Using an Adaptive Mesh Refinement proxy code to assess dynamic load balancing capabilities for exascale

Rob Van der Wijngaart

Intel Labs, Intel Federal

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Agenda

- Background Parallel Research Kernels (PRK) Suite
- Motivation Adaptive Mesh Refinement (AMR) kernel
- AMR PRK specification
- Reference implementations
- Experimental results
  - Shared memory
  - Distributed memory
- Conclusions and future work

Background Parallel Research Kernels

Create test suite to study behavior of parallel systems

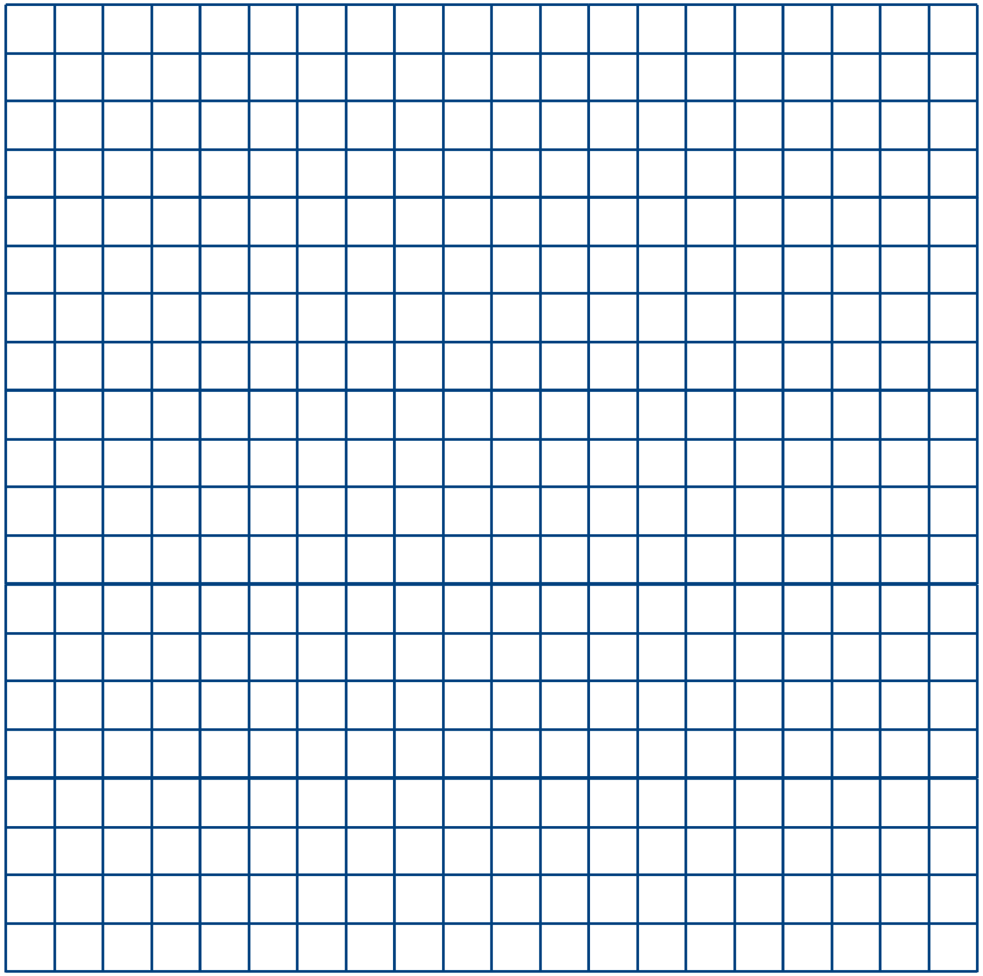
- Cover broad range of patterns found in real parallel applications
- Provide paper-and-pencil specification and generic reference implementations
- Keep kernels simple functionally
  - Easy porting to new runtimes/languages
  - Easy to understand by different domain scientists
  - Dominated by single feature, so convenient performance building block
- Parameterize kernels (problem size, iterations, # cores etc.)
- Make sure each kernel does actual work
- Include automatic verification test (analytical solution)
- Ensure enough expoitable concurrency (can be load balanced)
  - Make trivially statically load balanced

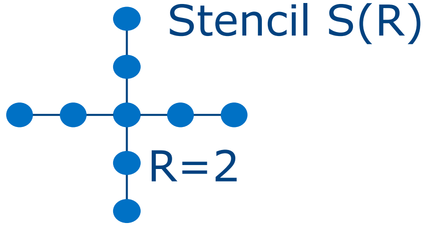
Motivation Adaptive Mesh Refinement (AMR) kernel

