Current state of the art QCD algorithms exploit the simplicity of a uniform space-time hypercubic lattice grid mapped onto a homogenous target architecture to achieve nearly ideal scaling. Nonetheless, this single grid paradigm is very likely to be modified substantially at extreme scales. Neither the lattice physics nor computer hardware are intrinsically single scaled. For example in QCD, uniquely non-perturbative quantum effects spontaneously break conformal and chiral symmetry giving rise to a ratio of length scales: \( m_{\text{proton}} / m_s \approx 7 \), which only recent advances in simulation are just beginning to fully resolve. As a consequence the most efficient Dirac solvers are just now becoming mult-scaled as well. Future advances will reveal more opportunities for multi-scale algorithms.

The exascale era promises to dramatically expand the ability of lattice field theory to investigate the multiple scales in nuclear physics, the quark-gluon plasma as well as possible dynamics beyond the standard model. Increasingly complex scale-aware QCD algorithms are a challenge to software engineering and the co-design of heterogeneous architectures to support them. At present the multi-GPU cluster offers a useful preview of the challenge at the level of 100's of cores per node with a relatively low bandwidth interconnect. Development of new algorithms to meet this challenging architecture include communication reduction by (Schwarz) domain decomposition, multi-precision arithmetic, data compression and on the fly reconstruction. The QUDA library[4] developed at Boston University is being used as a software platform for these early investigation.

Visualization of the scales in a gluonic ensemble. For example in QCD, uniquely non-perturbative quantum effects spontaneously break conformal and chiral symmetry giving rise to a ratio of length scales: \( m_{\text{proton}} / m_s \approx 7 \), which only recent advances in simulation are just beginning to fully resolve. As a consequence the most efficient Dirac solvers are just now becoming mult-scaled as well. Future advances will reveal more opportunities for multi-scale algorithms.

Adaptive multigrid automatically discovers the near null space to construct the coarse grid operator. Applied to the Wilson-clover Dirac inverter on 32\( \times \)256 lattice, it outperforms single grid methods by 20x at the lightest quark mass[2]. Extensions of adaptive multigrid are under development for Domain Wall and Staggered fermions as well as to Hamiltonian evolution for lattice ensembles.

The Force Gradient integrator is an optimized 4\(^{th}\) order multi-time step algorithm for Hybrid Monte Carlo (HMC) sampling of the gauge field ensemble. The error in the true Hamiltonian plotted as function of step size demonstrates its superiority for light quark masses[3].

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Visualization[1] of the scales in a gluonic ensemble a(lattice) \( \ll 1/m_{\text{proton}} \ll 1/m_s \ll L \) (box)

Heterogeneous Computer Architectures

At the same time hardware suited to exascale performance is expected to become increasingly heterogeneous with O(1000) cores per node, coupled to hierarchical networks -- the GPU cluster being an early precursor of this trend. As a test of concept the Wilson multigrid inverter combined with GPU technology is estimated to reduce the cost per Dirac solve by O(100).