end; -- of class X
\end{verbatim}

Before we discuss the result of the transformation, let us briefly recall the semantics of pSather. The local variable myLocal which is declared (line 8) inside the body of the original par statement is not shared among all threads. When a new thread is started in line 13 to execute the body of the fork statement, this new thread receives a unique copy of myLocal. Any changes that this new thread makes to its instance of myLocal are not exported and are thus never visible in other threads. Hence packing and unpacking of helper objects must be sensitive to the context in which they occur. The context sensitivity is even more complicated because the semantics allow nesting of fork statements. We will discuss the transformation of arbitrary nestings of attach, par, and fork statements and the proper generation of packing, unpacking, and update statements in section 6.

The following three code sections show the result of the transformation which is very similar to the one applied to the par statement. The first section (lines 26 to 33) shows the code for the new helper object, the second code fragment (lines 34 to 36) shows the result of the transformation of the fork statement. Finally, the third code fragment (lines 37 to 69) illustrates the result of the transformation of the body of the fork statement.
As usual, we declare a new helper object upon thread creation. This time, however, the original helper object helper is an attribute of the newly created helper object helper_2, see line 27. When helper objects are packed and unpacked, this nesting must be taken into account. See section 6 for details of nesting. Note, that an access to helper_2.helper.local reaches the same storage position as helper.local does, since all helper objects are reference objects.

The transformation moves the body of the fork statement to a new routine. Instead of the original fork statement, the THREAD macro is issued in line 51. Since the original thread that executes the fork statement is attached to the gate new_cohort which has been passed as parameter, the new thread that implements the body of the fork will be attached to the same gate.
SYS::import;
-- unpack helper_2: (see section 6)
local := helper_2.helper.local;
my_local := helper_2.my_local;
--
-- some code (2), update helper (1) object attributes
--
SYS::export;
end;  -- of class X

The routine fact_2 that implements the body of the fork statement is very similar to the one that implemented the par statement before. The only difference appears in the update statements in lines 64 to 66. Whereas in the par routine all changed local variables are updated in the helper object, in the fork routine only those changed local variables are updated, that are inherited from the helper object of the surrounding par. (If the transformation of the par and the fork statement were equivalent, then in line 65 the code should read . . . update helper_2 object attributes. Note the difference.) In particular, the local variable my_local is not updated.
6  Nesting of attach, par, and fork Statements

Several times during the transformation of the attach, par, and fork statement, we encountered the necessity to pack or unpack helper objects and to update some of their attributes. This section explains how packing, unpacking, and update work for arbitrary nestings of these statements and therefore for arbitrary nesting of helper objects.

6.1 Declaration of Helper Objects

Whenever a new helper object is created, the transformation must determine which attributes the new helper object should have. After the attributes of the helper object are collected, the declaration of local variables at the beginning of the routines that result from the transformation of par, fork, and attach statements are the easy part: for each attribute in the helper object a local variable is created.

6.1.1 Motivating Examples

Nesting Level 1.
The following code fragment shows a top level par statement on the left hand side and the corresponding helper object on the right hand side. (The top level attach statement has a similar helper object.)

```
a:TYPE_OF_LOCAL;
par
end;
```

```
{class HELPER_1 is
 attr a:TYPE_OF_LOCAL;
create is ... end;
end;
}
```

Nesting Level 2.
The situation for a second level par or fork statement is slightly more complicated, since the helper object of the surrounding par statement must be used to access shared variables. (The second level attach statement has a similar helper object.)

```
a:TYPE_OF_LOCAL;
par
  b:TYPE_OF_LOCAL;
  par/fork
end;
end;
```

```
{class HELPER_2 is
 attr helper_1:HELPER_1;
 attr b:TYPE_OF_LOCAL;
create is ... end;
end;
--
}
```

The reason for nested helper objects might need more explanation. Aside from the original thread the variable a in the above example is shared by two threads. One thread executes the body of the top level par statement. The other thread executes the body of the second level par or fork. The idea is to have only one single copy of a in the helper objects. Therefore, if the second thread changes helper_2.helper_1.a, this change is immediately visible in the first thread. There are two reasons for the desire to have only one copy. The first reason is a performance reason: without nesting of helper objects the second thread would need to update two copies of a: one copy in helper_1 and another copy in helper_2. The second reason is even stronger: Assume that helper_2 is passed to a third level par or fork. If now the outermost thread changes the value of a the thread can update this in helper_1.a. However, the thread cannot update its change in any other helper object because these are not declared in his scope. Hence, when the innermost thread tries to import the current value
of a, this thread cannot know which of the two versions of a is up-to-date. Hence, using nested helper objects is a prerequisite of easy import. The alternative would require a complex protocol for replication consistency handling.

