Vector Load Balancing in Charm++

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Dynamic Load Balancing

- Adaptively arrange work on PEs to maximize performance
- Execution time often determined by maximum load on a PE
- Enabled by migratable objects, load measurement
- Necessary for scaling all but very regular, static applications

What is Load?

- *Load* is a proxy value used to represent *performance*
  - Metric measuring utilization of a resource over a period
- Real goal is to minimize execution time, not balance load
- Traditionally, balancing for equal CPU time per PE by itself has been sufficient for high performance
- However, can we do better by considering a richer set of metrics?

Vector Load Balancing

- Rather than being a single scalar value, *load* is now a vector of multiple values
- Composed of things like:
  - Various resource measurements, e.g. CPU/GPU/network/memory/IO
  - Timings of separate phases of an iteration
  - Application specific parameters, e.g. number of particles

Measuring Vector Loads

- Features and APIs to add vector load measurement have been added to Charm++
  - Application can add call to indicate phase boundaries, RTS will automatically measure per-phase load
  - Runtime flags to automatically add communication load (msgs, bytes sent)
  - Can specify load vector explicitly
  - GPU load, memory use, etc. in the works

Vector Balancing

- Extra dimensionality makes vector load balancing computationally difficult
- Objects can no longer be totally ordered
- Want to minimize the "maximum" over all dimensions simultaneously
  - Single variable optimization is now multivariable
- New LB strategies are needed

Vector Strategies

- A simple strategy finds the object with maximum load across all dimensions and places it on PE with minimum load in that dimension
  - Only works well when object has load in only one dimension, e.g. $(0, 0, 0, l, 0)$
- For more realistic cases, have to consider vector holistically

Holistic Vector Strategies

- Place objects based on largest load in vector as before, then refine partitions to improve balance (used by METIS)
- Find object with maximum norm and place on PE with minimum norm after placement
  - Works well, but computationally expensive
  - PE "weight" varies with object, i.e. $\|(2,0)\|_2 < \|(0,3)\|_2$, but when adding object with $(3,0)$, $\|(5,0)\|_2 > \|(3,3)\|_2$

NormLB - Exhaustive

- Initial implementation orders objects by norm and then does exhaustive search across all PEs for placement
  - Quality is exactly as desired
  - Performance is very poor ($\Theta(p \cdot o)$)

Method	Makespan	Strategy Time (s)
Greedy	1965.83	0.32
Norm	1674.86	22.72

Table: Greedy vs Norm (*1e4 PEs, 1e6 objs*)

NormLB - k-d

- To improve performance, we use a k-d tree to guide PE selection
  - Arbitrary dimension space partitioning tree
  - Allows PE search to be bounded as candidates are found
- k-d works well for searching in static point set, but here, tree updated after every assignment
  - Costly update operations
  - Pattern of updates often results in unbalanced tree
- Can be worse than the naïve exhaustive version!

Random Relaxed k-d

- Random Relaxed k-d trees help solve these problems; two key differences from standard k-d:

  Relaxed Instead of cycling through discriminants, $1, 2, \ldots, k, 1, \ldots$, each node stores arbitrary discriminant $j \in \{1, 2, \ldots, k\}$

  Random Discriminant is uniformly randomly chosen and each insertion has some probability of becoming the root, or root of subtree, . . .