- However, exascale will require dynamic load balancing for mature workloads + system/network fluctuations
- Goal: Design and implement new kernels that:
  - Require dynamic load balancing at all system scales (algorithmic source)
  - Allow control of amount and frequency of workload adaptation
  - Have data dependencies, so load-balancing is non-trivial; improving load-balance usually increases communication
- Usage: Research vehicle to stress dynamic load-balancing capabilities of parallel runtimes + application frameworks
- Particle-in-Cell (PIC) PRK, IPDPS 2016: continually evolving mismatch between dependent data structures, fixed total work
- Adaptive Mesh Refinement (AMR) PRK, ISC 2017: abrupt, local variations in computational load (proxy for system disturbances), sudden increase/decrease in total work

AMR PRK Specification

Stencil PRK with Background Grid (BG) & periodic Refinement Grids (RGs)





Parameters:

- Size of BG
- Size + refinement level of RGs
- Frequency + duration of refinement
- Iterations on RGs

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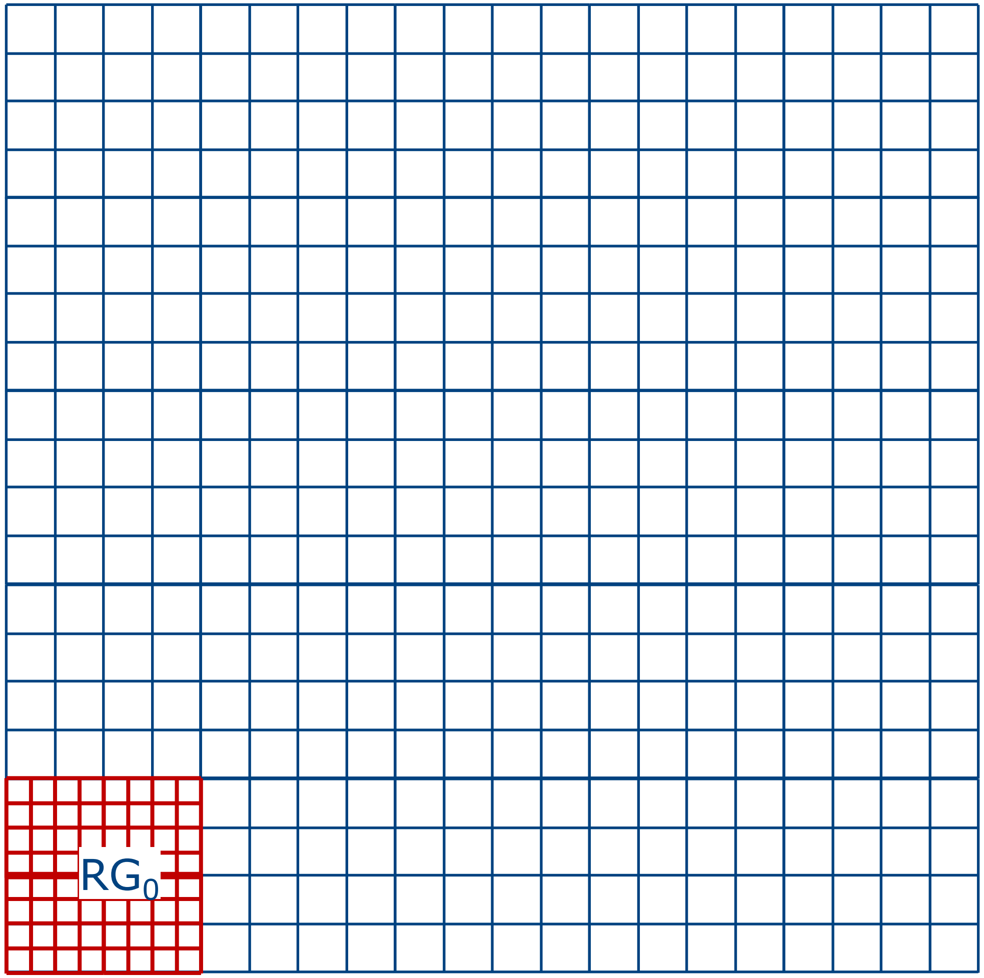