**Nesting Level 3.**

Beginning at the third level of par or fork statements, the structure of the helper object becomes sensitive to the context. We first present the situation of a third level par or fork statement inside a second level par statement. (The third level attach statement inside a second level par statement has a similar helper object.) The next example will present the second level fork statement.

```plaintext
a:TYPE_OF_LOCAL;
par
b:TYPE_OF_LOCAL;
par
c:TYPE_OF_LOCAL;
par/fork
end;
end;
end;
```

Note that both variables a and b are shared by all threads. Therefore, they are accessible through helper_2 in the new helper object HELPER_3.

The third level par or fork statement inside a second level fork statement requires a different helper object. (The third level attach statement inside a second level fork statement has a similar helper object.)

```plaintext
a:TYPE_OF_LOCAL;
par
b:TYPE_OF_LOCAL;
fork
c:TYPE_OF_LOCAL;
par/fork
end;
end;
end;
```

Here only the variable a is shared by the threads. Therefore, an individual copy must be passed into the innermost par or fork statement. To understand this demand more clearly assume a situation where the forked thread on level 2 has changed its copy of b. Clearly this new value must be made visible inside of the third level. Hence, the copy of b which is available from HELPER_2 in general holds a wrong value, namely the unchanged version of b seen by the thread that executes the body of the top level par statement.

### 6.1.2 Pseudo Code

The structure of the helper objects, i.e., the attributes of a newly created helper object are determined by the following pseudo code:
Transformation Algorithm make_attributes_of_helper:

make_attributes_of_helper is
  -- 1) link surrounding par helper
  if we are in a par or fork then
    surrounding_par_helper := par_helper_of (current_helper);
    add_attribute_to_helper (surrounding_par_helper)
  end
  -- 2) work on visible local variables and parameters
  loop local := active locals plus params!
    if user_defined (local) then
      if we are in a par or fork
        and reached via helpers (local, surrounding_par_helper)
        then -- skip this variable
      else add_attribute_to_helper (local)
    end
  end
  -- 3) pass cohort into helper object?
  if we are working on an attach and we are in a par or fork then
    add_attribute_to_helper (current cohort)
  end

Algorithm Description. The first step (line 2 to 6) is skipped for top level par and attach statements. For attach, fork, and par statements inside of par and fork statements the helper object of that surrounding statement is considered. If the surrounding level is a par level then the corresponding helper object becomes an attribute of the new helper. If the surrounding level is a fork level, then there must be a par level surrounding this fork. Hence, the current helper object of the fork has an attribute caused by the surrounding par level. This attribute is linked into the new helper object. In the implementation, the routine call par_helper_of (current_helper) finds the appropriate helper object that must be linked in.

In the second step (lines 7 to 16) all parameters and visible locally declared variables are considered. If one of those variables is the result of an earlier transformation step, it is ignored. The condition user_defined (local) in line 9 implements this. For all remaining variables a new attribute is added to the helper object, except for those variables for which the condition in lines 10 and 11 holds. If the transformation happens to be inside of a par or a fork statement, then several variables are inherited (transitively) by the helper of the surrounding par statement. This helper object is found in step 1 (surrounding_par_helper, line 4). Note that the shortcut semantics for the evaluation of boolean expressions makes sure that the surrounding_par_helper is not used if the transformation is applied to a top level statement.

To understand the requirement of the transitive inheritance of locals consider the above example again which introduced HELPER.3. The helper object of the surrounding par statement (helper_2) contains only the local variable b. However, by working the levels up, the local variable a can be accessed as well: helper_2.helper_1.a. Therefore, the new helper class HELPER.3 only has the attribute c in its body.

The same condition in lines 10 and 11 makes sure that HELPER.3b has both b and c in its body, because b cannot be transitively reached via the surrounding helper object which is helper_1 here.

