GPU TECHNOLOGY CONFERENCE

GPU Accelerated Solvers for ODEs Describing Cardiac Membrane Equations

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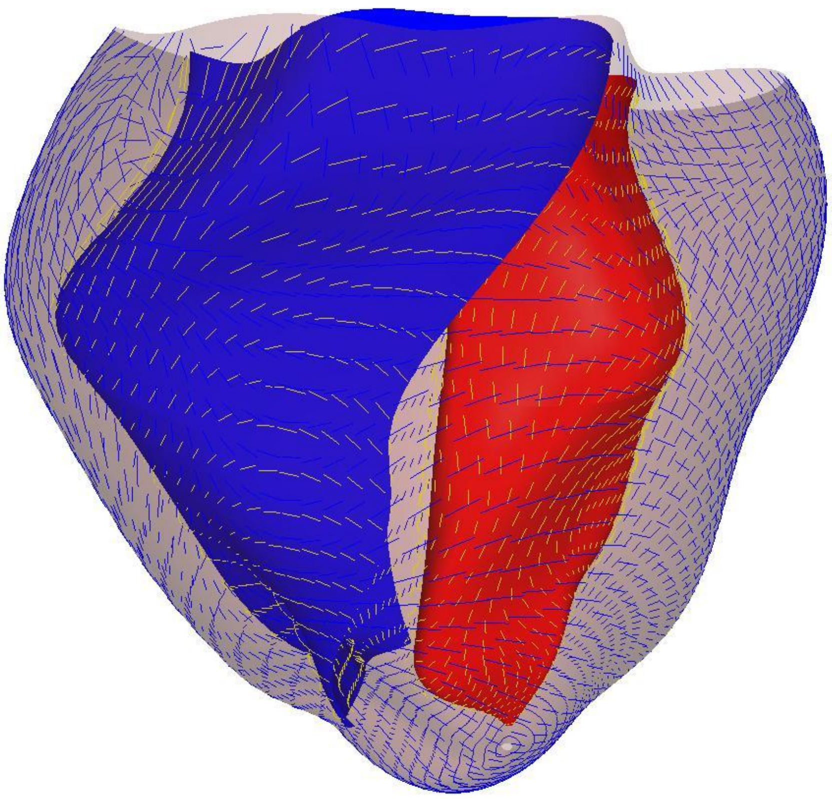
What is heart modeling?

- Bioengineer authors a mathematical model to describe certain aspects of the heart's behavior
- Develop and perform computer simulation of mathematical model

