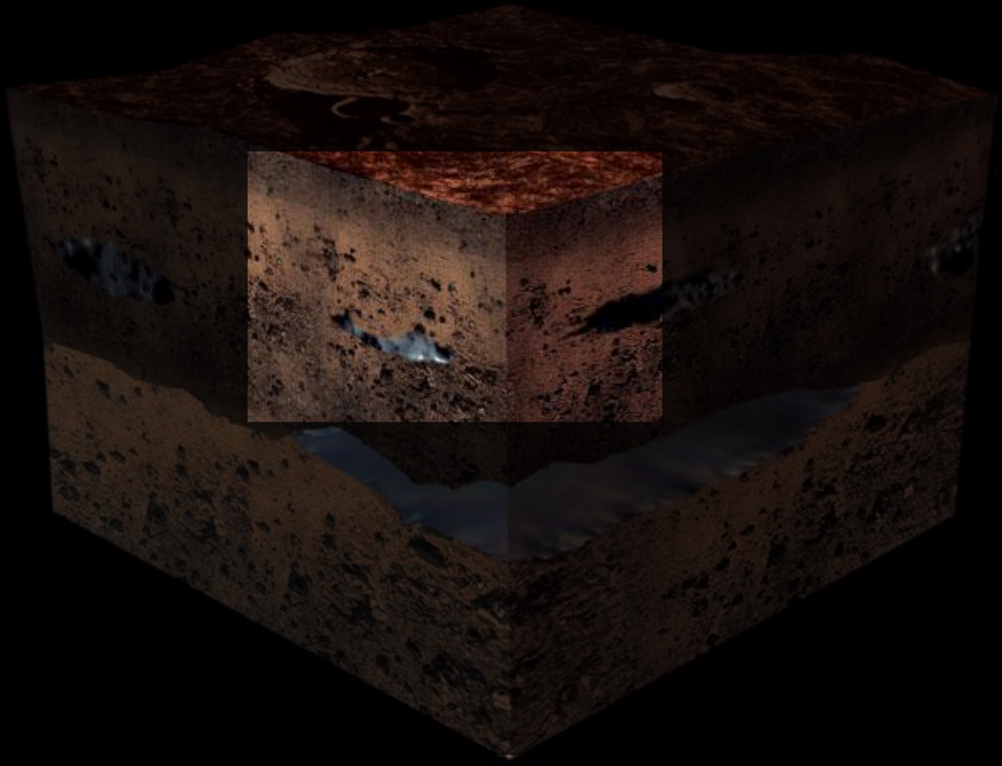
GPU TECHNOLOGY CONFERENCE

Scaling 3D Elastic Applications with Multi-GPU Systems

What is your view of the world?



Goal: Discover oil/gas

- Limited time
- Limited resources
- Reduce area of study

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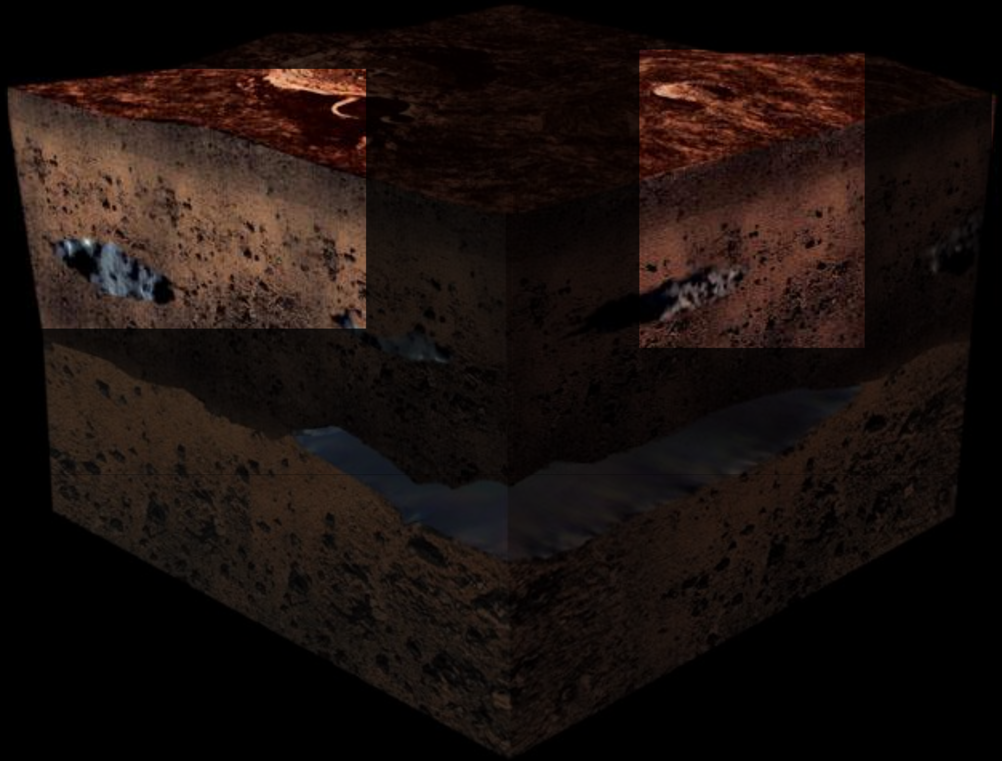