The third step of the pseudo code (lines 17 to 20) needs some discussion. In general helper objects transport only variables defined by the pSather programmer. Beyond that, local variables which are introduced during transformation are not used in the routine that receives the helper object. However
there is one exception. Inside of a \texttt{par} statement, the pSather programmer can freely use \texttt{cohort}. In particular, \texttt{cohort} can be used in the right hand side expression of an attach statement. Because the right hand side is moved into a newly created routine as has been presented in section 3, the name of the gate that implements \texttt{cohort} must be passed inside the \texttt{attach} routine. This is not necessary for the transformation of \texttt{par} and \texttt{fork} statements because the new threads are attached to \texttt{cohort} anyhow, i.e., the gate that implements \texttt{cohort} is accessible as third parameter of the \texttt{THREAD} macro.

6.2 Packing of Helper Objects, Export

After a new helper object is created during the transformation, the current values of the local variables and parameters are copied into the corresponding attributes of the helper objects. Since obviously all attributes must be filled initially, the pseudo code for \texttt{pack \_helper \_object} is very similar to the one of \texttt{make \_attributes \_of \_helper} given in section 6.1.2.

Transformation Algorithm \texttt{pack \_helper \_object}:

\begin{verbatim}
pack_helper_object(helper) is
  -- 1) link surrounding par helper
  if we are in a par or fork then
    surrounding_par_helper := par_helper_of(current_helper);
    update_attribute_in_helper(local_helper);
  end;
  -- 2) work on local variables and parameters
  loop local := active_locals_plus_params;
    if user_defined(local) then
      if we are in a par or fork
        and reach via helpers(local, surrounding_par_helper)
        then -- skip this variable
          else update_attribute_in_helper(local_helper);
        end;
      end;
    end;
  -- 3) pack cohort into helper object?
  if we are working on an attach and we are in a par or fork then
    update_attribute_in_helper(local_helper);
  end;
\end{verbatim}

The only differences occur in lines 5, 13, and 18. Instead of making a new attribute in the class definition of the helper object, an assignment statement is created. The first step creates an assignment statement that looks like:

\begin{verbatim}
helper_2.helper_1 := helper_1;
\end{verbatim}

This links the helper object of the surrounding \texttt{par} statement into the currently packed new helper object. The second step creates assignment statements for the local variables:

\begin{verbatim}
helper_2.local := local;
\end{verbatim}

Finally, in the third step that is only executed when an \texttt{attach} statement inside of a \texttt{par} statement is transformed, a reference to the current \texttt{cohort} of that \texttt{par} statement is copied into the new helper object:

\begin{verbatim}
helper_2.new_cohort := new_cohort;
\end{verbatim}
6.3 Update of Helper Object Attributes, Export

After a local variable is changed that is mirrored in a helper object the corresponding attribute of the helper object must be updated. See rule Hlp3: Whenever a local variable is changed (either by an assignment to it or by using it as an inout argument) and this variable is also available in a helper object, immediately after this change the corresponding attribute of the helper object is updated.

6.3.1 Motivating Examples

Nesting Level 1.
The following code fragment shows two top level par statements on the left hand side and the corresponding helper objects on the right hand side. (Top level attach statements have a similar helper objects.)

<table>
<thead>
<tr>
<th>a:TYPE_OF_LOCAL;</th>
<th>class HELPER_1a is</th>
</tr>
</thead>
<tbody>
<tr>
<td>par</td>
<td>attr a:TYPE_OF_LOCAL;</td>
</tr>
<tr>
<td>end;</td>
<td>create is ... end;</td>
</tr>
<tr>
<td>b:TYPE_OF_LOCAL;</td>
<td>class HELPER_1b is</td>
</tr>
<tr>
<td>par</td>
<td>attr a:TYPE_OF_LOCAL;</td>
</tr>
<tr>
<td>end;</td>
<td>attr b:TYPE_OF_LOCAL;</td>
</tr>
<tr>
<td></td>
<td>create is ... end;</td>
</tr>
</tbody>
</table>

Inside of the first par statement, the helper object helper_1 must be used. In the second par the helper object helper_2 is used. After the end of the first par statement, the first helper object is no longer of any interest since all threads that might use this helper object have terminated. Note that at all points of the program the last declared helper object is the one that gets used. Here the last declared helper object always is a helper object caused by a par statement.