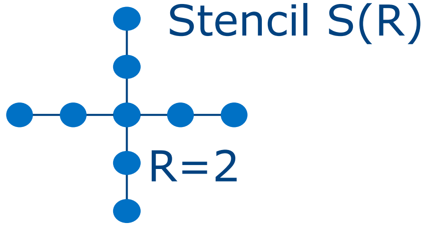

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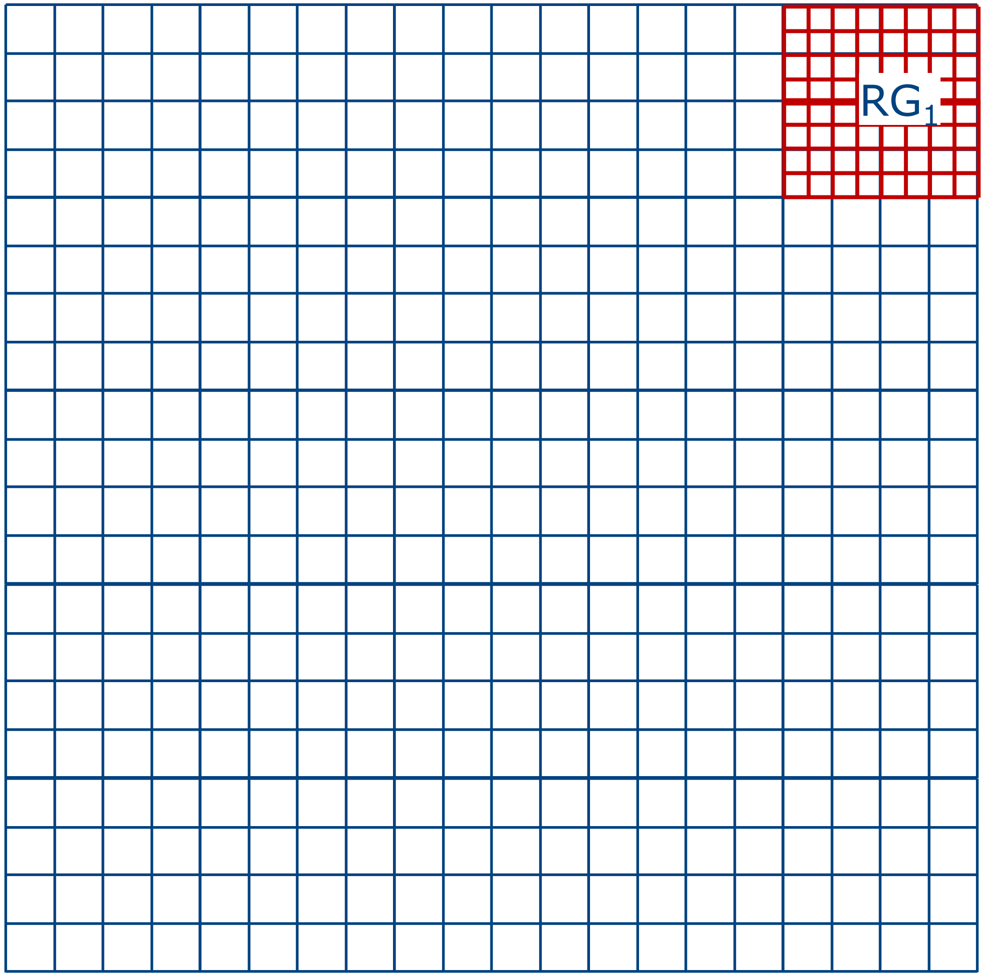

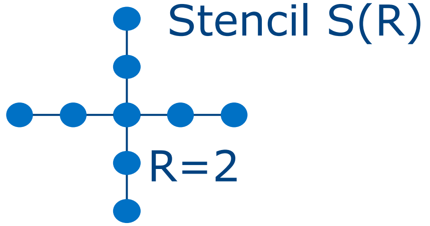

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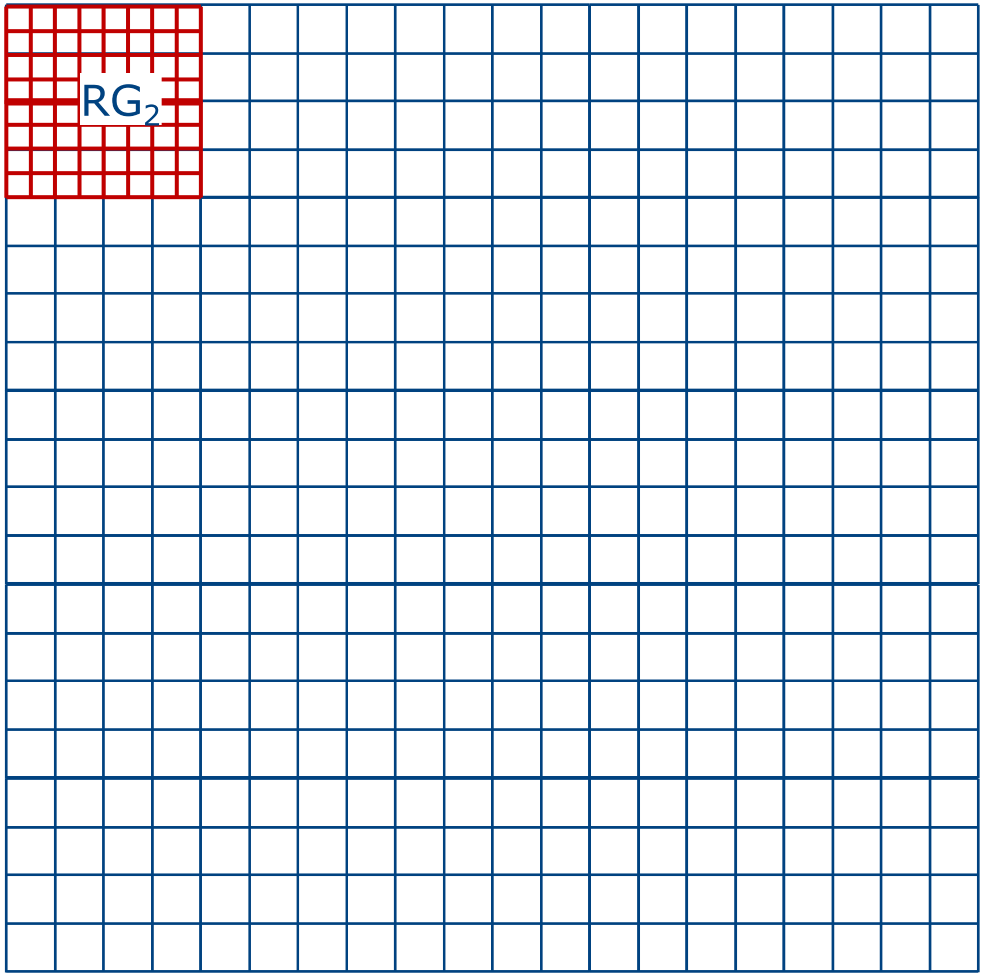

