Seismic Imaging on NVIDIA GPUs

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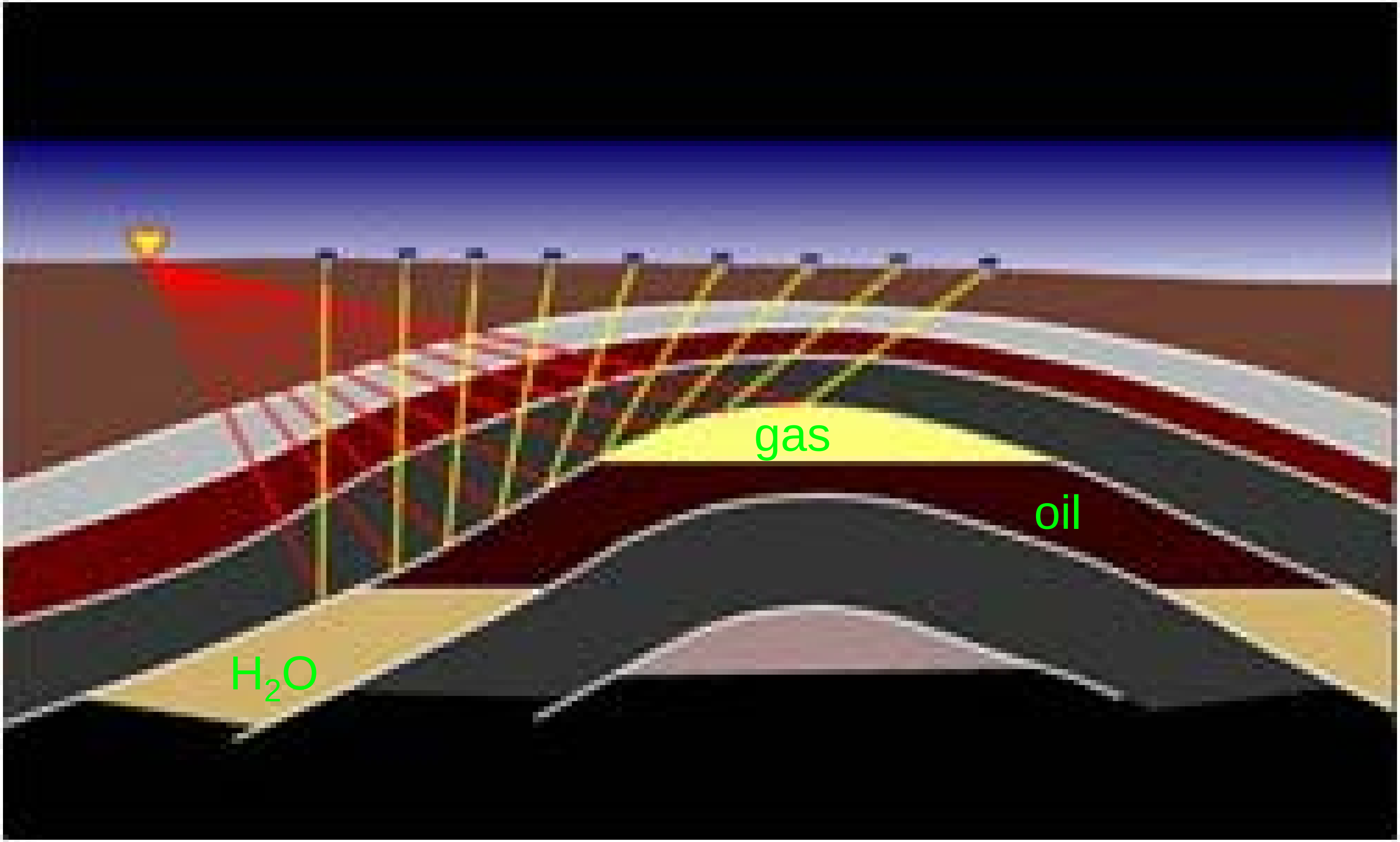
Hess Corporation