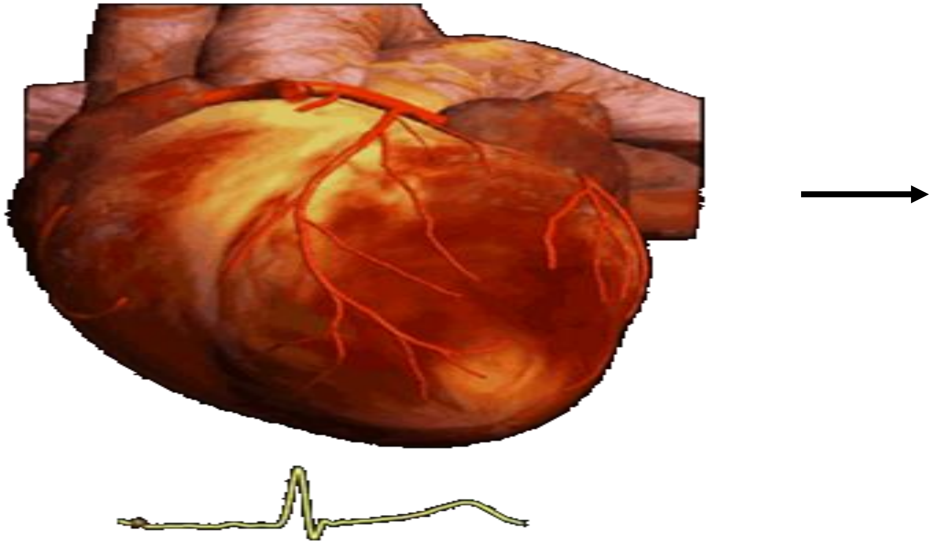


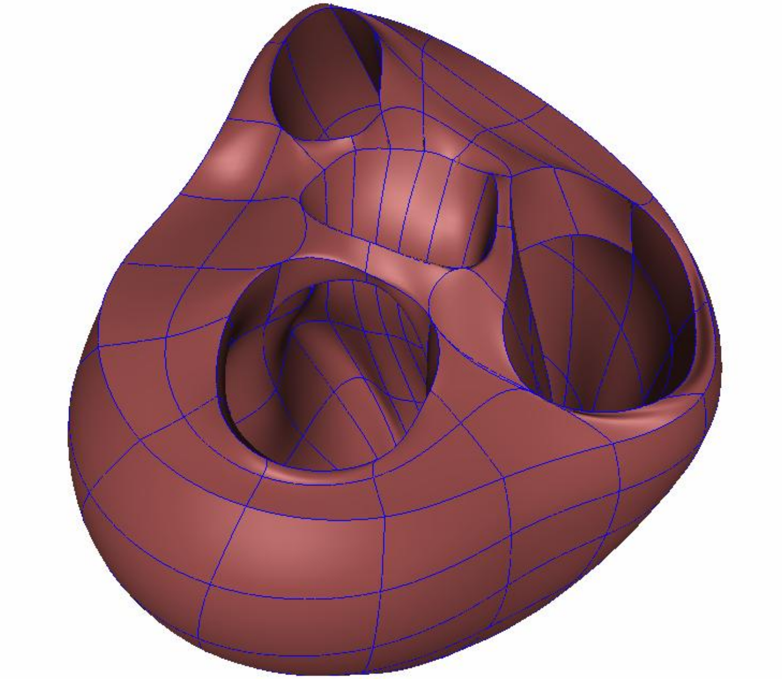
Why do heart modeling?

- Heart disease is the leading cause of death
- Basic Science
  - There still quite a bit about the heart we don't understand
- Clinical and therapeutic applications
  - Targeting ablation therapy for atrial arrhythmias
  - Defibrillator design
  - Cardiac resynchronization therapy (CRT)

How do we do heart modeling?

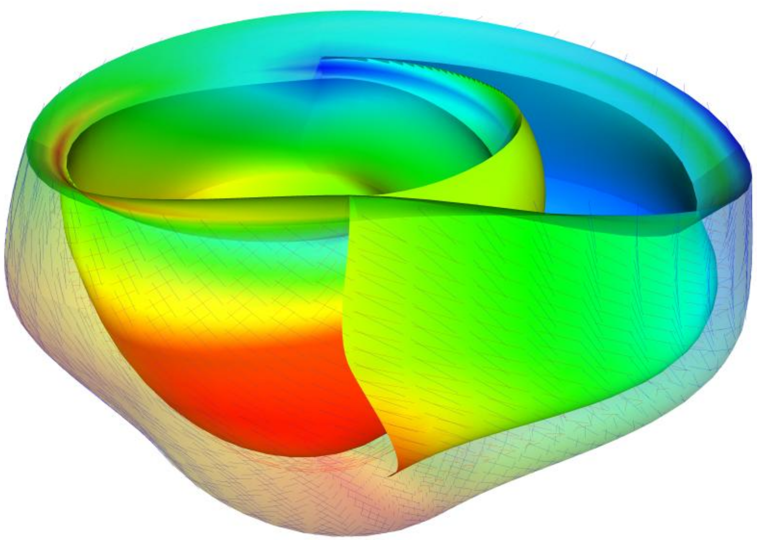
- Finite Elements Method
  - Discretizing a continuous domain into a set of discrete sub-domains.
  - Useful for bridges, airplanes, buildings, and even hearts