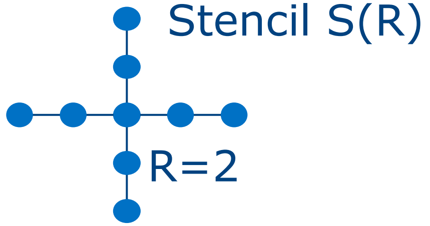

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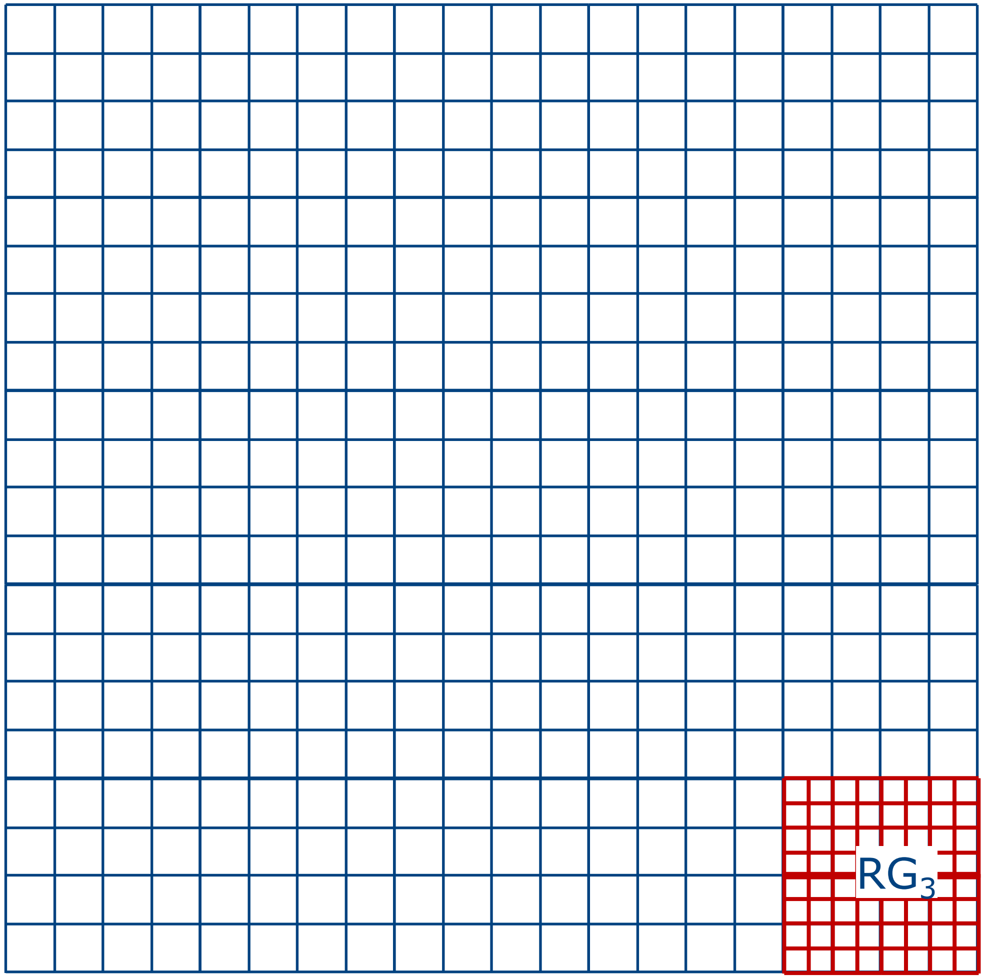