Add GPUs

- Process 5X faster
- Perform more studies
- Same amount of time

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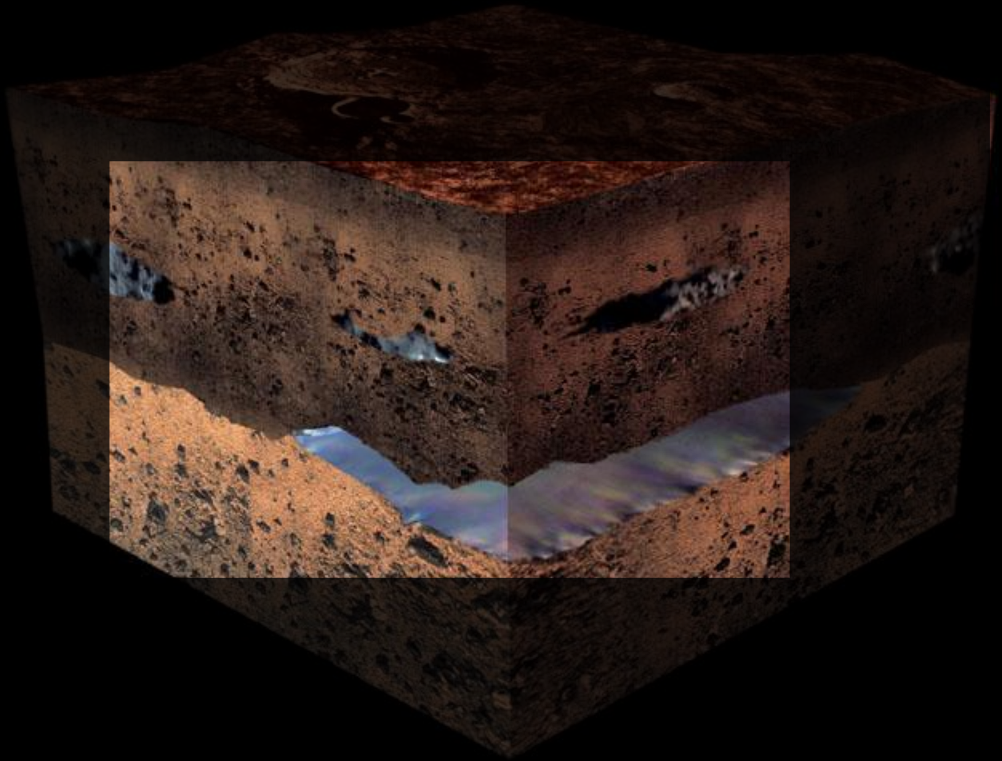
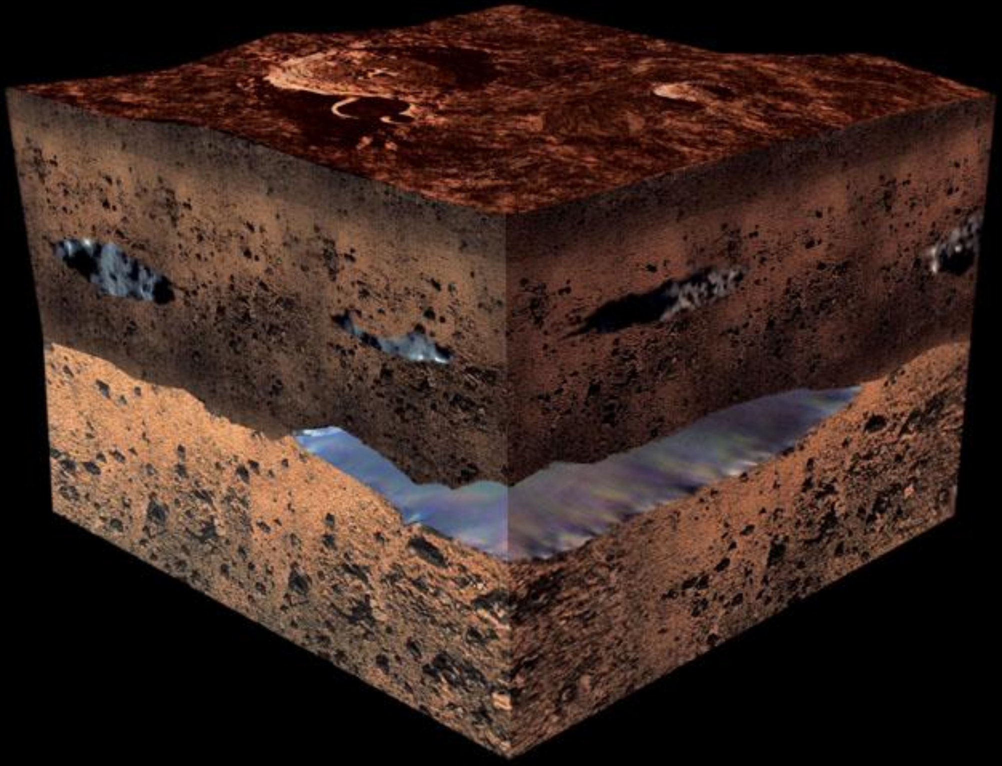


Add GPUs

- Also scale linearly
- Regional studies
- Same amount of time

What is your view of the world?