Seismic Imaging

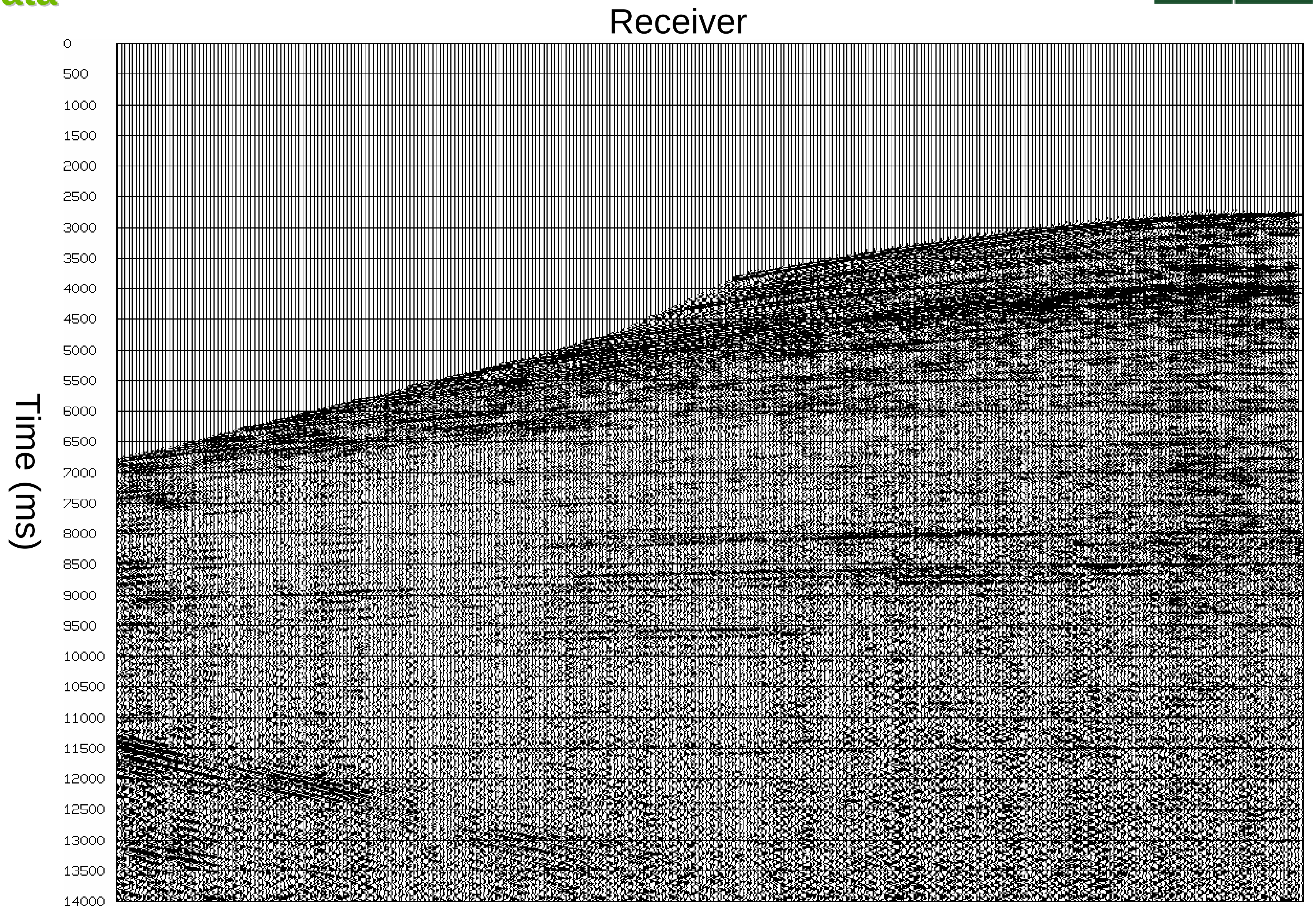
Outline

- **Seismic data & imaging**
- **NVIDIA GPUs + CUDA**
  - Why?
  - How?
- **Three imaging methods**
  - Algorithm
  - Challenges
  - Performance

Seismic Imaging
Data



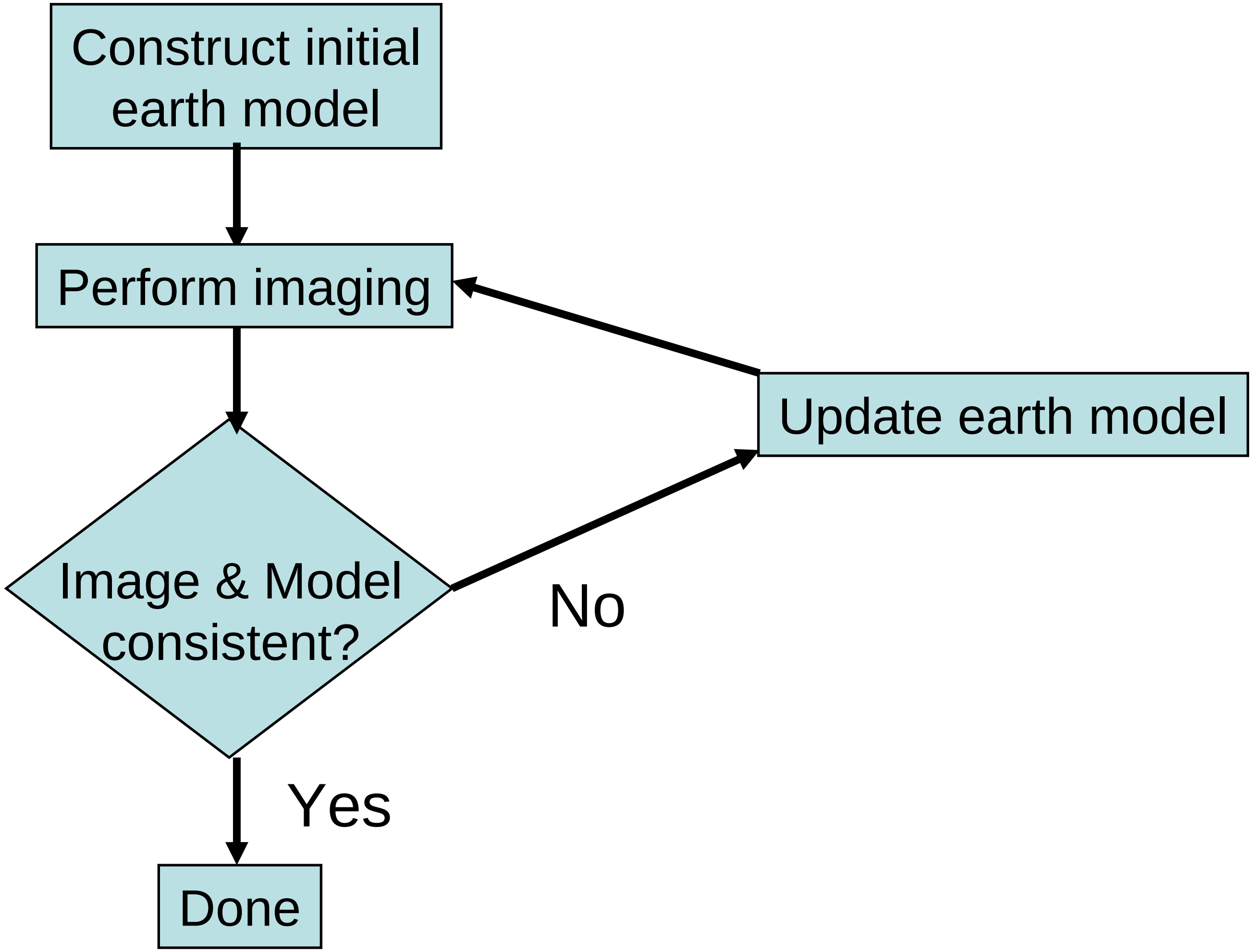
Seismic Imaging
Data



Seismic Imaging
Data

Seismic Imaging

An iterative process



Computation scales as size of data and image/model

Seismic Imaging
Why GPUs?