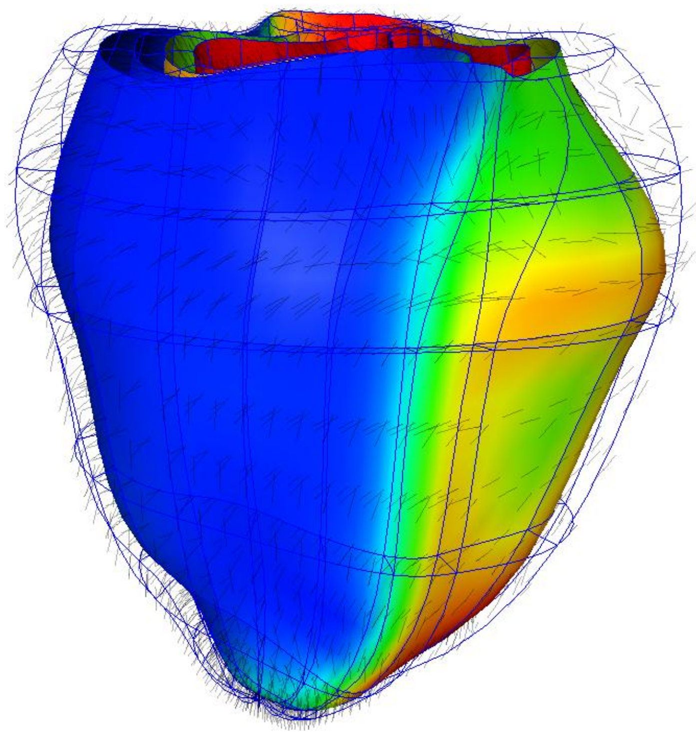


What kind of heart modeling simulations can we perform?

- Biomechanics

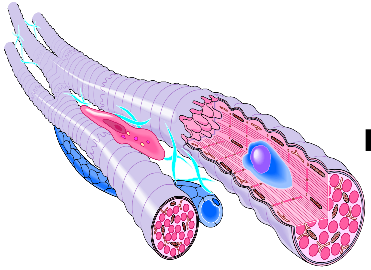


- Electrophysiology

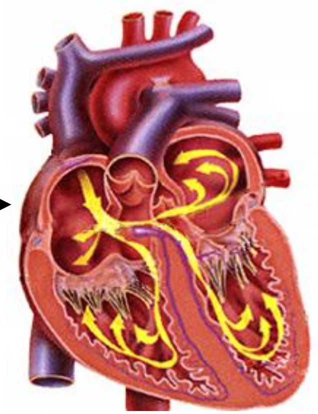


What are the bottlenecks?

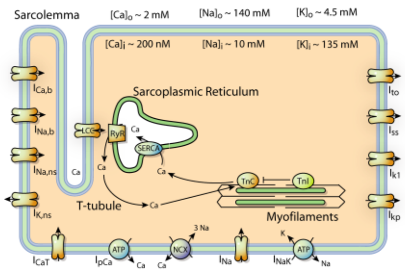
- ODEs = 98.7%
- PDEs = 1.3%



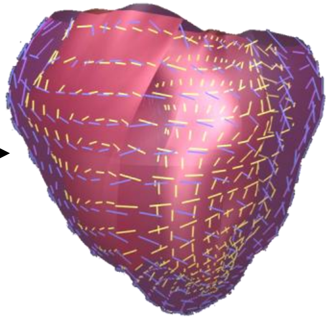
whole cell



ventricles



Whole cell ionic model (odes)



3-D mono- or bidomain finite element model (pdes)

How can we optimize our ODEs?

- Multithreaded OpenMP?
- MPI Cluster?
- GPU?

What about the GPU?