Add GPUs

- Reduce cycle time
- Improve earth model
- Understand reality

Seismic 3D Elastic Forward Wave Modeling

- Fit-for-GPU
- Acceleration with directives
- Method for sizing multi-GPU systems

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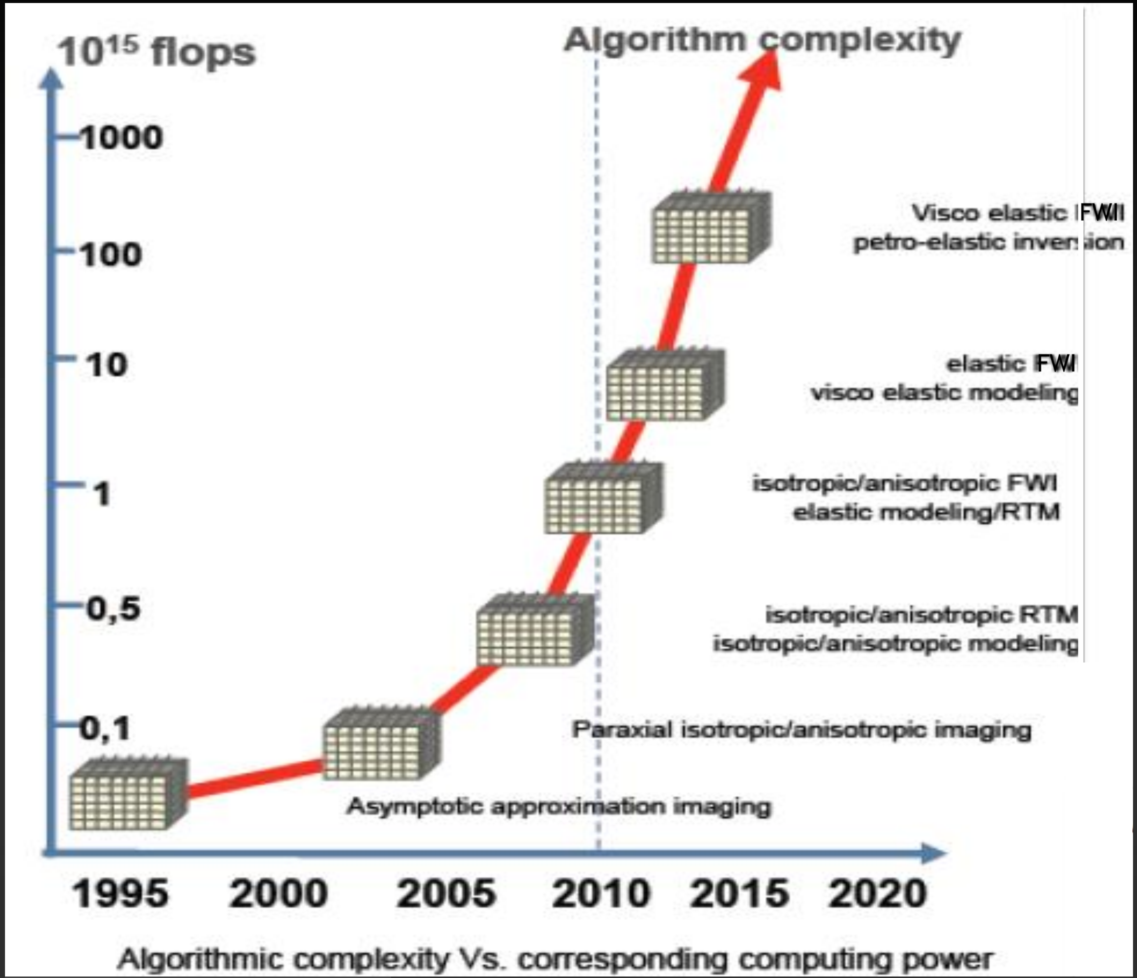
What are seismic modeling challenges?