Nesting Level 2.
The situation for a second level par or fork statement is slightly more complicated, since the helper object of the surrounding par statement must be used for access to shared variables. (The second level attach statement has a similar helper object.) The code on the left hand side has a sequence of par and fork statements in its body.

<table>
<thead>
<tr>
<th>a:TYPE_OF_LOCAL;</th>
<th>class HELPER_2a is</th>
</tr>
</thead>
<tbody>
<tr>
<td>par</td>
<td>attr helper_1:HELPER_1;</td>
</tr>
<tr>
<td>b:TYPE_OF_LOCAL;</td>
<td>attr b:TYPE_OF_LOCAL;</td>
</tr>
<tr>
<td>par</td>
<td>create is ... end;</td>
</tr>
<tr>
<td>end;</td>
<td>end;</td>
</tr>
<tr>
<td>c:TYPE_OF_LOCAL;</td>
<td>class HELPER_2b is</td>
</tr>
<tr>
<td>fork</td>
<td>attr helper_1:HELPER_1;</td>
</tr>
<tr>
<td>par</td>
<td>attr b:TYPE_OF_LOCAL;</td>
</tr>
<tr>
<td>end;</td>
<td>attr c:TYPE_OF_LOCAL;</td>
</tr>
<tr>
<td></td>
<td>create is ... end;</td>
</tr>
<tr>
<td>end;</td>
<td>end;</td>
</tr>
</tbody>
</table>

The interesting aspect here is that the thread that executes the top level par statement can use any of the helper objects when updating the value of a. Independent of the choice, the update will always reach helper_1.a. When updating the value of b however, this thread must be more careful.
Since \( b \) is shared with the thread that executes the second level \texttt{par} statement, the helper object \texttt{helper.2a} must be used. Moreover, \texttt{helper.2b} must not be used to update the value of \( b \), because the thread that executes the \texttt{fork} statement initially gets a copy of \( b \) and is intended not to see any changes that are made to the original \( b \). Hence, for a correct update of helper object elements, the last declared helper object must be used that is caused by a \texttt{par} statement.

\textit{Nesting Level 3.}

The only interesting case here is the following:

```
    a:TYPE_OF_LOCAL;
    par
        b:TYPE_OF_LOCAL;
        fork
            c:TYPE_OF_LOCAL;
            fork
            end;
        end;
    end;
```

At the moment when the transformation reaches the innermost \texttt{fork} statement there is no helper object visible that is caused by a \texttt{par} statement. In this case, of course that last declared helper object must be chosen.

\subsection*{6.3.2 Pseudo Code}

The following pseudo code creates a statement to update an attribute of the helper that mirrors a changed local variable. If a change of a local variable needs not to be updated, the pseudo code does not add a new statement.

\begin{verbatim}
Transformation Algorithm update_in_helper:

update_in_helper(local)
    -- 1) Find out the appropriate helper object for export
    if no_helper_is_visible then return;
    elsif no_par_helper_is_visible then helper_to_use := last_declared_helper;
    else helper_to_use := last_declared_par_helper;
    end;

    -- 2) Copy into helper object if applicable
    if reach_via_helpers(local_par_helper_of(helper_to_use)) then
        update_attribute_in_helper(local,helper_to_use)
    end;

end;
```

\textit{Algorithm Description.} Nothing is updated if no helper object is visible (line 3). Otherwise, the last declared helper object is considered which is caused by a \texttt{par} statement (line 5). If no such helper object can be found the last declared helper object is used instead (line 4). This has been motivated by the examples in the previous section.

The second step of \texttt{update_in_helper} makes sure that only those attributes are written which are accessible from helper objects that correspond to \texttt{par} statements. In the above example for nesting level 3, only changes to local variable \( a \) will make it into the helper object. The other two attributes of \texttt{helper.3b} cannot be reached in \texttt{par_helper_of(helper_to_use)}. In the example the following update code will be created for a change of \( a \):
helper_3b.helper_1.a := a;

6.4 Unpacking of Helper Objects, Import

Helper objects must frequently be unpacked, i.e., the local variables must be set to the values that are stored in the helper object. We must differentiate between two different cases. The first case is the initial unpacking that is needed at the beginning of routines which implement the bodies of \texttt{par} or \texttt{fork} statements or which implement the right hand side of \texttt{attach} statements. The second case is caused by rules \texttt{H1p}1 and \texttt{H1p}2, i.e., whenever an import operation occurs that requires the shared local variables to be set to the up-to-date value.

The pseudo code for the unpacking is a mixture of the one for packing of helper objects (see 6.2, \texttt{update\_attribute\_in\_helper}) and the pseudo code for the update of helper attributes (see 6.3.2, \texttt{update\_attribute\_in\_helper}).

Transformation Algorithm \texttt{update\_from\_helper}:

