The Virtual Heart: Working Towards Interactive CUDA Based Simulations of Cardiac Function

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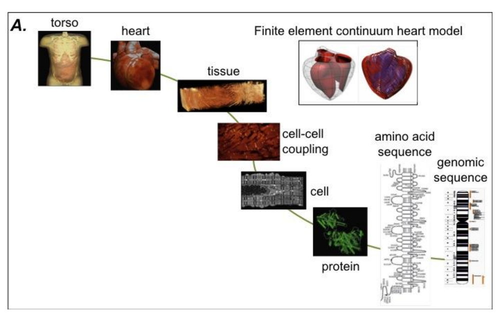
Introduction

Heart disease is the leading cause of death in the developed world. Despite this, our understanding of the mechanisms of cardiac dysfunction, particularly acute disorders related to the electrical system of the heart is limited. Our goal is to create a realistic virtual model of the heart to develop insight into this clinically important problem.

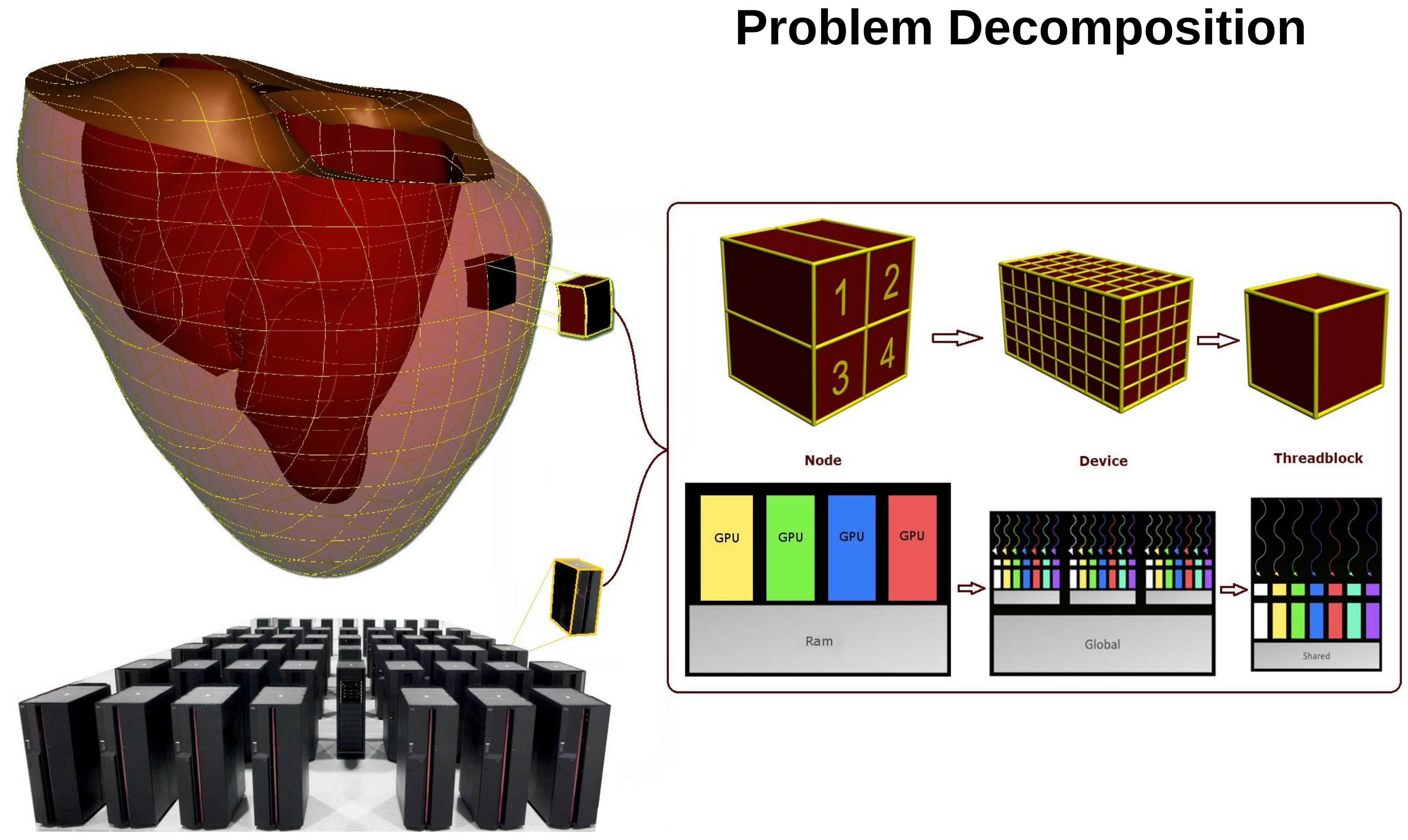


Using the multiscale modelling approach above, we began at the molecular level with mathematical descriptions of the ion channels, pumps and buffers present in every heart cell. Integration of these subcellular components reproduces the cardiac action potential waveform – the basic unit of cardiac electricity at the single cell level. From this building block we can extend our simulations to simple 1D, 2D and 3D arrays of cells before beginning to include descriptions of the overall architecture, anatomical detail and tissue heterogeneity necessary to simulate realistic hearts. At each level of complexity we have endeavored to gather appropriate experimental data to validate the model.