Develop realistic earth models

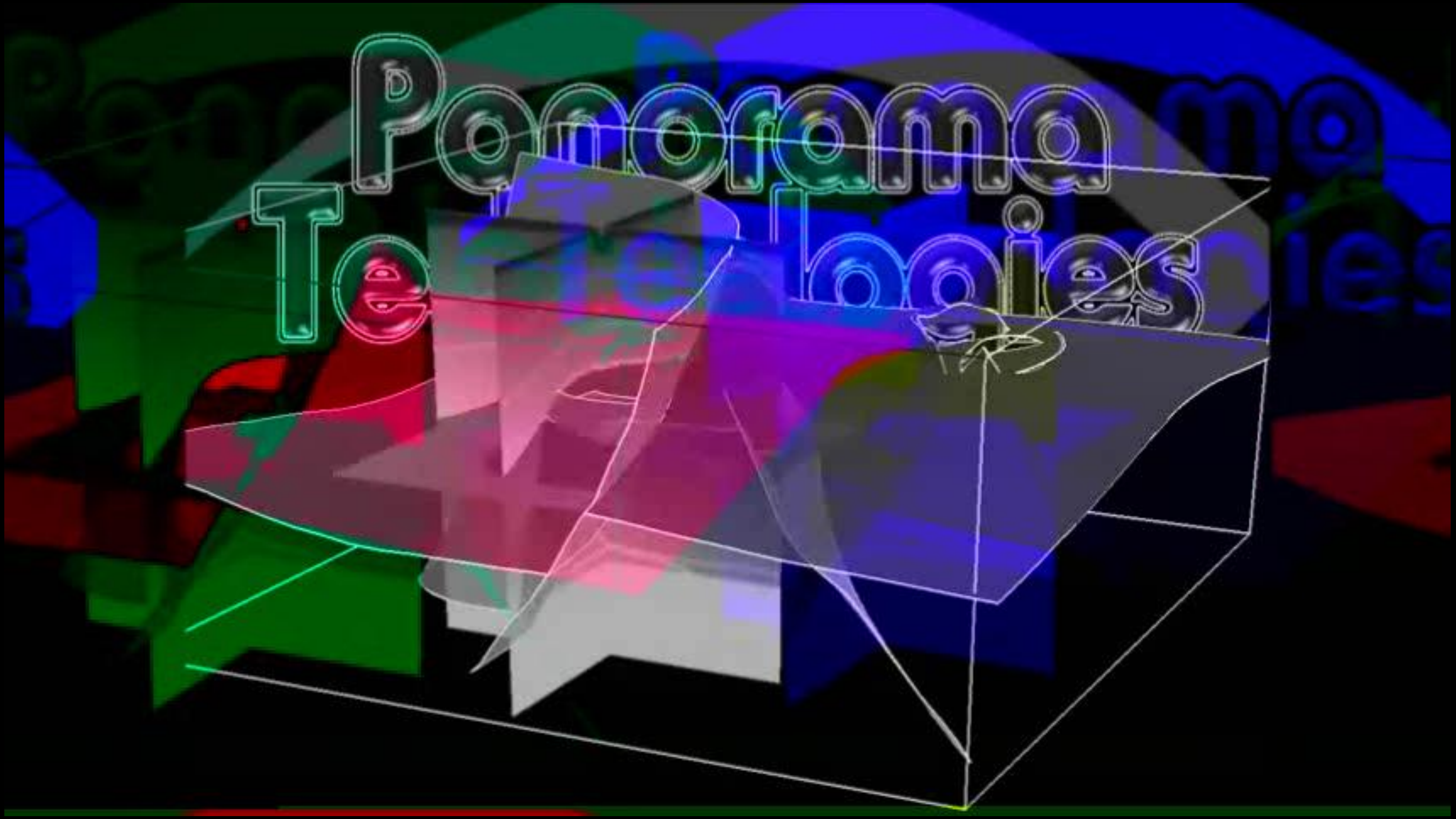
- Improve success rate for finding oil/gas
- Reduce risk and save money
- Compare synthetic seismic data to field data
- Refine layer properties (velocity, density, …)
- Optimize data acquisition strategies
- Maximize compute resources

Seismic imaging compute requirements



Source: exascale.org, TOTAL

Acoustic seismic wave modeling



Courtesy: Panorama Technologies

Why 3D elastic modeling?

Earth is heterogeneous and anisotropic

- Important oil/gas reserves hidden under geologic discontinuities
- Complex geology scatters seismic waves
  - Salt formations, faults, dipping layers, density contrast
- Acoustic methods make simplifying assumptions
- Use compression **and** shear wave formulation
  - Accurately model wave dispersion at discontinuities

What are 3D elastic modeling challenges?

Computer systems impose boundaries

- Discrete methods used to solve 3D wave equation
- Artificial edges from numerical grids
- Handle boundary conditions to absorb waves
- Divide domain to fit system requirements
- Single seismic shot records span multiple systems
- Need to store more field properties than acoustic

Research Project

- "Accelerating 3D Finite Difference (FD) wave propagation using GPUs" [1]
  - Extend 3D FDTD prototype developed by NVIDIA [2]
  - Convolutional Perfectly Matched Layer (CPML) boundary conditions
  - Velocity-stress formulation
  - Staggered grid, 4^{th} order space stencil, isotropic medium
  - Use GPU texture cache for absorbing layer
  - Use MPI to overlap communication and computation

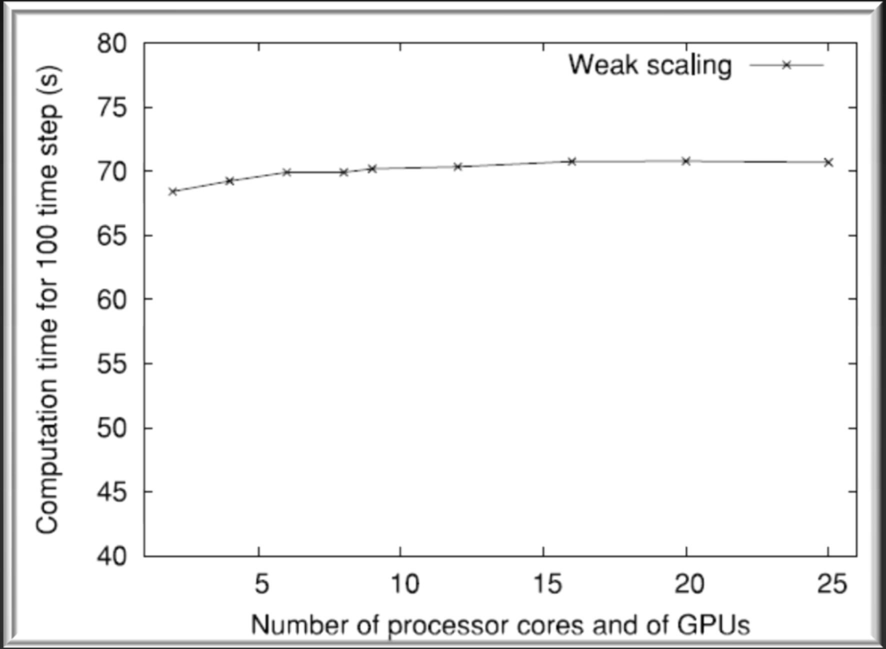
How do GPUs help accelerate imaging?

