High-performance spectral-element simulation of cardiac electrical function using GPUs

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Models of cardiac electrophysiology consist of a system of partial differential equations coupled with a system of ordinary differential equations representing cell membrane dynamics. Discretization with an average nodal spacing of 0.2 mm as required to prevent the onset of non-physical, spurious effects when these equations are solved numerically using finite element (FE), or finite difference (FD) methods generates a mesh with many millions of nodes, making whole heart simulation a demanding scientific computing problem. As an alternate choice, spectral-element method (SEM) can be adopted. SEM is designed to combine the good accuracy properties of pseudospectral techniques such as Legendre or Chebyshev methods with the geometrical flexibility of classical low-order FE methods. As a result, SEM is extremely efficient to model propagation phenomena on complex shapes using fewer mesh nodes than its FE equivalent (for the same level of accuracy).

Another issue is that current simulation software does not provide the required computational speed for practical applications. One reason for this is that little use is made of recent developments in hardware architecture for throughput-oriented computing and in the associated programming models, such as GPGPU (general purpose computation on GPUs).

Combining GPU programming with higher order discretization methods we developed a CUDA implementation of a spectral element code to perform the numerical simulation of cardiac action potential on a whole heart. We discuss the implementation and optimization of the code and compare it to an existing CPU based solver. We provide some examples that demonstrate the robustness of the method and the use of these numerical models, focusing specifically on some selected model problems.