- Benefits
  - ODEs have thousands or even millions of data parallel threads
  - nVidia GPUs have peak GFLOP rates that are 1 to 2 orders of magnitude higher than a quad core processor
  - CUDA provides straightforward implementation

CUDA Acceleration Challenges

- Performance
  - Memory access
  - Thread Divergence
- Accuracy
  - Precision
  - CUDA math library
- CUDA Code Generation
- CUDA ODE solver
  - Too stiff for Forward Euler or Explicit Runge-Kutta
    - Capture processes on a wider range of time scales
    - Stiff if step size required for stability << required for accuracy
  - Simplified Single Iteration Backwards Euler solver
  - Adaptive solvers lead to thread divergence

The precision problem

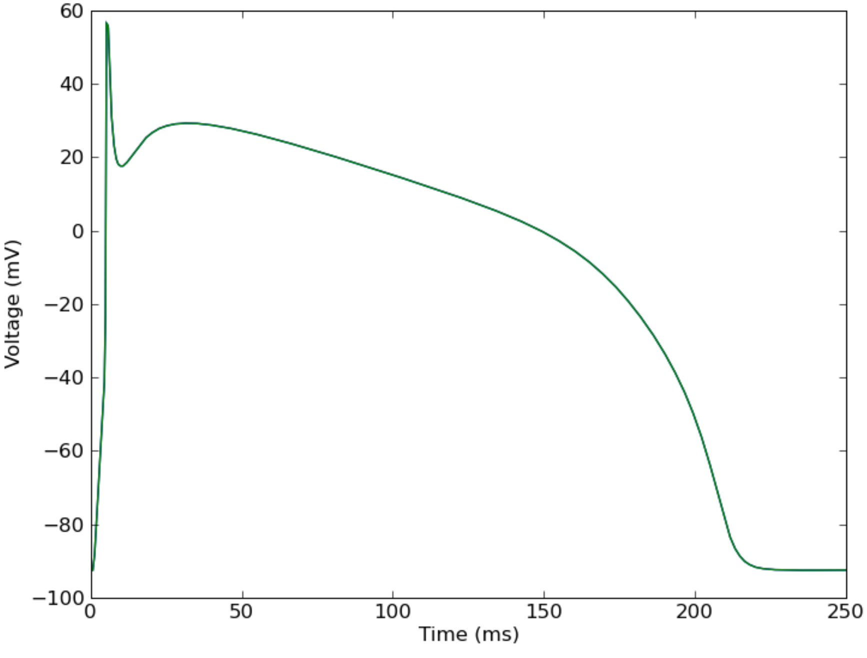
- Singularities at magic numbers
  - Nothing biologically significant about these numbers
- Must identify these problems and correct them
  - Reformulate equation
  - Add a workaround