Random Relaxed k-d

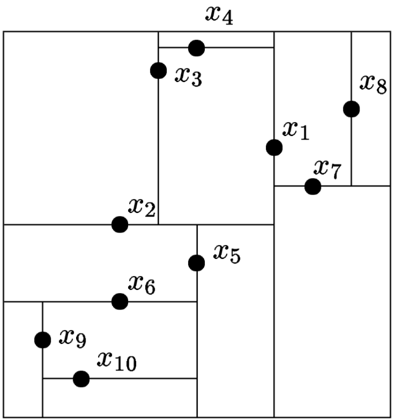


Figure: k-d

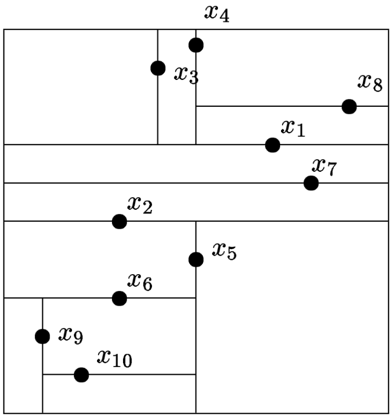


Figure: rk-d

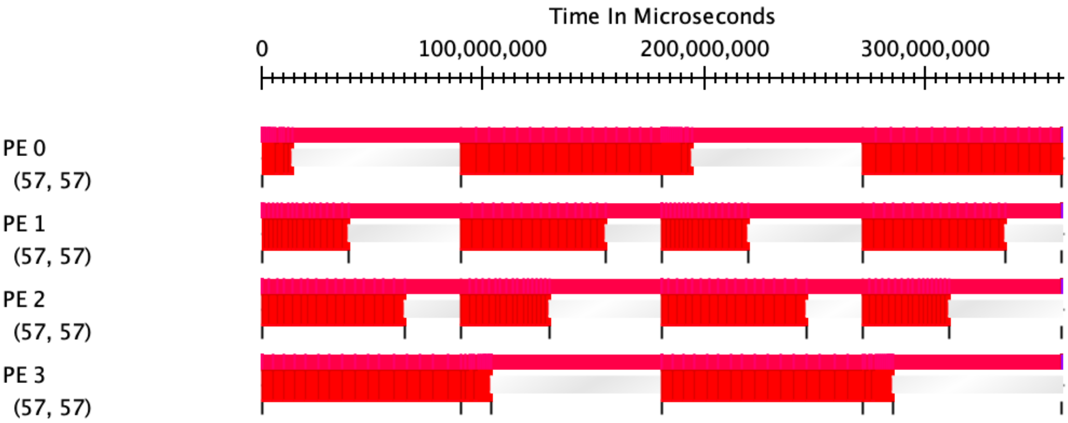
NormLB - rk-d

- These low-cost arbitrary updates and stochastic balancing improve LB (all provide same results)

Method	**Strategy Time (s)**	
	1e4 PEs, 1e5 objs	*1e4 PEs, 1e6 objs*
Exhaustive	2.18	21.54
Standard k-d	0.93	27.55
Relaxed k-d	0.57	7.96

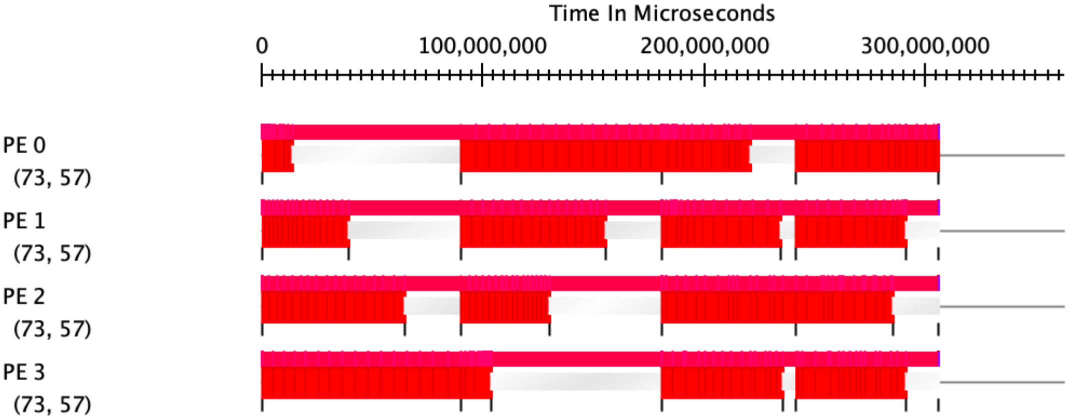
Table: Performance of Norm-Based Strategies