```plaintext
update_from_helper(mode) is
   -- 1) Find out the appropriate helper object for export
   if no_helper_is_visible then return;
   else if no_par_helper_is_visible then helper_to_use := lastDeclared_helper;
   else helper_to_use := lastDeclared_par_helper;
   end;
   -- 2) Consider different modes
   if mode /= init then
      helper_to_use := par_helper_of(helper_to_use);
   end
   -- 3) Copy into helper object if applicable
   loop local := activeLocals_plus_params;
      if ( user_defined(local)
         or (mode = init and is_cohort(local)))
         and reach_via_helpers(local, helper_to_use)
      then
         updateLocal_from_helper(local, helper_to_use)
      end;
   end;
```

\textit{Algorithm Description.} First of all, the routine decides in the first step which helper object to use. This is done in the same way and for the same reasons as it has been done for the update of helper attributes. In the second step (lines 7 to 10) the mode is considered. If called in init-mode the last declared helper object is the one that is passed as a parameter to the routine implementing the new thread. Since nothing is changed in step 2 (lines 11 to 19), all variables that are (transitively) reachable from this helper object are set in the third step.

However, if called in import-mode, \texttt{helper\_to\_use} is changed to point to the helper object of the surrounding \texttt{par} statement, if the current routine does not itself implement a \texttt{par} statement. In this case only those variables are copied from the helper object that are mirrored in the helper of the surrounding \texttt{par} statement, which exactly implements the sharing of the corresponding variables.
7 Complete Example

In this section we first show a pSather implementation of the consumer-producer problem. Afterwards we present the complete result of the transformation described in this document. Actually, except for the comments which are added manually, the resulting program is produced by the pSather compiler.

7.1 Original pSather Program

```plaintext
class MAIN is
  const pnum := 3; -- number of producers
  const cnum := 2; -- number of consumers
  const max_prod := 1000; -- number of 'items' a producer creates
  attr comm_gate.GATE[INT]; -- used to queue 'items'
  attr prod_gate.GATE; -- used to attach producers

The main program consists of a single par statement (lines 9 to 18). Inside of this par statement, two loop statements are used to create the producers and consumers by means of an attach and a fork statement.

In the first loop (lines 11 to 13) pnum producers are attached to the gate prod_gate, i.e., the producers are started to run concurrently. The producers must be attached to a named gate because the consumers must be able to check whether there are any producers left. If all producers have terminated and all produced items have been consumed, the consumers can terminate as well.

In the second loop (line 15 to 17) cnum consumers are started by the fork statement. The par statement terminates when all consumers have terminated.

main is
  comm_gate := #; prod_gate := #;
  par
    -- Create producers and attach to prod_gate
    loop pnum.times!
      prod_gate :– producer;
    end;
    -- Create consumers
    loop cnum.times!
      fork consumer end;
    end;
end;
```

The code of the producer is straightforward: there is a loop statement and inside of this loop items (which are consecutive INTs in the implementation) are enqueued into the communication buffer comm_gate. If max_prod items have been produced, the loop and thus the producer are terminated.

```plaintext
producer is
  res:NT:=0;
  loop -- some work
    comm_gate.enqueue(res);
    res := res+1; if res > max_prod then break! end;
end;
```
The code of the consumer is slightly more complicated because the consumer not only has to retrieve items from the communication buffer but in addition, the consumer must decide whether to terminate or to continue.