Natural domain decomposition

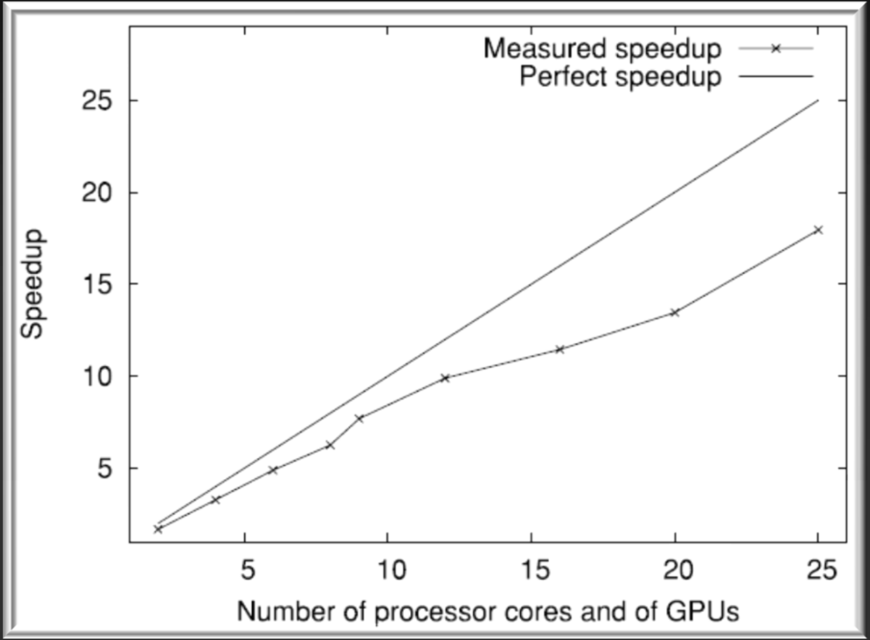
- Programming model grid of thread blocks
- Domain decomposition using 2D tiles
- Every grid point is a managed by lightweight thread
- Can benefit from shared memory and registers
- Can overlap communication with computation

Results

Multi-GPU cluster: Work/GPU constant



Multi-GPU cluster: Mesh size constant



Source: http://hal.inria.fr/docs/00/52/84/87/PDF/paper_David.pdf

Important 3D elastic modeling factors

- Computation patterns very similar to acoustic methods
- Elastic requires more property fields per grid point
  - Sub-domain dimensions per GPU may be smaller
- Stencil size
  - Smaller stencils require less memory accesses, however may not produce best image
- Grid implementation
  - Adjust mesh with depth

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Challenges

- Productivity
  - Focus more on Geoscience, less on computer science
- Portability
  - Unified approach that targets different accelerators
- Safety
  - Conservative approach that manages bookkeeping details
- Performance
  - Reuse common HPC patterns automatically

Solution: Accelerator directives

- Directives are added to source code
  - Manage loop parallelization
  - Manage data transfer between CPU and GPU memory
- Works with either C or FORTRAN
  - Can be combined with explicit CUDA C/FORTRAN usage
- Directives are formatted as comments
  - Do not interfere with serial execution
- Maintains portability of original code

Proof of Concept

- Seismic CPML [3]
  - Collection of 10 open source FORTRAN programs
  - Solve elastic wave equation
  - 3D FDTD, 4th order space, 2nd order time, isotropic medium
- Portland Group (PGI) Accelerator Directives
  - Mathew Colgrove, PGI [4]

Methodology

Use The Portland Group Accelerator Tools

- Identify Critical Regions
- GPU Device Assignment
- Add Compute Regions
- Add Data Regions
- Optimize Data Movement
- Optimize Loop Schedules

Identify critical performance regions

- Use PGI compiler as tool to identify opportunities
  - Complements profiler (PGPROF, or NVIDIA Visual Profiler)
  - Use built-in timing capability (compile option: -ta=nvidia,time)
  - Warn about data dependencies
  - Inform about data movement situations

Compute Region

```
!$acc region
do k = kmin,kmax
  do j = NPOINTS_PML+1, NY-NPOINTS_PML
      do i = NPOINTS_PML+1, NX-NPOINTS_PML

          total_energy_kinetic = total_energy_kinetic + 0.5d0 * rho*( vx(i,j,k)**2 + vy(i,j,k)**2 + vz(i,j,k)**2)

          epsilon_xx = ((lambda + 2.d0*mu) * sigmaxx(i,j,k) - lambda * sigmayy(i,j,k) - lambda*sigmazz(i,j,k)) / (4.d0 * mu * (lambda + mu))
          epsilon_yy = ((lambda + 2.d0*mu) * sigmayy(i,j,k) - lambda * sigmaxx(i,j,k) - lambda*sigmazz(i,j,k)) / (4.d0 * mu * (lambda + mu))
          epsilon_zz = ((lambda + 2.d0*mu) * sigmazz(i,j,k) - lambda * sigmaxx(i,j,k) - lambda*sigmayy(i,j,k)) / (4.d0 * mu * (lambda + mu))

          epsilon_xy = sigmaxy(i,j,k) / (2.d0 * mu)
          epsilon_xz = sigmaxz(i,j,k) / (2.d0 * mu)
          epsilon_yz = sigmayz(i,j,k) / (2.d0 * mu)

          total_energy_potential = total_energy_potential + 0.5d0 * (epsilon_xx * sigmaxx(i,j,k) + epsilon_yy * sigmayy(i,j,k) + epsilon_yy *
              sigmayy(i,j,k)+ 2.d0 * epsilon_xy * sigmaxy(i,j,k) + 2.d0*epsilon_xz * sigmaxz(i,j,k)+2.d0*epsilon_yz * sigmayz(i,j,k))

      enddo
    enddo
  enddo
!$acc end region
```

