Topology-aware and load balancing techniques using Charm++, AMPI and related technologies

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Charm++ and AMPI

- **Charm++ / Charmpy**
  - Object-oriented parallel programming model with *migratable* objects
  - Adaptive runtime system
    - asynchronous message driven execution (communication and computation overlap)
    - dynamic load balancing and communication optimization
    - fault tolerance

- **AMPI (Adaptive MPI)**
  - Run MPI applications on top of Charm++
  - Can have multiple migratable MPI ranks per process
  - Obtain benefits of Charm++ runtime system
PAID project goals

- Improve *resource utilization of applications* on Blue Waters
  1) Topology-aware placement of tasks, to improve communication performance
  2) Load balancing, to minimize CPU idle time

- Applications include:
  - HARM3D (Scott Noble) - Load balancing using AMPI
  - PSDNS-CCD3D (PK Yeung) - Topology-aware mapping for MPI
  - MILC (Steven Gottlieb) – Topology-aware mapping for MPI
  - NAMD, OpenAtom, ChaNGa (topology and load balancing)
Outline of talk

- Topology-aware mapping
- Load balancing
  - Charm++
  - AMPI
  - Recent developments in Charm++ load balancing
Topology-aware mapping

- Communicating tasks (e.g. MPI ranks) should be placed in same or nearby nodes
  - Reduce *latency* and *network load*

- **Goal**: place tasks such that load of network links is minimized $\rightarrow$ NP-hard

- Match the application communication graph to the machine topology
  - Effect is highly dependent on machine topology, application and job size
  - Blue Waters has 3D torus topology
  - On Blue Waters performance can improve by $> 2x$
Automatic task mapping tool

- Maps MPI ranks to cores in a given job allocation, during application launch
- Available as system module on Blue Waters
  - /sw/bw/topomapping/README.txt
- How it works
  - Do profiling run (obtain communication graph)
  - In production runs. Inside batch job (example):

```
$ module load topomapping
$ aprun -n 8192 mapper -t 30 -f comm_graph.txt  # comm graph from profiling run
$ export MPICH_RANK_REORDER_METHOD=3
$ aprun -n 8192 ./application app_parameters
```
Automatic task mapping tool

• Application observed speedup
  – MILC: up to $2.2x$
  – Qbox: up to 70%
  – CCDKernel: up to 22.6%
  – PSDNS-CCD3D: 3.5%

• Summary
  – Good for applications with heavy point-to-point communication
  – Harder to map applications with heavy use of collectives
Load balancing

- Many science applications (e.g. biology, cosmology, fluid) can exhibit load imbalance
  - Cores do different amount of work
  - All cores must wait for slowest core (many idle cores at very large scales)

- **Load balancing (LB) problem**:
  - Given set of tasks, each task $t$ has load $l_t$
  - Assign tasks to processors such that
  - Minimize maximum load $M$ (aka makespan) of processors
  - Performance can improve by up to $\frac{M^{\text{nolb}}}{M^{\text{opt}}}$
Challenges of load balancing in HPC

- **Increasingly larger machines**
  - Hundreds of thousands of cores, millions of tasks
  - Strong scaling makes tasks smaller, LB problem larger

- **Costs of LB in large parallel applications**
  - Collecting *statistics*
    - Efficiency of statistics communication
    - Comm-aware LB requires comm graph, but expensive to collect and use
  - Cost of calculating *task-to-core mapping*
  - *Migrating tasks*
    - Move fewer tasks
    - Move tasks within same node or nearby is cheaper
Load balancing with Charm++

- Charm++ provides automatic load balancing
  - Application transparent
  - Balance load within and across nodes

- How it works
  1) Runtime measures load of objects
  2) Calculates new assignment of objects to cores
  3) Migrates objects
Charm++ balancing results

Charm++ LeanMD results
LB for non-Charm++ applications

• Load balancing *library*
  – Subset of load balancing algorithms from Charm++
  – Application still has to measure load and move work

• AMPI
  – Run MPI applications on top of Charm++, without change (if no global variables) or by tagging globals
AMPI

- HARM3D: 10% speedup using Charm++ Greedy load balancer (of 20% max possible speedup)

- LULESH AMPI results
Types of load balancing

- **Centralized**
  - Global view of objects and cores

- **Hierarchical**
  - Cores/processes organized in tree structure
  - Information is aggregated in upper levels

- **Distributed**
  - Cores make decisions based on “local” info
Centralized load balancing

• *Greedy* heuristic very good for general load balancing problem
  – Sort objects by load, assign current object to current least loaded processor $O(n \log n)$
  – 4/3 (worst case) approximation ratio, cases where optimal or very close to optimal
• **But:** it can move all the objects, move them anywhere
GreedyRefine

- Greedy variant: in algorithm, assign current object to previous core if load doesn’t exceed a threshold $\Delta$, otherwise to least loaded
- $\Delta$ can be greedy maxload, or $\alpha \times \text{avgload}$ (avgload is lower bound of optimum maxload)
- Solution similar to greedy, while limiting object migration
- Load balancing time has been reduced by 4-7x compared to greedy
  - Less migrations
  - Faster implementation of algorithm
  - Performance optimizations in lb framework
- $\text{TopoGreedyRefine}$: constrain object migration to least loaded core in vicinity
# LB benchmarks

<table>
<thead>
<tr>
<th>Load balancing algorithm</th>
<th>Time per lb step (s)</th>
<th>Migration time per lb step (s)</th>
<th>Total program time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greedy</td>
<td>2.22</td>
<td>64.9</td>
<td></td>
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<tr>
<td>GreedyRefine</td>
<td>0.354</td>
<td>0.115</td>
<td>23.9</td>
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<tr>
<td>TopoGreedyRefine</td>
<td>0.316</td>
<td>0.064</td>
<td>19.93</td>
</tr>
</tbody>
</table>

- 3D stencil code with synthetic imbalance
- 1024 nodes on Blue Waters, 29k cores and 229k objects
- TopoGreedyRefine preserves initial mapping
  - Better communication performance
Hierarchical load balancing

- Added topology-aware trees
  - Tree is based on network topology
  - Cores are grouped based on their proximity

- NAMD
  - Uses hierarchical load balancing
  - Uses custom topology-aware load balancer
  - Topology-aware trees help preserve mapping: avg 10% speedup
Distributed graph refinement

- When load balancing, node sends load statistics to neighbor nodes
- Load tokens are exchanged between nodes to agree on load balancing
- Load is transferred after token exchange
- Can balance load and preserve topology-aware mapping
Summary

- Topology-aware mapping, load balancing important for efficient resource utilization
- Load balancing that preserves mapping efficient way to have best of both worlds
- Charm++ load balancing framework
  - Fast, scalable load balancing
  - Upcoming support for heterogeneous load balancing
  - AMPI applications automatically benefit
Vector Load Balancing

NullLB  GreedyLB  MultiGreedyLB  GreedyNormLB