The computational complexity of the 'virtual heart' has been prohibitive until very recently. However, the continued development of massive parallelization using CUDA and GPU technology has now made this a realistic and achievable goal.

Enter CUDA

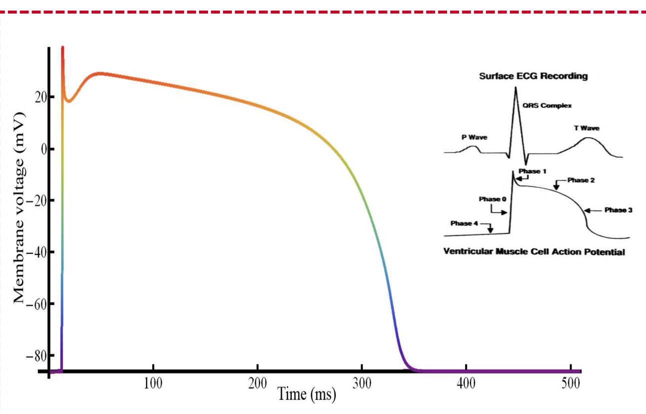
Problem Decomposition



The heart is composed of billions of interconnected cells. With this in mind we decided on a cell-centric, model. Working from the bottom up, each cell is handled by a single thread. In this way, the problem is sub-divided into chunks such that it maps onto the CUDA memory model and fits with the hardware in an optimal manner. Throughout this process there are many layers of abstraction that need to be considered – both from the biological and computational perspectives. From a CUDA point of view this is a consideration for performance and correctness. Synchronization is an integral component of such a system and it must be handled appropriately from the warp level, to the block level, the device level, the node level and finally the cluster. We expect our greatest challenge will be to handle this correctly and in a timely fashion so as not to inhibit scalability.

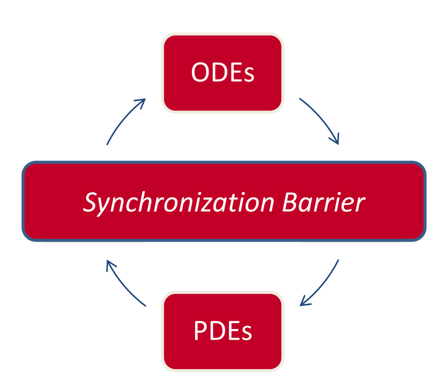
Progression

Single Cell



Our cellular model gives an output of voltage over time – an approximation of the cardiac action potential waveform. This involves solving a series of Ordinary Differential Equations (ODEs) about 100,000 times per second.

Multiple Cells



Each cell has an influence on others. So now, for each cell, and at each time step, the ODEs and Partial Differential Equations (PDEs) must be solved.