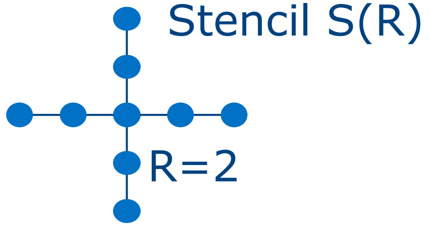

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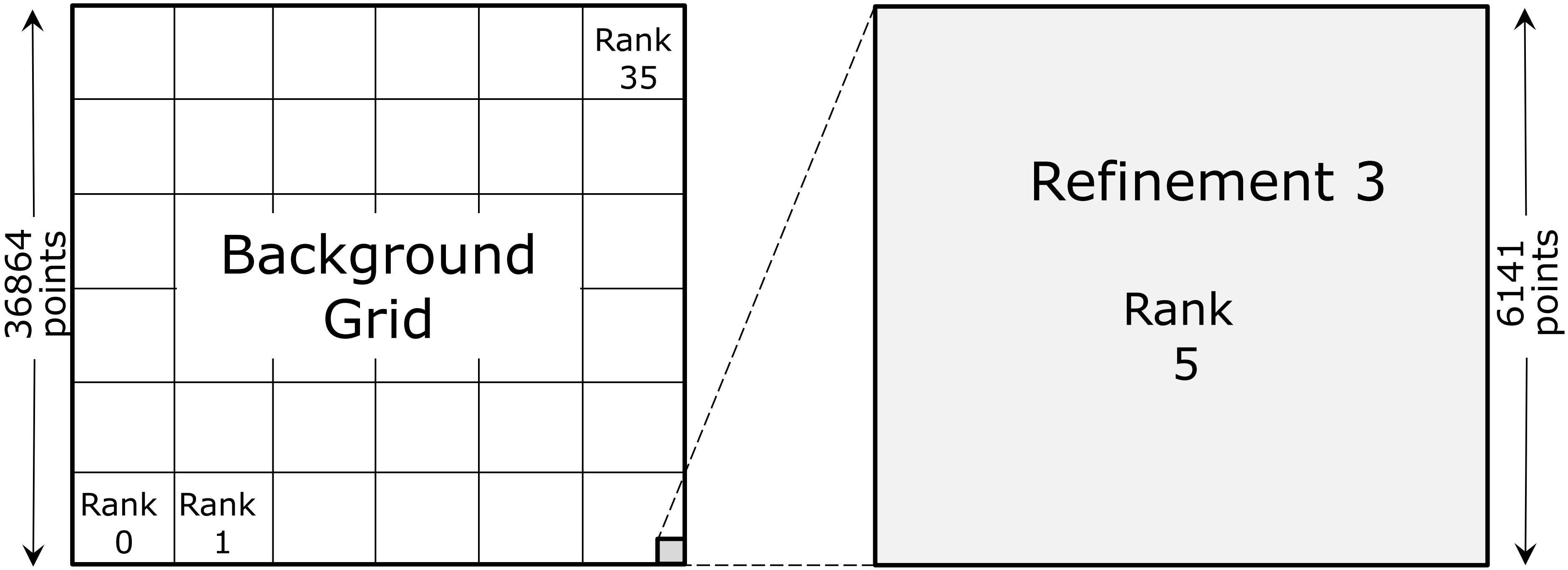
Reference implementations

- Application level "dynamic load balancing" (MPI)
  - No over-decomposition
  - When refinement appears:
    - FINE-GRAIN: Divide RG work evenly among all ranks
    - HIGH-WATER: Divide RG $\cup$ BG evenly among all ranks
    - NO-TALK: Assign RG work to rank(s) owning corresponding part(s) of BG
- Runtime orchestrated dynamic load balancing (Adaptive MPI)
  - Relies on canonical MPI partitioning (above), with over-decomposition

Experiments

- **Shared memory**: Intel® Xeon® E5-2699v3, 2.30 GHz, 64 GB memory, 2x18 cores (full occupation)
- **Distributed memory**: NERSC Edison, Cray XC30, Intel® Xeon® E5-2695v3, 2.40 GHz, 64 GB memory, 2x12 cores (full occupation)
- SMP experiment: NO_TALK, BG= 36864^2, RG=1536^2 (2-level refinement → 6141^2 points), 400 time steps, 1 RG iter/BG iter, RG Duration = {10,20,40} time steps, Period = 2*Duration Implications:
  - RG coincides with single BG patch, even with over-decomposition
  - RG size = BG patch size
  - #iters with refinements = #iters without refinements
- Adaptive MPI (AMPI): Over-decomposition = {2,4,8}, LB={refine,greedy}, migration delay = 1-5 time steps, use isomalloc to migrate ranks