- **Price-to-performance ratio improvement**
  - Want 10X to change platforms
    - Payback must more than cover effort & risk
    - Got 10X ten years ago in switching from supercomputers to PC clusters

Seismic Imaging
Why GPUs?

- **Price-to-performance ratio improvement**
  - Want 10X to change platforms
    - Payback must more than cover effort & risk
    - Got 10X ten years ago in switching from supercomputers to PC clusters
  - Several years ago there were indicators we can get 10X or more on GPUs
    - Peak performance
    - Benchmarks
    - Simple prototype kernels

Seismic Imaging
Why CUDA & NVIDIA GPUs?

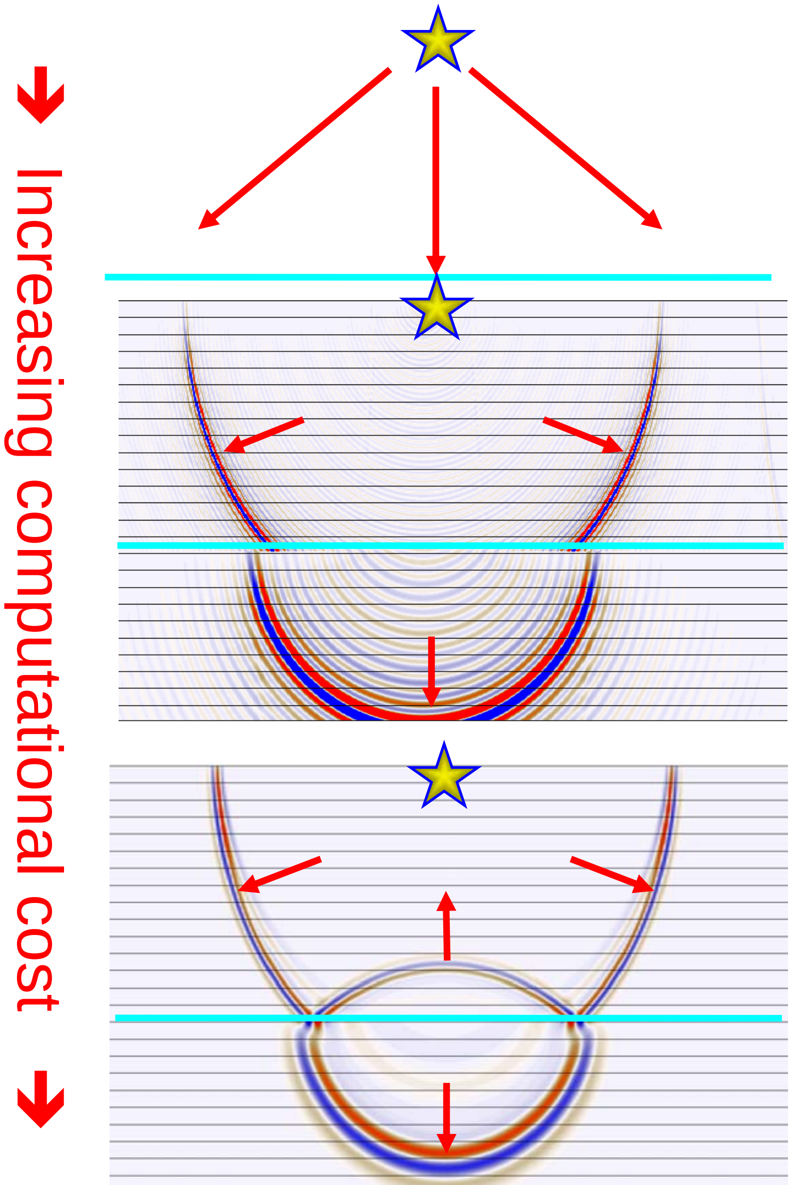
- **Ease of programming**
  - Must be able to port, maintain & modify production codes (relatively) easily
    - These costs must be included
  - Have tried Cg, Brook and Peakstream
    - All lacking in some aspect
  - CUDA programming model straightforward
    - SIMD-like thread-based parallelism
    - In 1.5 days
      - Took "intro to CUDA" class
      - Wrote a working 2-D seismic modeling code
    - Programming memory hierarchy for optimization is the biggest challenge

Seismic Imaging

How to port a code?

- **Design GPU algorithm**
  - Optimize for memory hierarchy
  - Keep main data structures in GPU memory
- **Create prototype GPU kernel**
  - Include main computational characteristics
  - Test performance against CPU kernel
  - Iteratively refine prototype
- **Port full kernel & compare with CPU kernel**
  - Verify numerical results
  - Compare performance results
- **Incorporate into production code & system**

Seismic Imaging
Imaging methods



- **Kirchhoff imaging**
  - High-frequency propagation
  - Ray or eikonal travel-times
- **“Wave-equation” imaging**
  - One-way propagation: z ~ t
  - Frequency-domain method
  - ADI (alternating direction implicit) finite difference
- **“Reverse-time” imaging**
  - Two-way propagation
  - Time-domain
  - Explicit finite-difference