```
consumer is
  loop
    lock
      when comm_gate.not_empty then
        #OUT+comm_gate.dequeue;
      end;
      when comm_gate.empty, prod_gate.no_threads then
        break!;
      end;
  end; -- consumer
end: -- MAIN
```

Whereas the producer will terminate after `max_prod` elements are enqueued into the buffer, the consumer uses the multi-branch `lock` statement to decide about termination. The `lock` statement (lines 29 to 34) has two branches. The first branch is entered if there is an element in the communication buffer. If this is the case, the buffer is locked, the element dequeued from the buffer, and the buffer is unlocked again. If there is no element in the communication buffer and there is no thread attached to `prod_gate` then the consumer can terminate. This is achieved by the `break!` in the second branch of the `lock` statement.

7.2 Result of the Transformation

The following code is basically generated by the implemented transformation of pSather. However, the code is beautified by hand to enhance readability. For example, helper objects and compiler declared temporary variables have been renamed to be more intuitive. Moreover, we re-introduced syntactic sugar that has been lost during the compilation, e.g., incrementing `res` in the producer is written as `res+1` instead of `res.plus(1)`.

To avoid confusion when referring to line numbers in the code, the resulting code starts at line number 100.

```
class MAIN is
  const pnum := 3; -- number of producers
  const cnum := 2; -- number of consumers
  const max_prod := 1000; -- number of 'items' a producer creates
  attr comm_gate : GATE{INT}; -- used to queue 'items'
end: -- MAIN
```

The `main` routine is shortened during the transformation. The whole body of the original `par` statement is moved into the new routine `pS.par`. Instead first the gate used as `cohort` is created in line 108. Then the helper object `pS.par.hlp` is created, which is of type `PS.PAR.HLP`. Since there are no locally declared variables, the helper object has no attributes which otherwise would have been packed afterwards. Before the new thread that executes the body of the original `par` is started, changes are exported. The new helper object is thus made visible to other threads that might use it. The new thread is started in line 111. The thread is attached to the `pS.coherent` and runs routine
pS_par(pS_par_hlp, pS_cohort). The fourth argument of \texttt{THREAD} is void, since the new thread should run, where the original thread was executed. The initial thread continues after evaluating \texttt{THREAD} and is stopped in the \texttt{lock} statement of line 112. There the initial thread is blocked until all threads which are attached to the \texttt{pS_cohort} have terminated. Afterwards the initial thread imports any changes other threads might have made.

\begin{verbatim}
main is
  comm_gate:=#; prod_gate:=#;
  -- par:
  pS_cohort:=#GATE;
  pS_par_hlp:=#PS_PAR_HLP;
  SYS:=export;
  THREAD(pS_par, pS_par_hlp, pS_cohort, void); -- conc.
  lock when pS_cohort.no_threads then end;
  SYS:=import;
end; -- of main
\end{verbatim}

\textit{Potential Optimization.} In the basic transformation template there is a lot of room for optimization. In the above code fragment some of the problems an optimization phase could address are obvious:

- It is not necessary, to create and and pass empty helper objects.
- If this can be avoided, no export needs to occur, since no objects are changed.
- No import needs to occur if the thread does not use any of the potentially imported new versions of objects.

The code of the producer did not change significantly. However, since import and export operations must be explicit in \texttt{pSather_le4_thread} the exclusive gate operation (lines 119) is enclosed in calls of export and import.

\begin{verbatim}
producer is
  res:INT:=0;
  loop
    SYS:=export;
    comm_gate.enqueue(res);
    SYS:=import;
    res := res+1; if res > max_prod then break! end;
  end;
end; -- of producer
\end{verbatim}

The code of the consumer has been changed a little more. In addition to the explicit export and import code that surround the exclusive gate operation in line 130, there are additional import and export operations enclosing each branch of the \texttt{lock} statement (lines 128+132 and lines 134+136).

\begin{verbatim}
consumer is
  loop
  lock
    when comm_gate.not_empty then
\end{verbatim}
SYS::import;
SYS::export;
# OUT+ comm_gate.dequeue;
SYS::import;
SYS::export;
when comm_gate.empty, prod_gate.no_threads then
SYS::import;
break!;
SYS::export;
end;
end;
end: -- of consumer

The transformation moves the former body of the par statement into the new routine pS_par. At the very beginning of the body there is the explicit import operation (line 141) that makes the helper object visible. At the end of the body (line 158) there is an explicit export operation.

Although the two loop statements are still present, their bodies have been changed significantly.

Lines 143 to 149 show the transformation of the attach statement. Lines 152 to 156 show the transformation of the fork statement.

For the attach statement, at first a new gate pS_gate is created that is subsequently used instead of prod_gate. Then a helper object of type PS_ATTACH_HLP is created and used to make the local variables and arguments visible in the routine that will implement the right hand side of the attach. Here a reference to the surrounding helper object of the par statement and the current cohort are copied into this helper object. After an explicit export operation in line 148, the routine pS_attach is started concurrently (line 149).

private pS_par (pS_par_hlp:PS_PAR_HLP, pS_cohort:GATE, pS_att:INT) is
loop pnum.times!
  -- attach:
    pS_gate:=prod_gate;
pS_attach_hlp:=#PS_ATTACH_HLP;
pS_attach_hlp.pS_par_hlp:=pS_par_hlp;
pS_attach_hlp.pS_cohort:=pS_cohort;
SYS::export;
THREAD(pS_attach, pS_attach_hlp, pS_gate, void); -- conc.
end; -- of loop
loop cnum.times!
  -- fork
    pS_fork_hlp:=#PS_FORK_HLP;
pS_fork_hlp.pS_par_hlp:=pS_par_hlp;
SYS::export;
THREAD(pS_fork, pS_fork_hlp, pS_cohort, void); -- conc.
end; -- of loop
SYS::export;
end; -- of pS_par

The fork statement is transformed slightly differently. In contrast to the helper object we have used for the attach statement, the helper object pS_FORK_HLP of the fork statement does not include the current cohort. The reason for this is that the routine that implements the body of the fork
statement always has the cohort gate as its second parameter. Since the routine that implements the right hand side of an **attach** statement is in general not attached to the cohort, the cohort had to be passed through the helper object.

**Potential optimization.** Again several special cases can be noted that could be exploited by optimization:

- It does not make much sense to link empty helper objects into new helper objects, as it is done with the empty helper object `ps_par_hlp` in lines 146 and 154.
- Data flow analysis could reveal that the thread created for the **attach** statement does not need access to `ps_cohort`. Therefore, passing this reference through the helper object could be left out without any harm.

The following code fragment shows the routine that results from the transformation of the **attach** statement. In line 161 a local variable is declared that mirrors the one which is visible at the point of the original **attach** statement. After the initial import operation (line 162), the helper object is unpacked, i.e., the mirroring local variables are filled according to the values their original counterparts have at the point of the **attach** statement (line 163).

The producer is started in line 164. The **enqueue** operation is as uninteresting as the side effect of the initial **attach** statement to count the number of terminated producers. The implementation of **THREAD** makes sure that the invocation of `pS_attach` is properly attached to `pS_gate`, which is needed for the **lock** statement in the consumer (lines 126 to 137) to work.