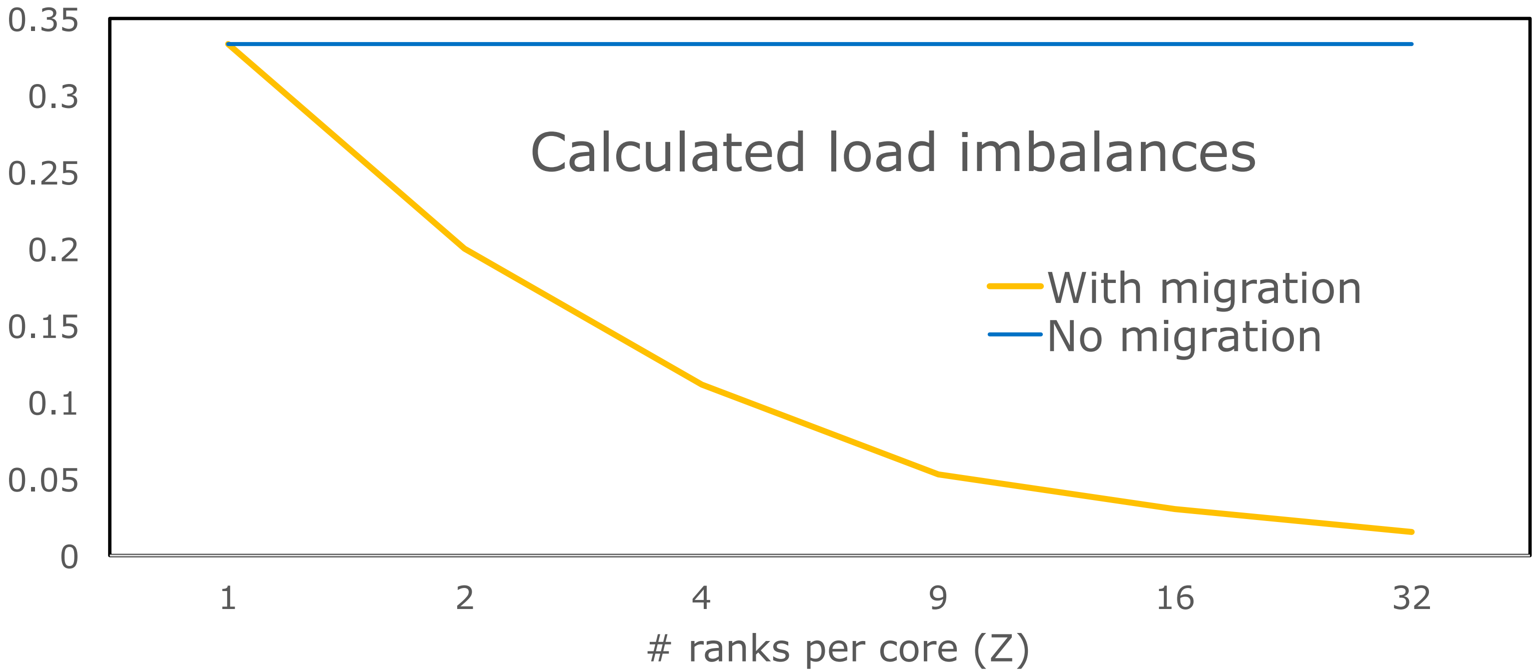
Experimental grid configuration



Work assignment policy NO-TALK

Experimental results, shared memory

- Theory (load imbalance = $1\text{-}T_{avg}/T_{max}$):
  - If over-decomposed (Z ranks per core) but no rank migration allowed (equivalent to plain MPI), load imbalance = 1/3
  - If rank migration allowed (optimum if core with RG rank moves off all ranks with only BG tiles), load imbalance = 1/(2Z+1)