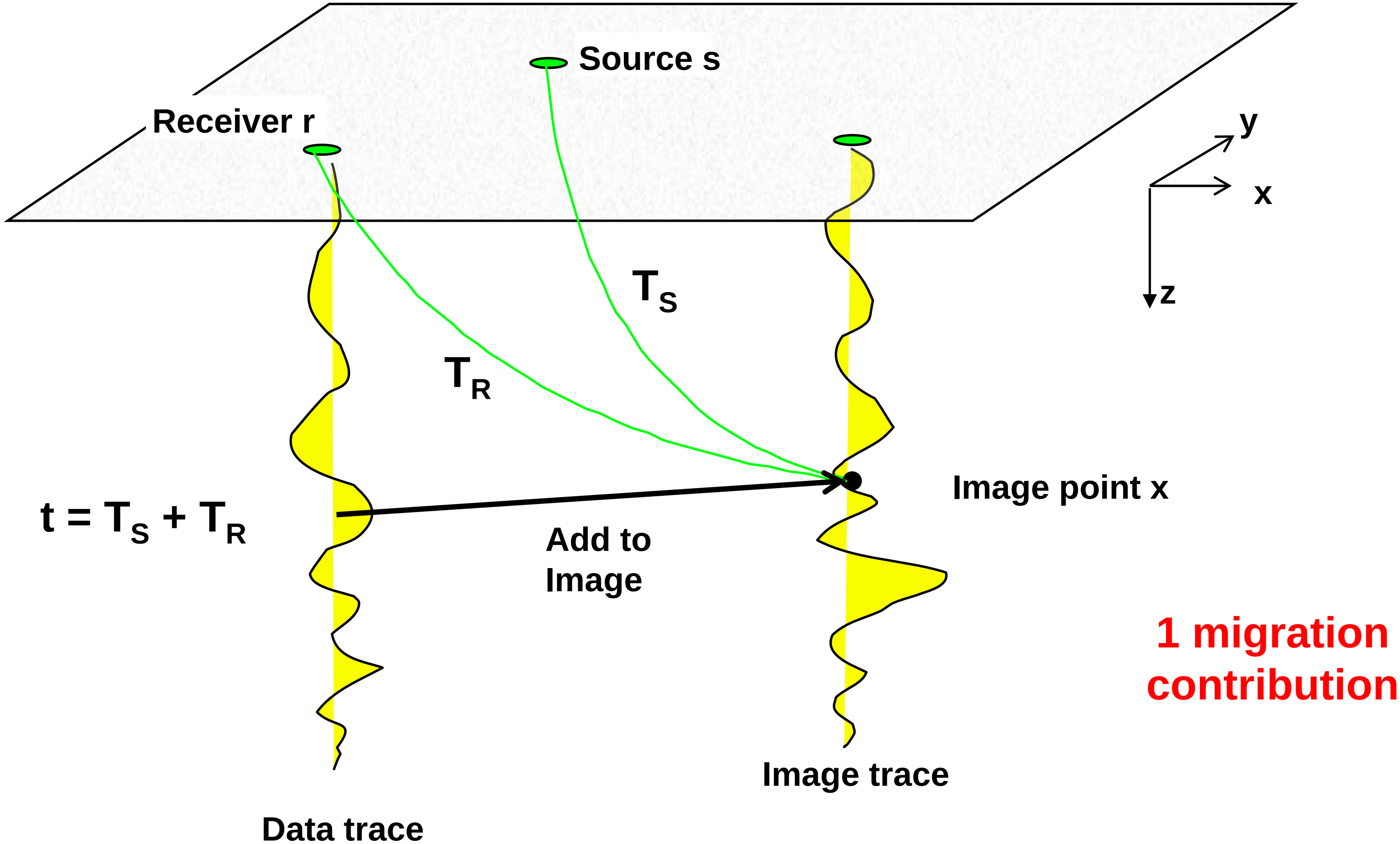
Kirchhoff Imaging
Physical algorithm

- **Based on the Kirchhoff integral**
  - Pre-compute coarse travel-times for propagation from surface locations to image points: $\mathrm{T}(\vec{\mathbf{s}},\vec{\mathbf{x}})$
  - 4-D surface integral through a 5-D data set

$$\mathrm{I}(\vec{\mathbf{x}}) = \iint d^2\mathbf{s}\; d^2\mathbf{r}\; \mathrm{D}\big(\vec{\mathbf{s}},\vec{\mathbf{r}},t = \mathrm{T}(\vec{\mathbf{s}},\vec{\mathbf{x}}) + \mathrm{T}(\vec{\mathbf{x}},\vec{\mathbf{r}})\big)$$

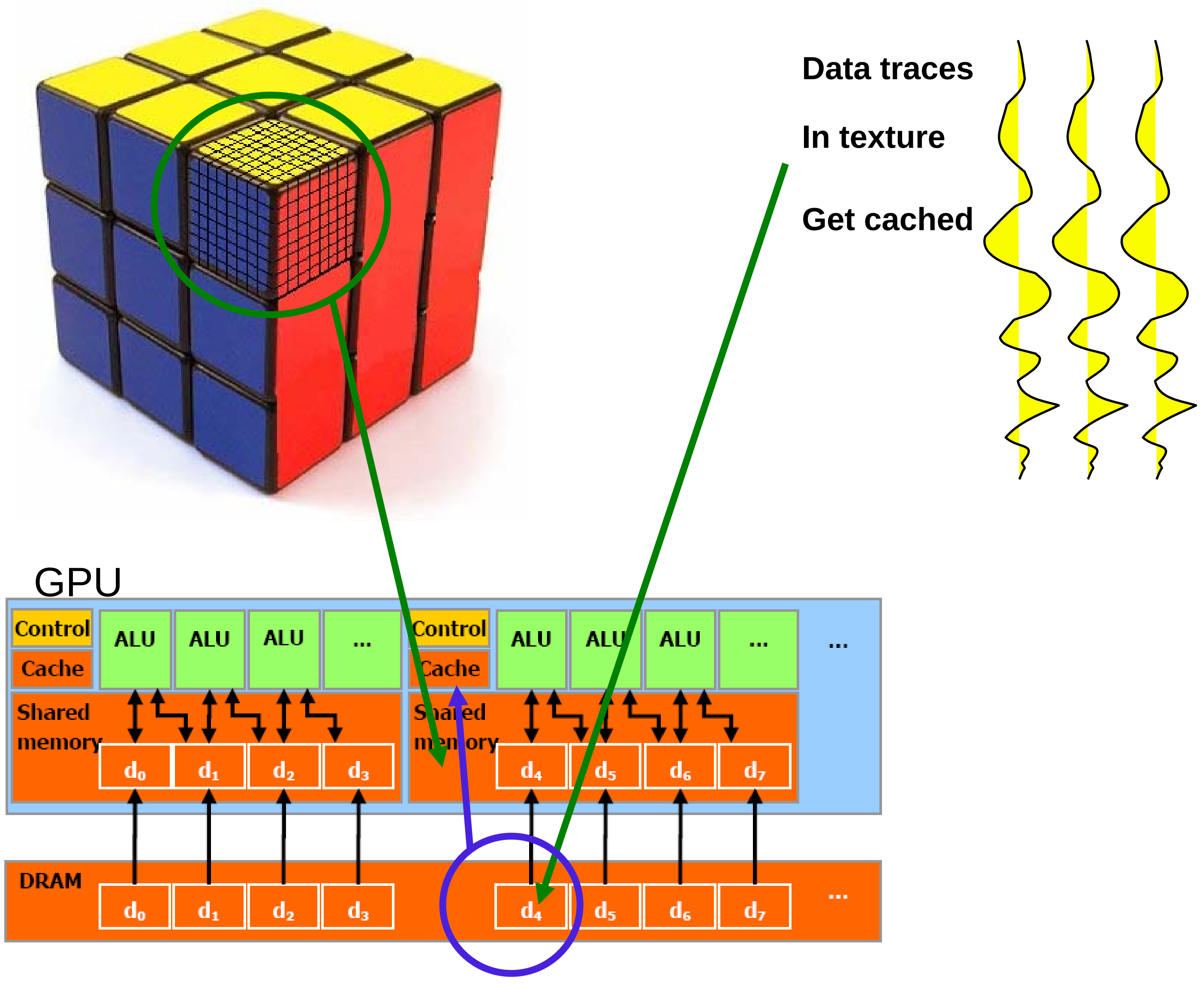
  - Computational complexity:
    - $N_I \sim 10^9$ is the number of output image points
    - $N_D \sim 10^8$ is the number of input data traces
    - $f \sim 10$ is the number of cycles/point/trace
    - $f\, N_I\, N_D \sim 10^{18}$ cycles ~ 10 CPU-years

