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Process Mapping onto Complex Architectures and Partitions Thereof

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Context
Current trend in high-end computer architectures

- Combine features from all the paths followed in the past 50 years
- Very large numbers of PEs
  - Above the million for exascale-class machines
  - Small(er) amounts of memory per PE
- Non uniform architectures
  - Mix of the distributed- and shared-memory paradigms
  - Communication latency and bandwidth depends on the respective locations of intercommunicating processes
- Hierarchical architectures
  - Clusters of multiprocessor blades
  - Multi- or even many-core processors
Impact on application software

- Target architectures have to be taken into account
  - Data locality is essential to achieve performance
- Writing and running software is likely to become more complex
  - Task-based programming models, runtime environments, etc.
- Interactions between software and system components will become the norm
  - Especially, the batch scheduler should tell the application what processing elements it assigns for its execution
- Process and/or data placement tools have to take scheduler information into account
The SCOTCH way
**The SCOTCH project**

- Toolbox of graph partitioning methods, which can be used in numerous contexts
- **Sequential SCOTCH library (v6.0)**
  - Graph and mesh partitioning
  - Static mapping (edge dilation)
  - Graph and mesh reordering
  - Clustering
  - Graph repartitioning and remapping
- **Parallel PT-SCOTCH library (v6.1)**
  - Graph partitioning (edge)
  - Static mapping (edge dilation)
  - Graph reordering
  - *Graph repartitioning, remapping*
Static Mapping

- Defined as two applications from $V(S)$ and $E(S)$ of source graph $S$ to $V(T)$ and $\{E(T)\}^*$ of target architecture graph $T$, respectively.

- Communication cost function accounts for distance

$$f_C(\tau_{S,T}, \rho_{S,T}) = \sum_{e_S \in E(S)} w(e_S)|\rho_{S,T}(e_S)|$$

- SCOTCH was designed to compute mappings since its inception in 1992.
Multilevel framework

- **Principle**
  - Create a family of topologically equivalent coarser graphs by clustering groups of vertices
  - Compute an initial partition of the smallest graph
  - Propagate back the result, with local refinement

- **Speeds-up computations**
- **Improves partition quality**
- **Used both for k-way partitioning and bi-partitioning**

![Diagram of multilevel framework](image)
Dual Recursive Bipartitioning (DRB)

- Recursive process
  - Follows a “divide & conquer” approach
- Associates a part of the source graph to each part the target graph
- Until each target subgraph is reduced to a single vertex, do:
  - Bipartition target graph
  - Use target graph bipartition imbalance to bipartition associated source graph
Partial cost function

- Distance information regarding external edges accounts for current knowledge within the recursive bi-mapping process

\[
f'_c(\tau_{S,T}, \rho_{S,T}) = \sum_{v \in V(S')} w(\{v, v'\}) |\rho_{S,T}(\{v, v'\})|
\]

\[\{v, v'\} \in E(S)\]
In order to evaluate the partial cost function while (bi)partitioning the source graph, a target architecture description must provide three abstractions:

- **Domain structure**: represents a set of processors in the target architecture
- **Domain bipartitioning function**: bipartitions a given domain into two disjoint subdomains
- **Domain distance function**: provides (an estimate of) the distance between two domains in the target architecture

**SCOTCH** implements two families of target architecture descriptions:

- Decomposition defined
- Algorithmically defined
Decomposition-defined architectures

- Based on a graph representation of the target architecture
- Described by two elements:
  - *Vertex labeling*: describes the bipartitioning tree
  - *Distance matrix*: shortest distance between all processing elements
- Vertex labeling is defined through recursive bipartitioning

```
1
3 2
7 6 4 5
15 14 12 13 9 11 8 10
```

deco 0
8 15
0 1 15
1 1 14
2 1 13
3 1 11
4 1 12
5 1 9
6 1 8
7 1 10
1
2 1
2 1 2
1 1 1 2
3 2 1 1 2
2 2 2 1 1 1
3 2 3 1 2 2 1
Algorithmically-defined architectures