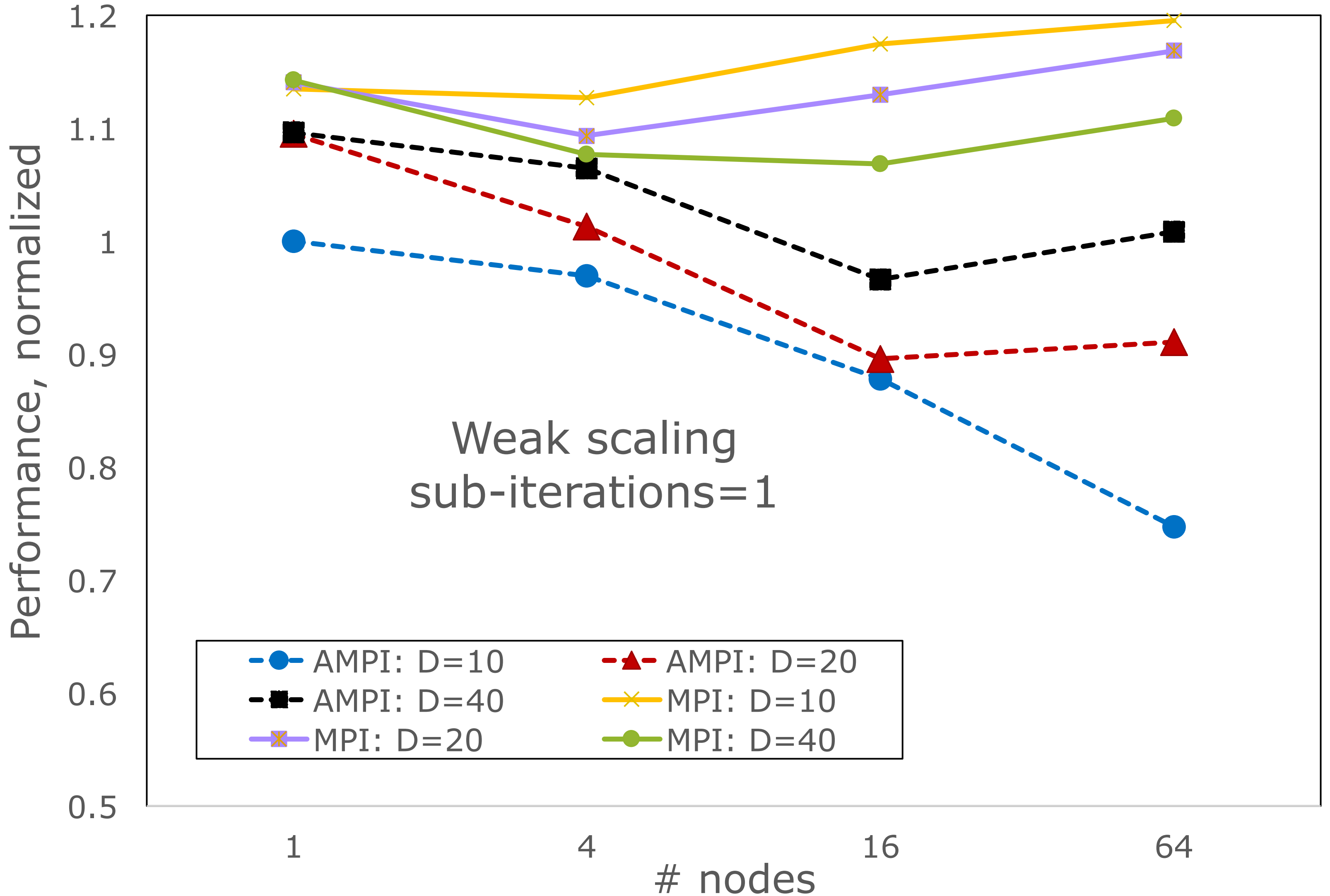
Experimental results, shared memory

- Observations:
  - LB=Refine: plain MPI and AMPI perform the same for all parameters: 41.1 GFlops/s ±2.7% (~5% migrate)
  - LB=Greedy: 35.5 Gflops ±5.3% (~100% migrate)
  - AMPI performance independent of "noise" frequency, migration delay, degree of over-decomposition
  - #ranks migrating irregular, despite regular disturbances
  - Plain Stencil PRK iteration times for RG on 1 rank and BG on 36 ranks 0.14s and 0.58s, respectively
  - If increasing work on RGs by 4x and 16x while keeping BG work unchanged, again AMPI perf ≈ plain MPI perf
  - If reducing RG and BG work by 16x (noise Hz 16x), AMPI perf for durations 20 & 40 ≈ plain MPI perf, but AMPI perf for duration 10 down 24%

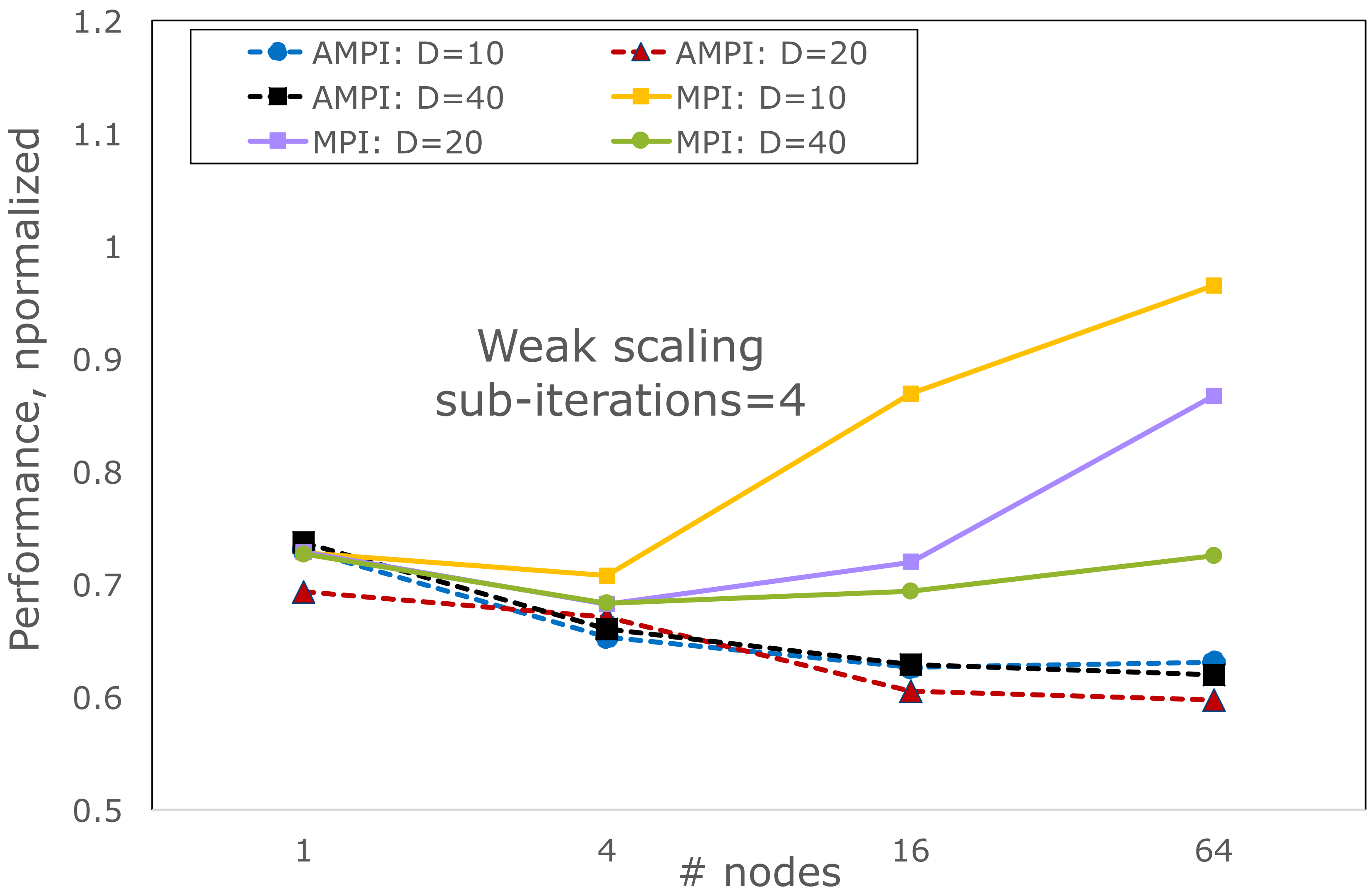
Experimental results, distributed memory

