4.1 Closeness Function

The nodes of the data flow graph shown in Fig. 1 represent arithmetic operations. The edges are labeled with the bit widths of the required data types. The following closeness function is given:

$$Closeness(o_i, o_j) = \left( \frac{Conn(o_i, o_j)}{TotalConn(o_i, o_j)} \right) + \frac{FU_{cost}(o_i) + FU_{cost}(o_j) - FUGROUP_{cost}(o_i, o_j)}{FUGROUP_{cost}(o_i, o_j)}$$

The different terms in this function have the following meanings:

- $Conn(o_i, o_j)$: the number of common wires between objects $o_i$ and $o_j$.
- $TotalConn(o_i, o_j)$: the sum of all wires that connect to objects $o_i$ and $o_j$. Common wires are counted twice - once for each object.
- $FU_{cost}(o_i)$: the cost of the functional unit that implements $o_i$.
- $FUGROUP_{cost}(o_i, o_j)$: the cost of the minimal number of functional units that are required to execute objects $o_i$ and $o_j$. (For example, should both $o_i$ and $o_j$ be additions, they would be assigned to one functional unit of type adder.)

4.1.a) Physical interpretation

Find a physical interpretation of the closeness function.

4.1.b) Hierarchical clustering

- Compute the closeness values for all pairs of objects in Fig. 1 according to the given closeness function. The cost of an adder and the cost of a subtractor are 1.
- Define a suitable closeness function for clustering hierarchical objects based on the function given above. Cluster the graph until you receive a bi-partitioning.

Solution:

The physical interpretation of $Closeness(o_1, o_2)$ is that it denotes the relative benefit of clustering $o_1$ and $o_2$. There are two considerations for the clustering: wires between clusters and the functional unit costs. For either consideration, we have an expression that denotes the gain due to clustering divided by a normalizing term.
One possible solution for finding a hierarchical clustering is to cluster operations \( o_1 \) and \( o_3 \) into a "supernode" \( o_{13} \) and treat this node like any initial node. This involves re-computing all closeness values and repeating the clustering procedure.

\[
c(o_{13}, o_2) = \frac{8}{50} + \frac{2 - 1}{1} = \frac{2}{15} + 2 = 2.133
\]
\[
c(o_{13}, o_4) = \frac{9}{62} + \frac{2 - 1}{2} = \frac{9}{62} + \frac{1}{2} = 0.645
\]
\[
c(o_2, o_4) = \frac{9}{52} + \frac{1 + 1 - 2}{2} = \frac{9}{52} = 0.173
\]

The updated closeness values suggest to put \( o_{13} \) and \( o_2 \) into one new partition \( o_{123} \). We have now a bi-partition \( o_{123} \) and \( o_4 \).
\[ P = \{\}, O \}; /* all in HW */ \]

PROCEDURE PARTITIONING
REPEAT
\[
\begin{align*}
P_{\text{old}} &= P; \\
&\text{FORALL } o_i \in HW \\
&\quad \text{AttemptMove}(P, o_i); \\
&\text{ENDFOR} \\
&\text{UNTIL } (P == P_{\text{old}}) \\
&\text{END PROCEDURE}
\end{align*}
\]

PROCEDURE AttemptMove\((P, o_x)\)
\[
\begin{align*}
&\text{IF } \text{SatisfiesPerformance}(\text{Move}(P, o_x)) \text{ AND } \\
&\quad (f(\text{Move}(P, o_x)) < f(P)) \\
&\quad \quad P = \text{Move}(P, o_x); \\
&\quad \text{FORALL } (o_y \in \text{Successors}(o_x)) \\
&\quad \quad \text{AttemptMove}(P, o_y); \\
&\quad \text{ENDIF} \\
&\text{ENDIF}
\end{align*}
\]

END PROCEDURE

Figure 2: Pseudo code for a greedy HW/SW partitioner

4.2 HW/SW partitioning

Fig. 2 shows the pseudo code of a greedy algorithm for HW/SW partitioning. The algorithm starts with a partition where all objects are realized in hardware. Then, objects are migrated to software as long as the performance requirement is satisfied (function SatisfiesPerformance) and the cost of the new partitioning is lower (function \(f\)). If an object is migrated, the algorithm also tries to migrate all successor nodes (function Successors).

- Apply the algorithm to the sequence graph shown in Fig. 3. The function SatisfiesPerformance\((P)\) should return TRUE if \(P\) satisfies the latency bound \(L \leq 7\). To determine the latency of a partitioning, you have to construct a valid schedule. The execution times of start- and end nodes of the sequence graph are 0, all other node execution times are given in Fig. 3, split into HW \(d_{HW}\) and SW \(d_{SW}\). For a communication between HW and SW, a delay of 0.5 per edge has to be accounted for. For HW nodes there are no resource constraints, i.e., all ready nodes can be executed in parallel. The SW nodes have to share one processor. The function \(f\) determines the cost. For a SW node the cost is 0, and for a HW node the cost is 1.

Solution:

We assume in this solution that the main procedure processes hardware elements in the increasing order of their indexes. This problem intrinsically has many solutions because the main routine, at a certain step, allows the free choice of a node.

Communication delay between hardware and software always adds to the latency and cannot be hidden by other operations because software tasks are running strictly sequential.

<table>
<thead>
<tr>
<th>Latency</th>
<th>Cost</th>
<th>Tasks in SW</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 = 4</td>
<td>C0 = 11</td>
<td>-</td>
<td>move op1 to SW</td>
</tr>
<tr>
<td>L1 = 5.5</td>
<td>C1 = 10</td>
<td>op1</td>
<td>move op3 to SW</td>
</tr>
<tr>
<td>L2 = 6.5</td>
<td>C2 = 9</td>
<td>op1,op3</td>
<td>move op4 to SW</td>
</tr>
<tr>
<td>L3 = 6.5</td>
<td>C3 = 8</td>
<td>op1,op3,op4</td>
<td>move op5 to SW</td>
</tr>
<tr>
<td>L4 = 6</td>
<td>C4 = 7</td>
<td>op1,op3,op4,op5</td>
<td>try to move op2 to SW</td>
</tr>
<tr>
<td>L5 = 8</td>
<td>C5 = 6</td>
<td>op1,op3,op4,op5,op2</td>
<td>Terminate, no other node can be moved to SW without violating Latency constraint</td>
</tr>
</tbody>
</table>
**Result:** Nodes 1, 3, 4, 5 are implemented in software and nodes 2, 6, 7, 8, 9, 10, 11 are implemented in hardware.

**Remark:** The solution is given when the main procedure processes elements in increasing order of their indexes. However, if we do not stick to this assumption, other nodes may also be added to the software partition.

The above solution also assumes that communication delay cannot be covered by processing of software tasks; otherwise, node 9 can also be moved to software.