```plaintext
private pS_attach (pS_attach_hlp:PS_ATTACH_HLP, pS_gate:GATE, pS_at:INT) is
  pS_cohort: GATE;
  SYS: import;
  pS_cohort:=pS_attach_hlp.pS_cohort;
  producer;
  pS_gate.enqueue;
  SYS: export;
end; -- of pS_attach
```

**Potential Optimization.** See above.

The routine `pS_fork` does not need much discussion. Since there are no attributes in the helper object, no mirroring local variables need to be declared or initialized. Hence, the body of the routine simply consists of explicit import and export operations that enclose the call of **consumer**.

```plaintext
private pS_fork (pS_fork_hlp:PS_FORK_HLP, pS_cohort:GATE, pS_at:INT) is
  SYS: import;
  consumer;
  SYS: export;
end; -- of pS_fork
```

**Potential Optimization.**

- Closer analysis can avoid many of the import and export operations that are required by the language specification.
Finally, for the sake of completeness, we present the class definitions of the helper objects:

```vhdl
class PS_PAR_HLP is
    create: SAME is
        return new;
    end;  -- of PS_PAR_HLP
end class PS_PAR_HLP

class PS_ATTACH_HLP is
    attr pS_cohort : GATE;
    attr pS_par_hlp : PS_PAR_HLP;
    create: SAME is
        return new;
    end;  -- of PS_ATTACH_HLP
end class PS_ATTACH_HLP

class PS_FORK_HLP is
    attr pS_par_hlp : PS_PAR_HLP;
    create: SAME is
        return new;
    end;  -- of PS_FORK_HLP
end class PS_FORK_HLP
```

References