• Provide all the necessary information thanks to hard-coded routines
• Algorithmically-defined architectures are implemented as instances of an abstract “class”
  - E.g.: mesh2D, hcub, etc.
  - The decomposition-defined architecture module also falls in this category, yet values are read from tables rather than being computed on the fly
• Distances are provided as shortest path length
  - E.g.: for mesh2D, Manhattan distance between centers of rectangular domains
• Need to recompile SCOTCH whenever a new architecture has to be added
  - One could think of dynamic loadable libraries in the future...
Limitations of existing architecture descriptions

- **Algorithmically-defined architectures can only describe complete computer systems**
  - A part of a torus is not a torus!
  - Disconnected parts are not managed, either
- **The decomposition-defined architecture is not scalable**
  - Distance matrix is in $O(P^2)$ in space (and time)
  - Yet, it can manage disconnected parts
3

Handling sub-architectures in SCOTCH
Multilevel Rule!

- Recursive bipartitioning makes sense only when all vertices and edges of the target architecture are meaningful.

- We want to extract locality information out of the target architecture so as to bipartition the source graph in a way consistent with processor allocation.

- Multilevel is the usual suspect when thinking about locality.
  - Matching is a local process by nature!
Using coarsening to build the bipartitioning hierarchy

- Recursive matching and coarsening allows one to build a locality-based bipartitioning tree of the sub-architecture

- By traversing the coarsening tree from its root, one can build a locality-preserving bipartitioning tree

- Tree is unbalanced but processors are distributed that way
How it works in practice for algorithmic architectures (1)

- Mapping onto 5 processors
  - On a complete graph
  - On a part of a 4x2 2D mesh architecture
How it works in practice for algorithmic architectures (2)

- Recursive coarsening is traditionally performed using:
  - A graph description of the original architecture
  - Matchings that are computed on the given graphs
- In fact, we only need the matching to build the bipartition tree
  - Distances will be computed algorithmically and do not require graph data
- An algorithmically-defined target architecture should just provide a matching routine
  - Less prone to coarsening artifacts
  - Less resources required
  - Handles architectures for which graph representations are inadequate
    - E.g., tleaf architecture
How it works in practice for decomposition architectures (1)

- Graph representation is mandatory to compute:
  - Matchings
  - Distances
- That sounds much like the original deco architecture...
  - But we want to get rid of the $O(P^2)$ storage!
- In fact, we do not want exact distances
  - We just want to sort out local edges from long-distance edges
- Keep the family of coarsened graphs to compute distances at the proper level
  - Use Dijkstra’s algorithm on weighted graphs
    - Weight of coarsened edges is not adequate
  - Use a cache to hide part of the computation cost
  - Storage becomes $O(P)$
  - Multilevel Rul3z indeed!
How it works in practice for decomposition architectures (2)

- Mapping of bump on the previous subset of the 4x2 2D mesh:
  - Relative average difference in distances between deco0 and deco2: 0.60
  - Standard deviation of distance difference between deco0 and deco2: 0.36

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<thead>
<tr>
<th></th>
<th>deco0</th>
<th>deco2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping time for bump</td>
<td>0.02s</td>
<td>0.04s</td>
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<tr>
<td>Edge cut</td>
<td>525</td>
<td>531</td>
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<tr>
<td>Edge dilation</td>
<td>657</td>
<td>549</td>
</tr>
</tbody>
</table>

- Mapping of bump onto a 16x16 2D mesh:
  - Relative average difference in distances between deco0 and deco2: 0.58
  - Standard deviation of distance difference between deco0 and deco2: 0.50

<table>
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<th>deco0</th>
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</table>
Conclusion

• Multilevel architecture descriptions allow one to describe efficiently (disconnected parts of) large architectures
• To date, implemented in SCOTCH only, not in PT-SCOTCH
  - Released soon in SCOTCH 6.0.5
• PT-SCOTCH is planned to perform parallel static mapping starting from branch 6.1
  - Prototype available since the PhD of Sébastien Fourestier, but needs intensive regression testing before release
Thank you for your attention!

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