Verbose compiler output

% pgfortran -Mmpi=mpich2 -fast **-ta=nvidia -Minfo=accel** seismic_CPML_3D_isotropic_MPI_ACC_1.F90 -o gpu1.out

```
seismic_cpml_3d_iso_mpi_openmp:
  1107, Generating copyin(vz(11:91,11:631,kmin:kmax))
        Generating copyin(vy(11:91,11:631,kmin:kmax))
        Generating copyin(vx(11:91,11:631,kmin:kmax))
        Generating copyin(sigmaxx(11:91,11:631,kmin:kmax))
        Generating copyin(sigmayy(11:91,11:631,kmin:kmax))
        Generating copyin(sigmazz(11:91,11:631,kmin:kmax))
        Generating copyin(sigmaxy(11:91,11:631,kmin:kmax))
        Generating copyin(sigmaxz(11:91,11:631,kmin:kmax))
        Generating copyin(sigmayz(11:91,11:631,kmin:kmax))
        Generating compute capability 1.3 binary
        Generating compute capability 2.0 binary
1108, Loop is parallelizable
1109, Loop is parallelizable
1110, Loop is parallelizable
        Accelerator kernel generated
  1108, !$acc do parallel, vector(4) ! blockidx%y threadidx%z
  1109, !$acc do parallel, vector(4) ! blockidx%x threadidx%y
  1110, !$acc do vector(16) ! threadidx%x
        Using register for 'sigmayz'
        Using register for 'sigmaxz'
        Using register for 'sigmaxy'
        Using register for 'sigmazz'
        Using register for 'sigmayy'
        Using register for 'sigmaxx'
        CC 1.3 : 38 registers; 2176 shared, 24 constant, 0 local memory bytes; 25% occupancy
        CC 2.0 : 43 registers; 2056 shared, 140 constant, 0 local memory bytes; 33% occupancy
  1116, Sum reduction generated for total_energy_kinetic
  1134, Sum reduction generated for total_energy_potential
```

Data Region

```
!$acc data region                                                    &
!$acc      copyin(a_x_half,b_x_half,k_x_half,                        &
!$acc             a_y_half,b_y_half,k_y_half,                        &
!$acc             a_z_half,b_z_half,k_z_half,                        &
!$acc             ix_rec,iy_rec,                                     &
!$acc             a_x,a_y,a_z,b_x,b_y,b_z,k_x,k_y,k_z),              &
!$acc     copyout(sisvx,sisvy),                                      &
!$acc      local(memory_dvx_dx,memory_dvy_dx,memory_dvz_dx,          &
!$acc             memory_dvx_dy,memory_dvy_dy,memory_dvz_dy,         &
!$acc             memory_dvx_dz,memory_dvy_dz,memory_dvz_dz,         &
!$acc             memory_dsigmaxx_dx, memory_dsigmaxy_dy,            &
!$acc             memory_dsigmaxz_dz, memory_dsigmaxy_dx,            &
!$acc             memory_dsigmaxz_dx, memory_dsigmayz_dy,            &
!$acc             memory_dsigmayy_dy, memory_dsigmayz_dz,            &
!$acc             memory_dsigmazz_dz,                                &
!$acc             vx,vy,vz,vx1,vy1,vz1,vx2,vy2,vz2,                  &
!$acc             sigmazz1,sigmaxz1,sigmayz1,                        &
!$acc             sigmazz2,sigmaxz2,sigmayz2)                        &
!$acc      copyin(sigmaxx,sigmaxz,sigmaxy,sigmayy,sigmayz,sigmazz)
```

What about data movement?

- If data is not contiguous, then compiler has to copy data in successive segments multiple times

- Not only interested in how much data is being copied
  - Also need to know how often you copy data

- Used conditional compile (preprocessor macro _ACCEL) to sub-divide 3D data into 2D tiles

Results: single system scaling

Programming Iteration	MPI Processes	OMP Threads	GPUs	Time (sec)	Approx. Programming Time (min)
Baseline	2	2	0	948	
Naïve approach	2	0	2	3599	10
Data regions	2	0	2	610	60
2D tiling	2	0	2	194	120
Scheduling	2	0	2	167	120

Just over 5 hours effort to obtain 5.5X speedup

Source: Portland Group
4 Core Intel Core-i7 920 2.67Ghz
2 Tesla C2070 GPUs
MPICH-2

Multi-GPU cluster scaling with directives

	Model Size	MPI Procs	OMP Threads	GPUs	Time (sec)	Speedup
MPI_OMP	101 x 641 x 1536	24	96	0	1324	-
MPI_ACC	101 x 641 x 1536	24	0	24	353	3.8X
MPI_OMP	101 x 641 x 3072	24	96	0	2081	-
MPI_ACC	101 x 641 x 3072	24	0	24	508	4.1X

Source: Portland Group
HP SL390 G7 Starter Kit: 8 Node Cluster
Each node contains 2 socket Westmere @3.06 GHz (96 cores total)
MPICH over GbE
24 Tesla M2070 GPUs

Are Directives appropriate for your code?