$$a = \frac{b}{e^{voltage} - 1}$$

$$\lim_{v \to 0} \frac{1}{e^{v} - 1} = \infty$$

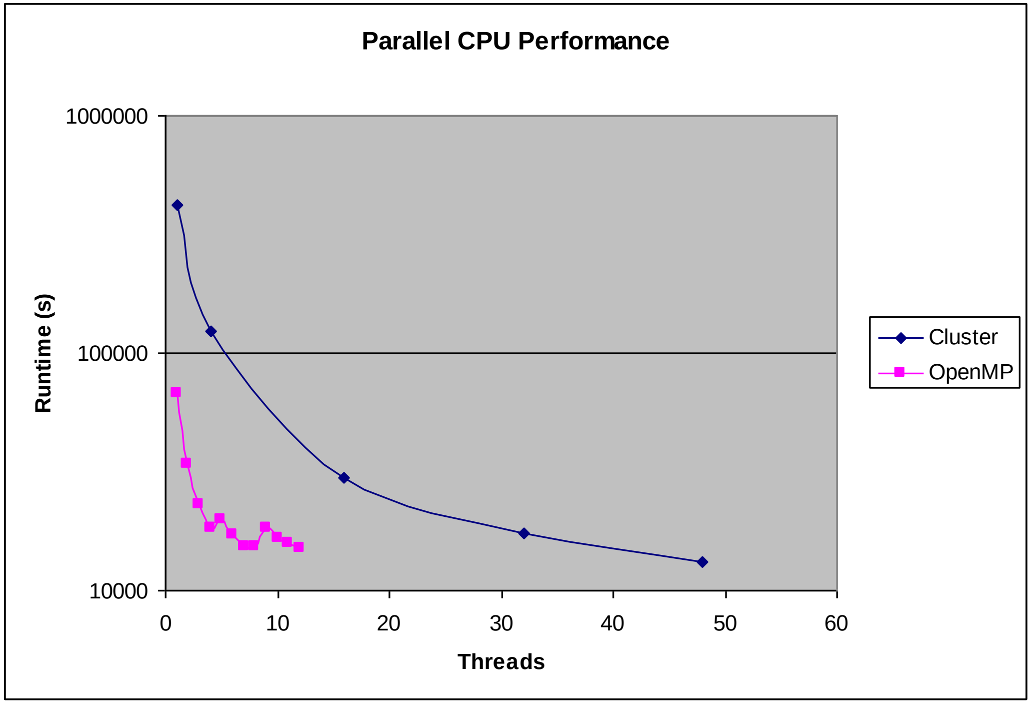
The Flaim Cell Model

- Developed by Sarah Flaim in 2006
- 87 ODEs
- Dog heart



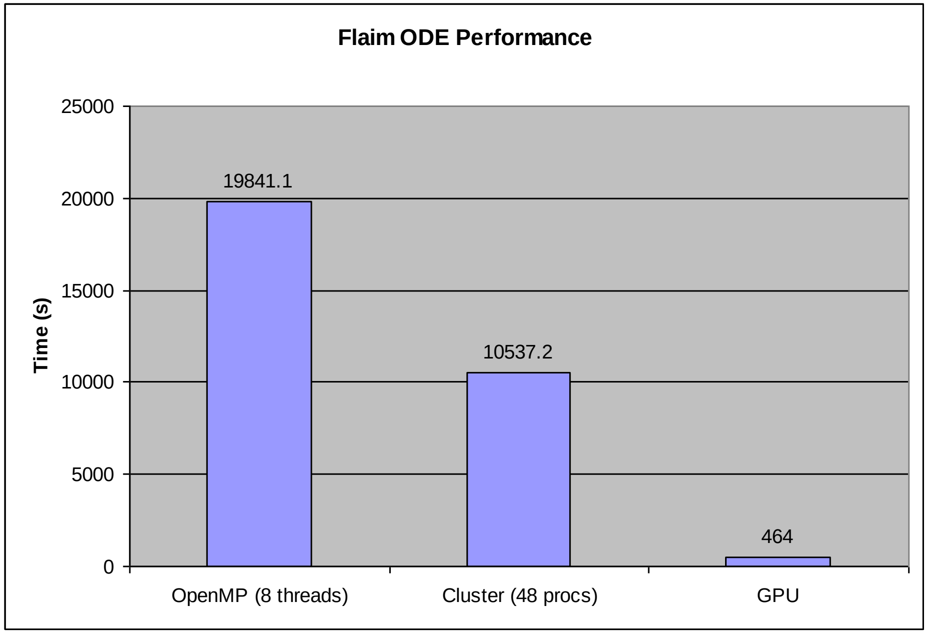
Conventional Acceleration of the Flaim Model

- Desktop (assembled in 2009)
  - Intel i7 quad core processor at 2.93GHz with 12 GB ram
  - OpenMP
- Cluster (assembled in 2007)
  - AMD Opteron 2216 dual core processors 2.4 GHz
  - Each of the 66 compute nodes has 4 cores, 4 GB of RAM.
  - MPI