Kirchhoff Imaging
Computational kernel

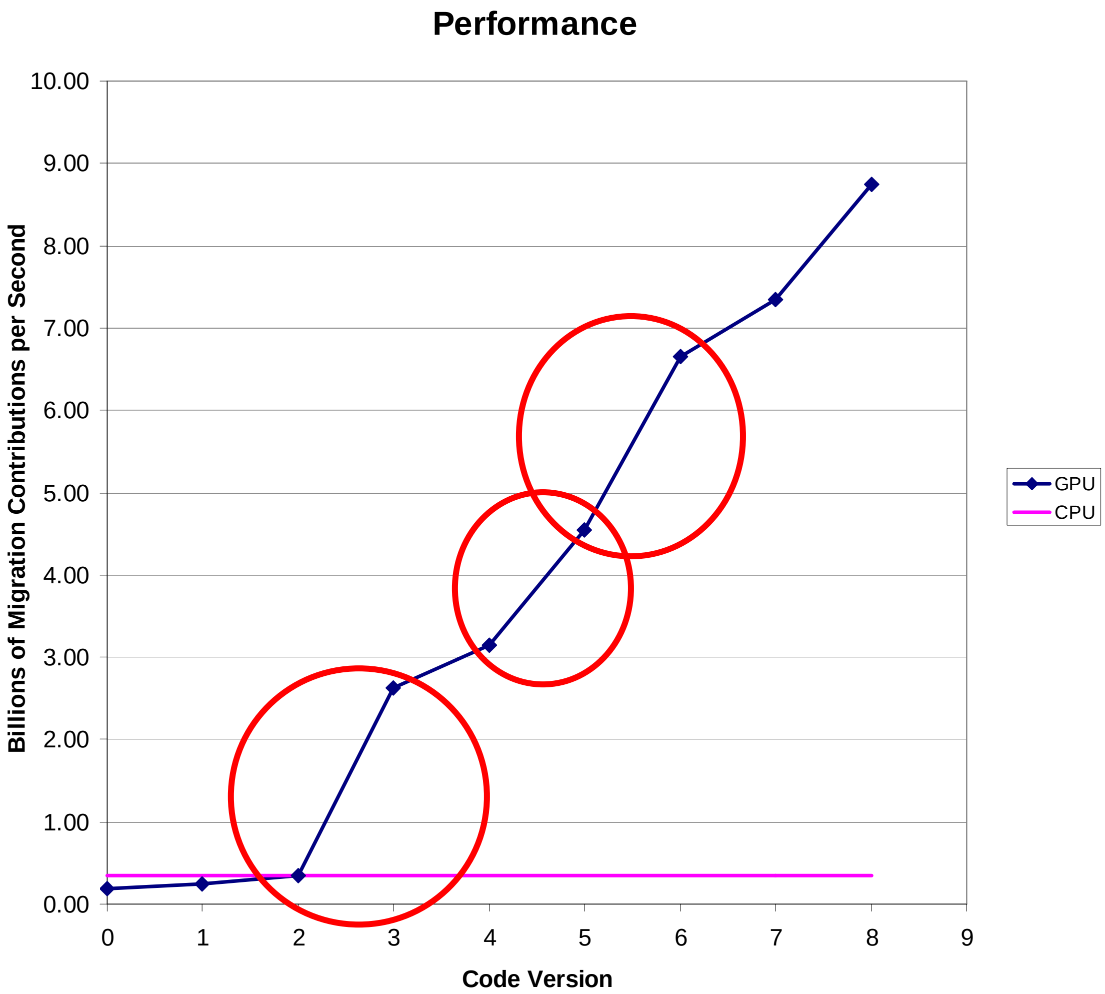


$$I(\vec{\mathbf{x}}) = \sum_{\vec{\mathbf{s}},\vec{\mathbf{r}}} D\left(\vec{\mathbf{s}}, \vec{\mathbf{r}}, t = T(\vec{\mathbf{s}}, \vec{\mathbf{x}}) + T(\vec{\mathbf{x}}, \vec{\mathbf{r}})\right)$$