- Need loops with large loop counts
  - Parallel nested loops with large loop indices
  - Best if loops are rectangular
- Locality is important to enable use of GPU
  - Take advantage of shared memory on GPU
  - Exploit data parallelism (accessing contiguous data at same time)
- Lag time to adopt new CUDA features (Peer-to-Peer)
  - Compilers must be conservative, don’t support host pinned memory
  - New async directive on the horizon

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Challenges

- Develop system sizing information
  - Consider power and space constraints
  - Recommend CPU / GPU ratios
- Need application-driven approach
  - Must be meaningful for seismic industry
  - Optimized for CPU as well as GPU
- Measure power consumption of system components
  - Separate GPU power from CPU power

Possible solution

- Use 3D elastic forward wave modeling test
  - Supports MPI and OpenMP so can obtain CPU baseline
  - GPU accelerated version available
  - Measure single system, multi-GPU, cluster scalability
- Power monitoring
  - HP Proliant Power Interface Controller (PPIC)
  - Per outlet power monitors
  - NVIDIA Management Library (NVML) power usage

How is performance related to power?

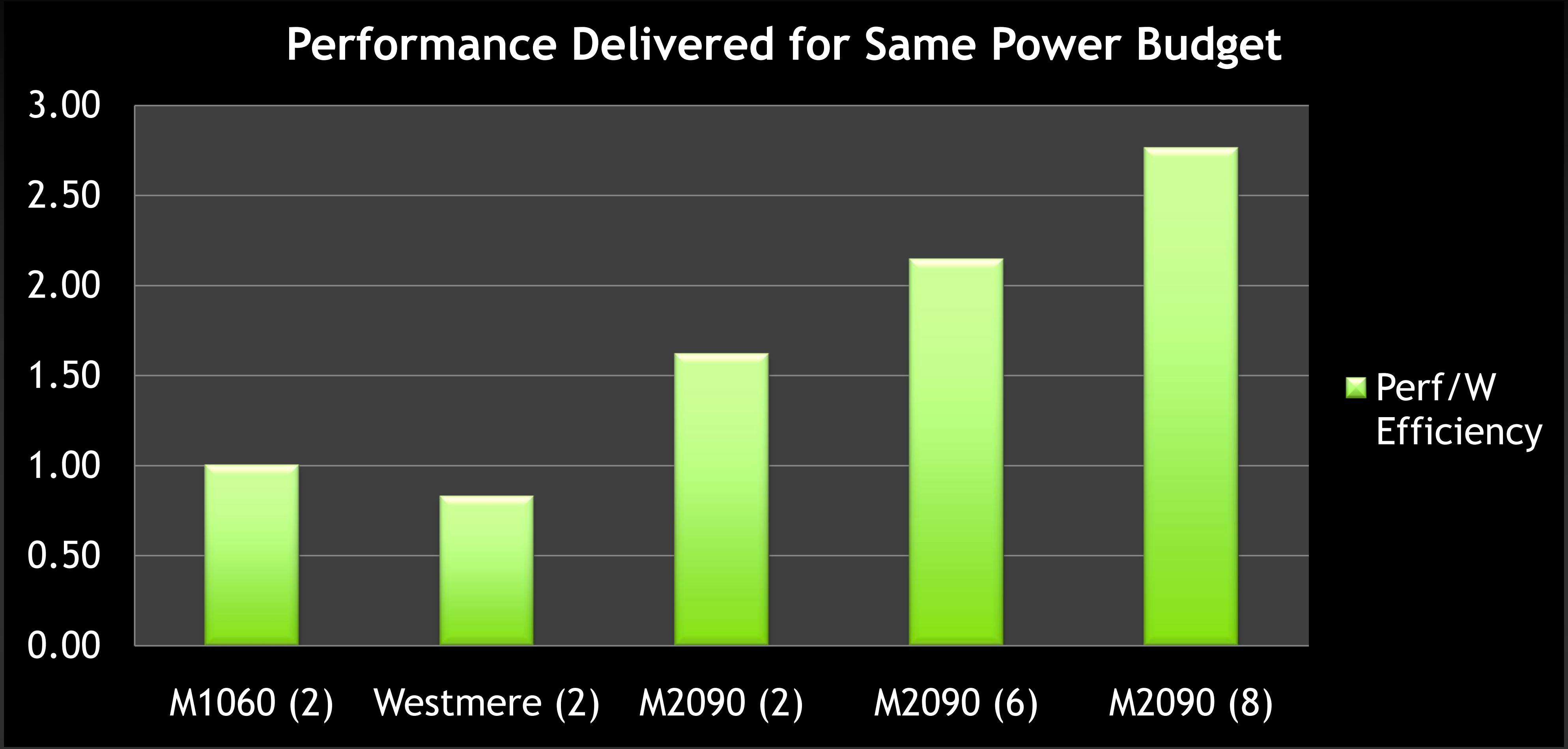
3D Elastic Forward Wave Modeling

CPU (2 Westmere Sockets)	GPU (Server + 2 M2090s)
598 Mpoints/s	1,877 Mpoints/s
577 Watts	927 Watts
Perf/W: 1.04	Perf/W: 2.03