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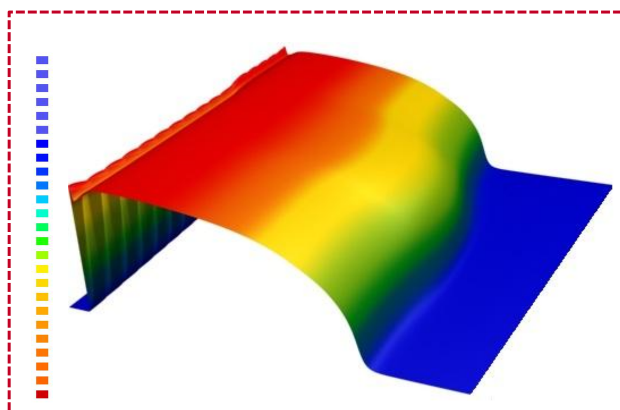
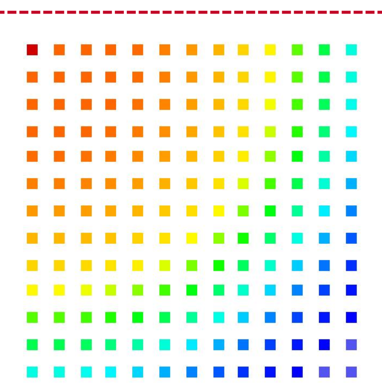
foreach (time step):
    solveODEs<<<g,b>>>(...);
    solvePDEs<<<g,b>>>(...);
```

Cable



The solution of the cable equation, a Partial Differential Equation (PDE), distributes the effect of changing voltage in each cell to all the others in a linear 'string' of cells. This allows us to simulate propagation of the action potential in one dimension.

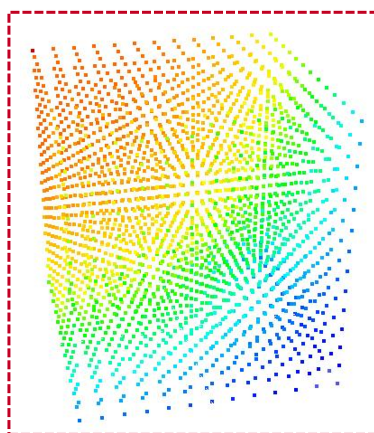
2D Array



We can simulate a sheet of tissue by extending the cable into two dimensions. The cable equation needs to be adjusted accordingly and even more thread divergence occurs.

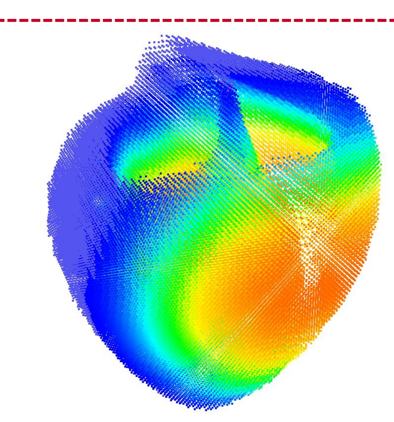
2D simulations can be experimentally verified using optical mapping of the surface of intact hearts.

3D Cube-Voxels



A cube – representative of a 'wedge' of cardiac tissue is formed by arranging cells along 3 dimensions and the cable equation is extended accordingly. At this level descriptions of simple tissue architecture such as fibre orientation and cellular distributions can be included.

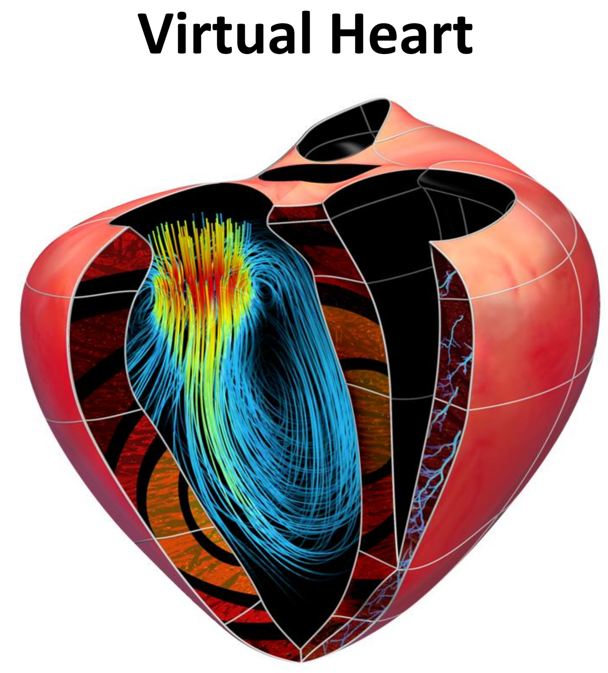
Heart-Voxels



The next step is to create a heart-shaped arrangement of voxels/cells. Every cell must now also know its position, orientation and type for the propagation algorithms to work correctly. 3D simulations can be experimentally verified using arrays of transmural plunge electrodes in intact hearts.

Future

Virtual Heart



Our long term goal is to develop realistic simulations of electrical activity in anatomically correct hearts. Our research will provide insight into how genetic defects in ion channel function as well as pharmacological agents contribute to arrhythmogenesis and sudden arrhythmic death.

Discussion points

Biological Complexity

- Billions of cells
- Multiple cell types
- Compartments
- Fiber orientation
- Fibrous and scar tissue
- Electrotonic interactions
- Cell contractility
- Fluid dynamics

Computational Complexity

Data Volume

- Outputting Data Is Slow
  - Device->Host->HDD transfer
- Lots of Data
  - Storage issue
  - Analysis issue

Synchronization

- Biggest Bottleneck
- Inter VS Intra Synchronization
- Many Levels
- Effects on Scalability
  - Device/Node Ratio
  - Many Node VS Many Device

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Heart Foundation ™