Kirchhoff Imaging
CUDA kernel



Kirchhoff Imaging
Kernel optimization



0 – Initial Kernel

1 – Used Texture Memory

2 – Used Shared Memory

3 – Global Memory Coalescing

4 – Decreased Data Trace Shared Memory Use

5 – Optimized Use of Shared Memory

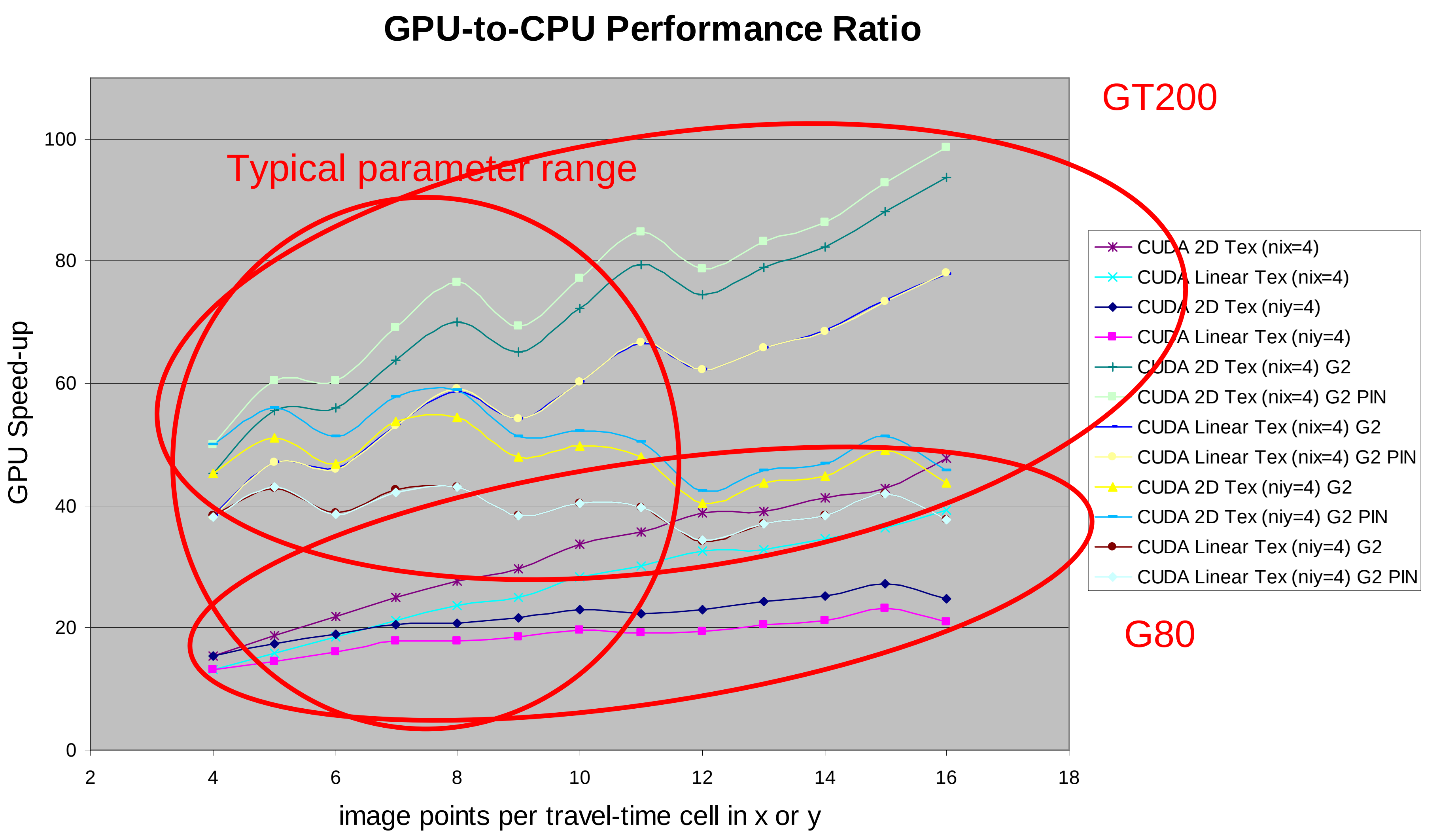
6 – Consolidated “if” Statements, Eliminated or Substituted Some Math Operations

7 – Removed an “if” and “for”