Vector LB Performance - AMPI



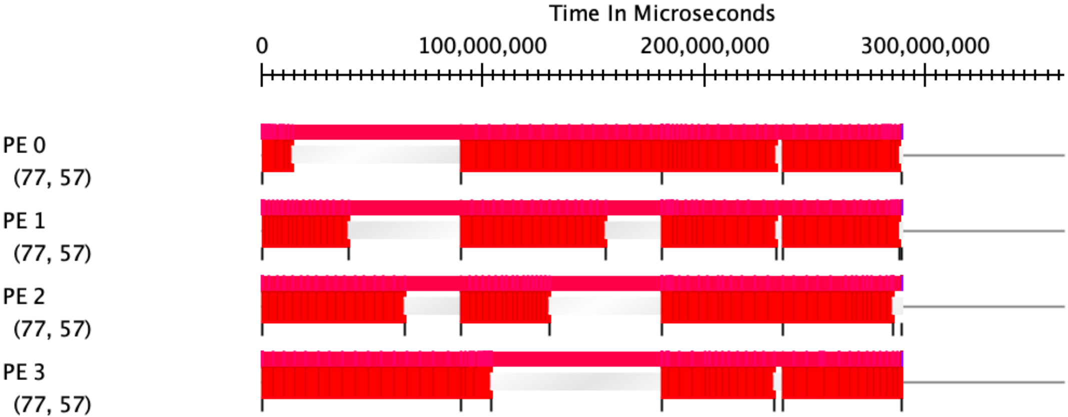
AMPI - No Load Balancing

Vector LB Performance - AMPI



AMPI - Regular Load Balancing

Vector LB Performance - AMPI



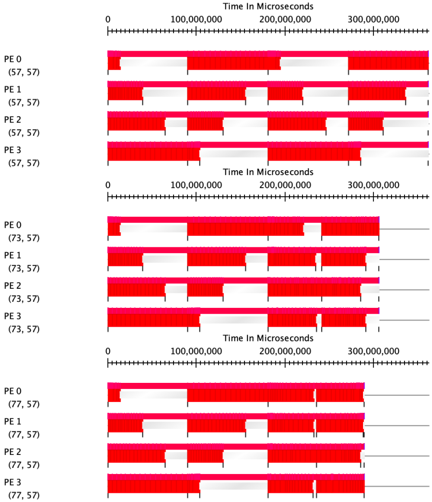
AMPI - Vector Load Balancing

Vector LB Performance - AMPI

LB Off

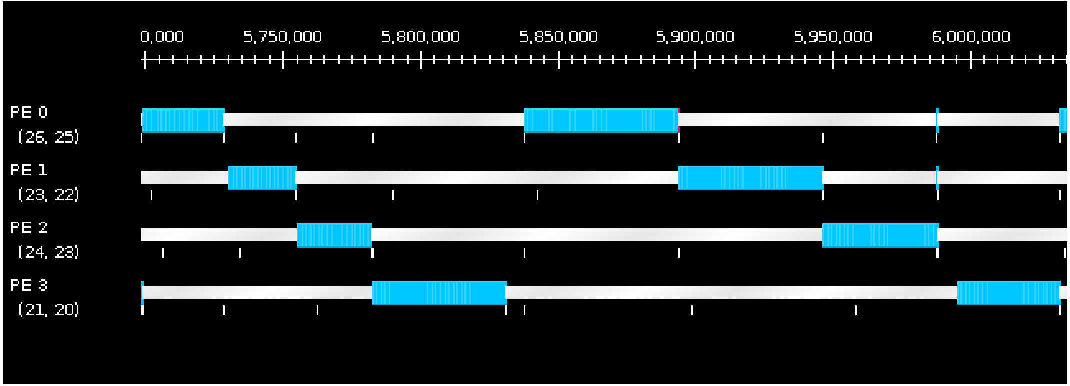
Phase Unaware
(1.44x speedup)

Phase Aware
(1.67x speedup)

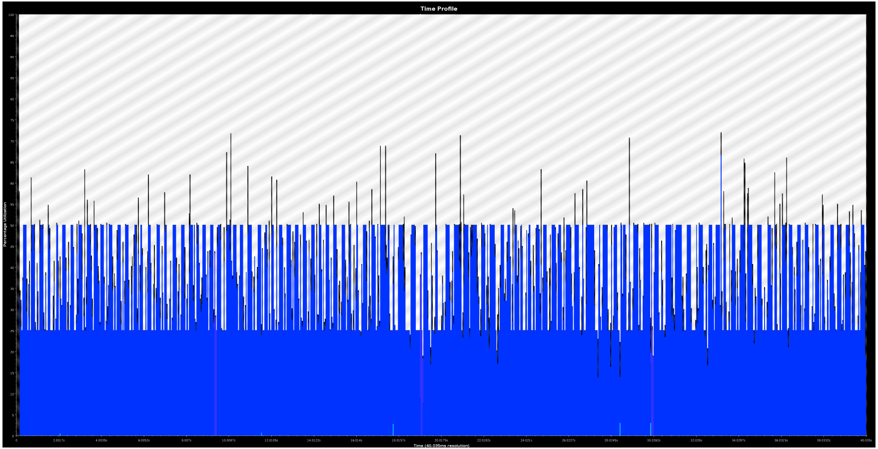


Vector LB Performance

Timeline of phase-based application:

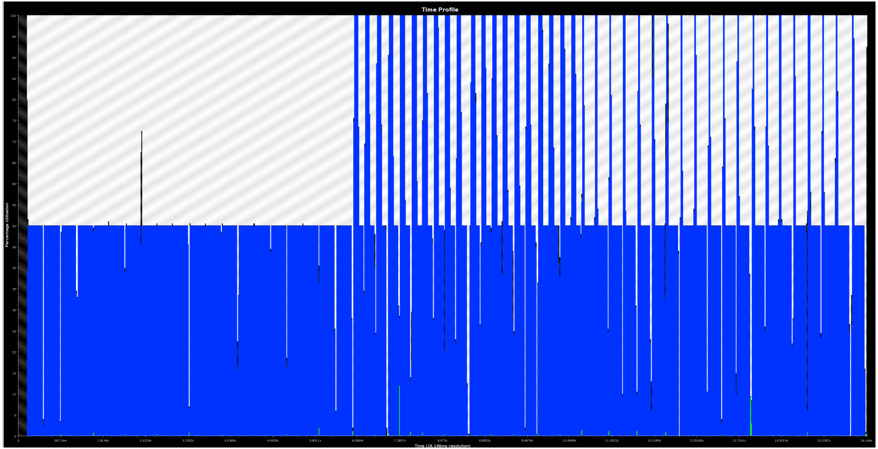


Vector LB Performance



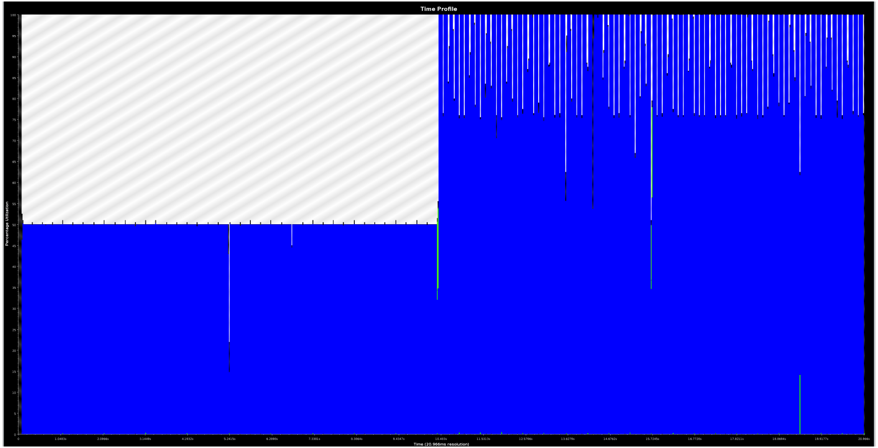
No LB

Vector LB Performance



Scalar LB

Vector LB Performance



Vector LB

Locality in LB

- Vector loads give performance insight with increased nuance and detail
- However, performance may also vary based on the location of objects
    - The distance between communicating objects changes latency, load on links, routers
    - Balanced via graph partitioners, geometric strategies
- Currently captured via RTS communication graph or application provided positions
    - For vector: first application positions, then comm graph

LB Position API

- Geometric strategies use *ad hoc* data passing
  - e.g. ChaNGa uses `LBRegisterObjUserData` to pass in `void*`
  - Each application needs its own custom LB strategies
- Adding standardized LB position API to Charm++
  - `setObjPosition(const vector<LBRealType>& pos)`
  - Allows positions of arbitrary dimension
  - Load balancers can opt-in for positions at registration time
- Allows for generic, application agnostic strategies
- Fully implemented, no results yet, currently testing with ChaNGa and other applications, slated in 7.1

Vector Geometric Strategies

- Currently using orthogonal recursive bisection with position API
- In scalar world, find split coordinate that minimizes differences in load between both halves
- In vector world, things are more complicated
  - Each dimension may have a different split coordinate
  - Select by taking average, minimizing square difference, etc.
  - Rather than splitting at a single coordinate, allow objects in some neighborhood to go to either half
  - Still topic of active experimentation

Future Vector LB Work

- Dimensionality reduction to simplify problem
- Performance can still be an issue
  - Have bounded versions of Norm LBs to tradeoff quality and performance
  - Further optimizations of search space are possible
  - Can use relaxation and approximation to tune
- Add support for constraint based objective functions rather than always minimizing everything
- Support for GPU, cache, memory, I/O load, comm graph

Conclusions

- Complex, modern applications need sophisticated performance measurement
- Combining different metrics into a vector has been shown to improve the quality of LB
- New techniques must maintain communication locality to be useful for certain class of applications