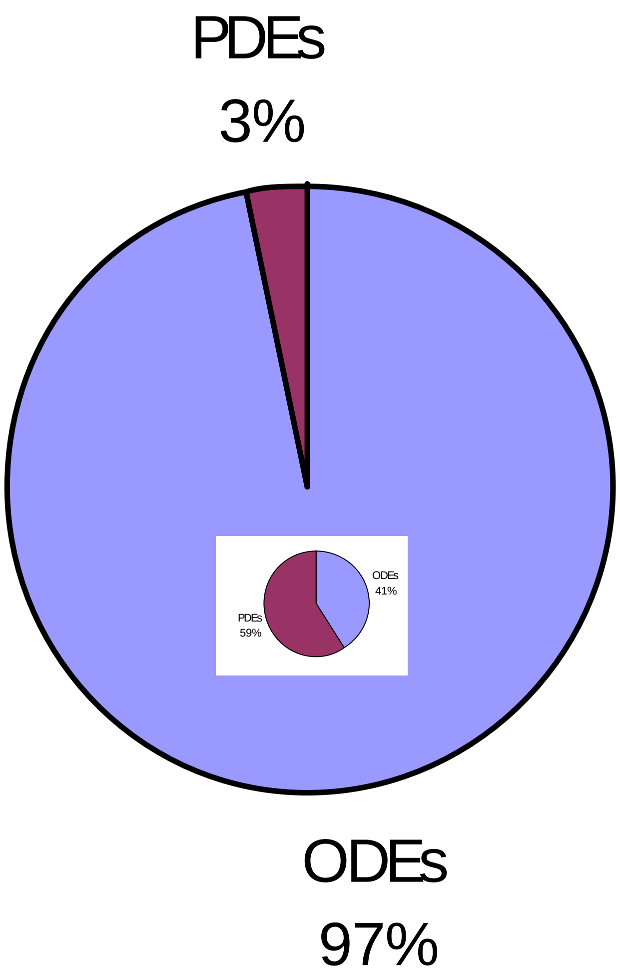


GPU Acceleration of the Flaim Model

- nVidia GTX 295
- Approximately 1 beat (300ms)
- Speedup Over OpenMP: 31x
  - 5.5 hours → 7.7 minutes
- Speedup Over Cluster: 23x
  - 3 hours → 7.7 minutes
- Singe Precision Error: 0.85%
- Excellent GPU Occupancy
  - 8 blocks of 64 threads



Electrophysiology Bottleneck



Cell Model Results

	Year	ODEs	Registers and local memory (words)	Speedup over OpenMP	Runtime CUDA (s)	Runtime OpenMP (s)	% Error
FitzHugh-Nagumo	1961	2	16/0	21.9x	7.8	171	0.06%
Beeler-Reuter	1977	8	32/0	172.2x	16.2	2789.1	2.23%
Puglisi	2001	18	32/60	63.7x	101.4	6461.1	1.34%
Flaim	2006	87	32/392	31.3x	462	14446.2	0.85%

Conclusions

- Single precision must be handled carefully, but is acceptable for many applications
- Maintaining high occupancy can be very important
- Went against some conventional wisdom
  - Spilling to local memory not so bad
  - Shared memory limited

The Future

- GPU is changing the way we think about heart modeling
  - A simulation that took 3 hours on our *cluster* can now be performed in ~7 minutes on a *desktop!*
  - Larger problems are now feasible
  - Essential component in hospital of the future?
    - Patient specific modeling
    - Much broader “parameter sweeps” now feasible
    - Interactive (e.g. real time) simulations are within reach for small problems
    - Save lives

Acknowledgements

- Stuart Campbell for the discussions on ODE Solvers
- Jazmin Aguado-Sierra for supplying the sample Electrophysiology model.
- Simula Research Lab
- National Biomedical Computational Resource (NIH grant P41RR08605) for the support of this work

Questions?