8 – Used Texture Memory for Data-Trace Fetch

Kirchhoff Imaging

Kernel performance



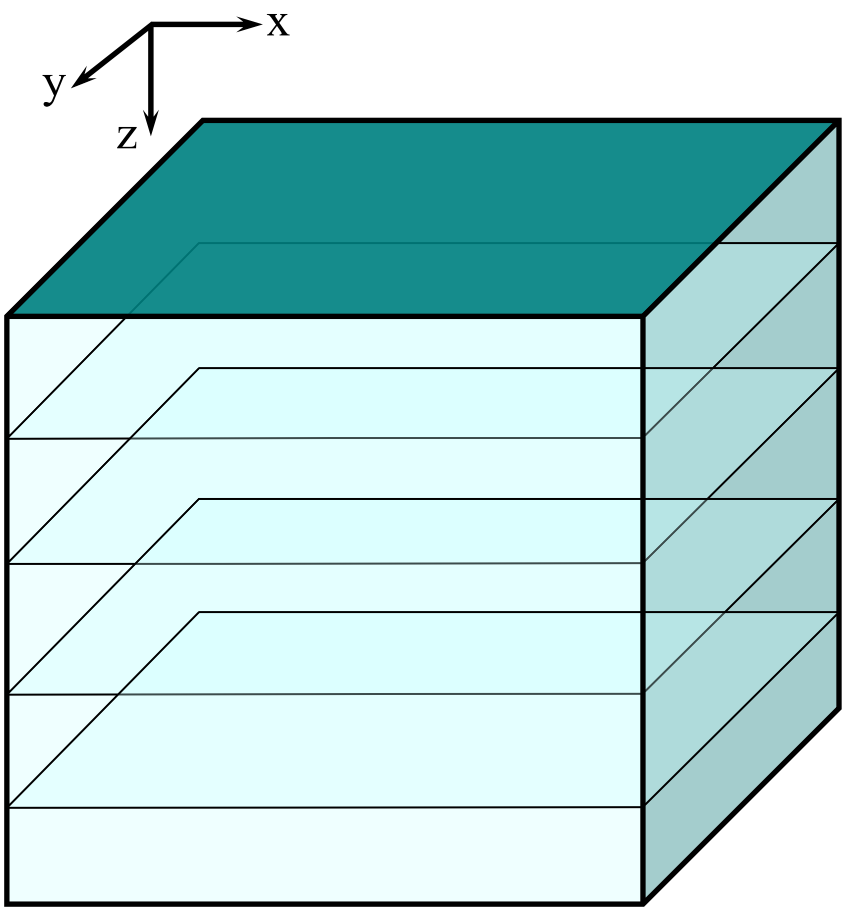
Kirchhoff Imaging
Production status

- **GPU kernel incorporated into production code**
  - Large kernel speed-ups results in "CPU overhead" for task setup dominating GPU production runs
- **Further optimizations**
  - create GPU kernels for most "overhead" components
  - optimized left-over CPU code (which helps CPU version also)

Time (hr)	Set-up	Kernel	Total	Speed-up
Original CPU code	5	20	25	
Main GPU kernel	5	0.5	5.5	5
Further optimizations	0.5	0.5	1	25

"Wave-equation" Imaging

One-way propagation



- **Based on scalar wave equation**

$$\frac{1}{V(\vec{\mathbf{x}})^2}\frac{\partial^2 P}{\partial t^2} = \nabla^2 P$$

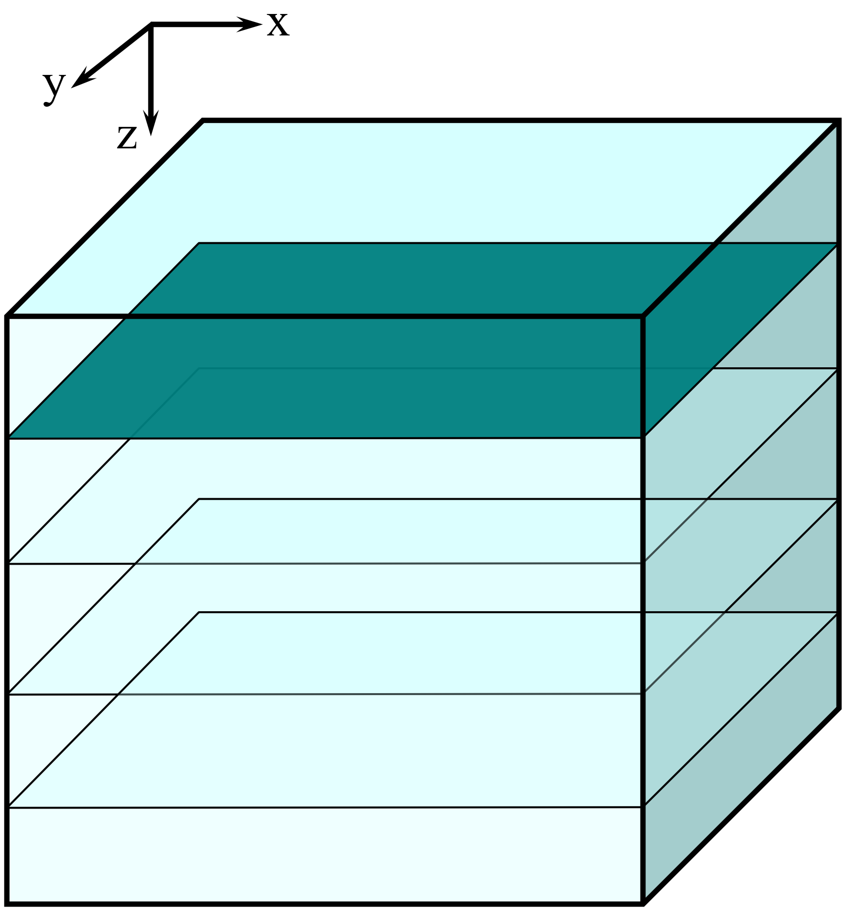
- **Frequency-domain**
- **Preferred direction of propagation: z ~ t**

$$\frac{\partial P}{\partial z} = \frac{\pm i\omega}{V(\vec{\mathbf{x}})}\sqrt{1 + \frac{V^2(\vec{\mathbf{x}})}{\omega^2}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)}\; P$$

  - Evolution in depth

“Wave-equation” Imaging

One-way propagation



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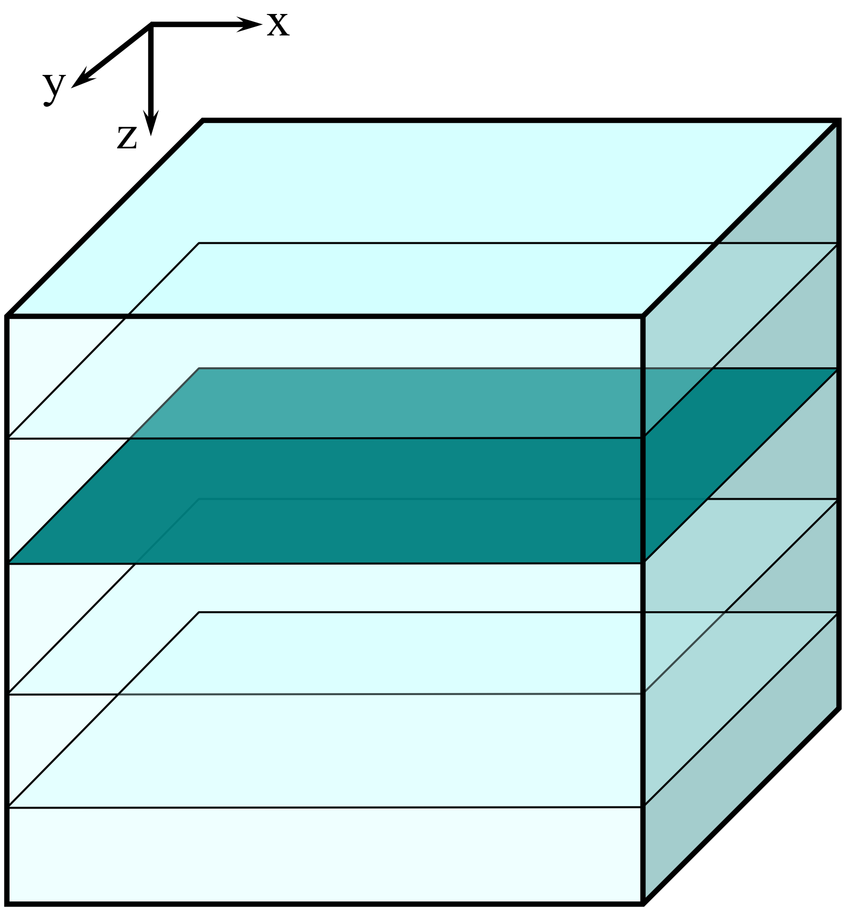