- Only used LB=Refine
- Weak scaling, so 4x number of nodes, BG grows by 2x in each coordinate direction
- RG size constant and same as in shared memory case: ratio of BG/RG work for rank receiving RG remains constant
- Fix overdecomposition at 4, migration delay at 2 iters
- Duration = {10,20,40}
- Use Pack/Unpack for rank migration
- First experiment: 1 RG iter/ BG iter (same as shared memory experiment).

Distributed memory results, 1 subiteration



Distributed memory results, 4 subiterations



Conclusions and future work

- Conclusions
  - AMR good, flexible proxy for localized disturbances
  - Adaptive MPI convenient vehicle for quick comparison with legacy runtime
  - Adaptive MPI implementation with dynamic load balancing does not manage to improve performance over non-adaptive MPI
- Future work
  - Repeat AMPI experiments with “oracle load balancer”
  - Test dynamic load balancing capabilities of other disruptive, task-based runtimes (Legion, OCR, HPX3/5) with AMR

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Backup material

Specification details

Parameters

- T : total number of iterations (background grid)
- R: radius of difference stencil
- n: linear dimension of square background grid (n^2 points, mesh spacing is unity)
- r: refinement level (mesh size of refined grid is 2^{-r})
- k: linear dimension of refinement in terms of BG cells ($(k*2^r+1)^2$ points in each refinement)
- P : duration in terms of iterations on the BG of one full cycle of activation of one refinement until that of the next (*period*)
- D: duration in terms of iterations on the BG of activity on each refinement; $D \leq P$
- d: number of iterations on a refinement per iteration on the BG

Specification details

(Re-)initialization

- $In[0](x,y) = c_x x + c_y y$
- $In_i[t] = \phi\,(In[t])$, with ϕ bi-linear interpolation (exact for linear field)

Update

- Increase In and In_i by constant after each stencil application

Verification

- S is numerical equivalent of ∇ (exact for linear field): $\nabla(c_x x + c_y y + \text{const}) = c_x + c_y$
- Count number of iterations η_i on $g_i \rightarrow Out_i[T](x,y) \equiv \eta_i * (c_x + c_y)$
- $Out[T](x,y) = T * (c_x + c_y)$
- $In[t](x,y) = c_x x + c_y y + t$, so: $\underline{In[T](x,y)} = (c_x + c_y)(n-1)/2 + T$
- Count number of updates ν_i on g_i since last interpolation at time $\theta_i \rightarrow \underline{In_i[T](x,y)} \equiv (c_x + c_y) * k/2 + \nu_i + f(corner_i) + \theta_i$

$corner_i$ = coordinates of bottom left corner point of g_i

Three example AMR scenarios

1. n=1000, 10 workers, r=1, k=100, P=3, D=1, d=1. Refinement has 1% of work of BG, lasts 1 iteration, then waits for 2 iterations until next refinement. OK to add refinement work to worker covering same part of BG (~10% load imbalance)
2. n=1000, 100 workers, r=1, k=100, P=3, D=1, d=1. Not OK to add refinement work to worker covering same part of BG (100% load imbalance). Rapid (dis)appearance requires frequent load balancing
3. n=1000, 100 workers, r=4, k=6, P=30, D = 10, d = 5. Refinements ≈number of grid points as in scenario 1, but cover much smaller fraction of the BG; activated 10x slower than in that case, persist 50x longer, so automatic load balancing may respond effectively to changes in load