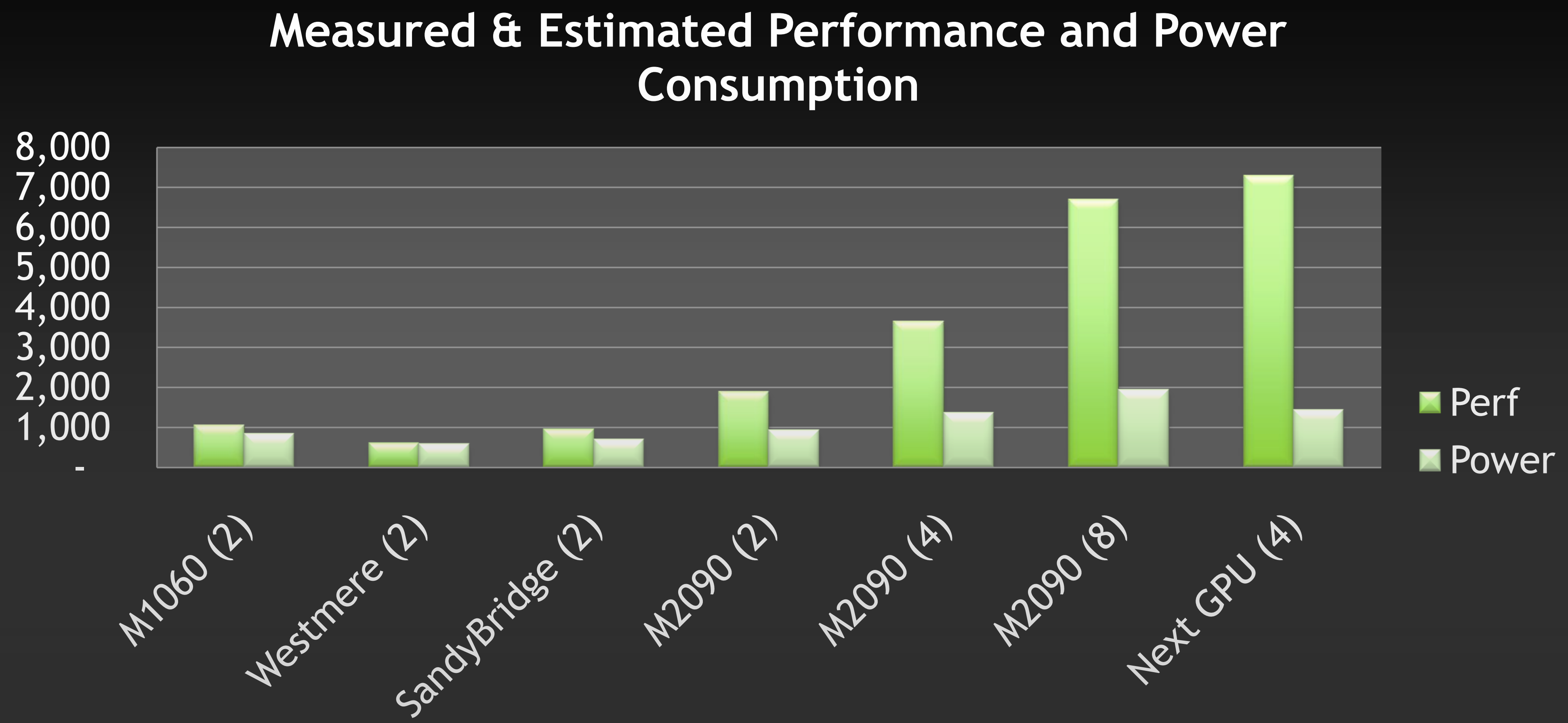
GPU delivers 1.95X more performance for same power budget

Power measured by: HP Proliant Power Interface Control (PPIC) tool
CPU: Dual Westmere x5670 2.93 GHz

Result: Perf/W of multi-GPU systems



Estimate for next-generation systems



Summary

- GPUs are used to develop realistic earth models
  - Elastic methods are an extension of acoustic methods
- Tuning approach used with native CUDA apply to directives
  - Optimize data movement
- Use Perf/Watt for systems sizing recommendations
  - Application-driven approach

Conclusions

- Favorable scaling results for 3D elastic modeling codes
  - Using CUDA and PGI acceleration directives
- Accelerator directives + tools
  - Improve productivity, offer portability, and deliver performance
  - Should be added to programmers toolbox
- Multi-GPU systems offer Performance/Watt advantage
  - Solve datacenter issues constrained by power and space

References

- [1] “Accelerating a 3D finite-difference wave propagation code using GPU graphics cards”
  - David Michea and Dimitri Komatitsch, Geophysical Journal International
  - http://hal.inria.fr/docs/00/52/84/87/PDF/paper_David.pdf
- [2] “3D Finite Difference Computation on GPUs using CUDA”
  - Paulius Micikevicius, NVIDIA DevTech
  - http://developer.download.nvidia.com/CUDA/CUDA_Zone/papers/gpu_3dfd_rev.pdf
- [3] Seismic Convolutional Perfectly Matched Layer
  - Dimitri Komatitsch and Roland Martin
  - http://www.geodynamics.org/cig/software/seismic_cpml
- [4] “5x in 5 hours, accelerating Seismic CPML using PGI Directives”
  - Mat Colgrove, PGI
  - http://nvidia.fullviewmedia.com/fb/nv-sc11/tabscontent/archive/315-wed-colgrove.html

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- Thomas Toy, Portland Group, USA

Questions?