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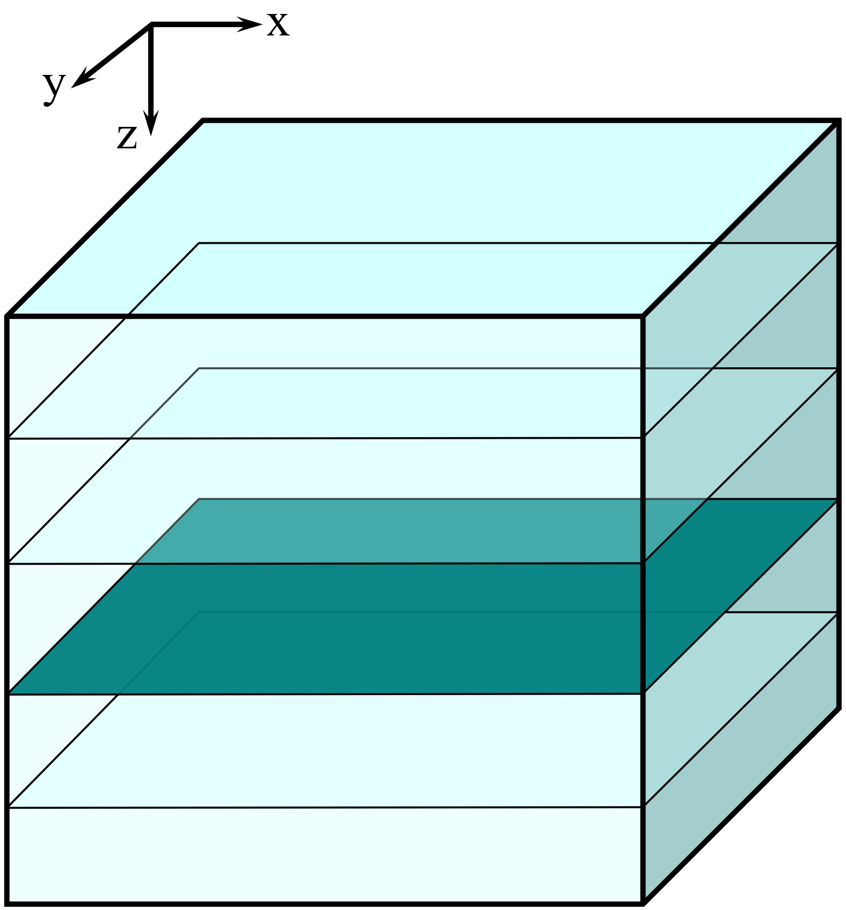

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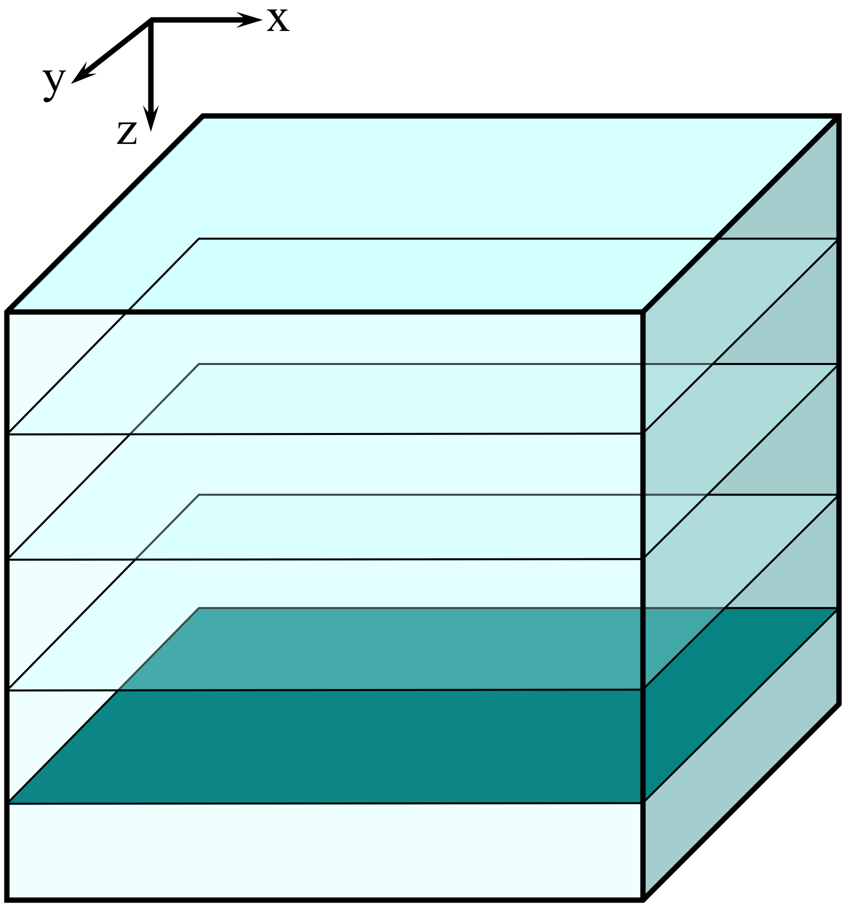

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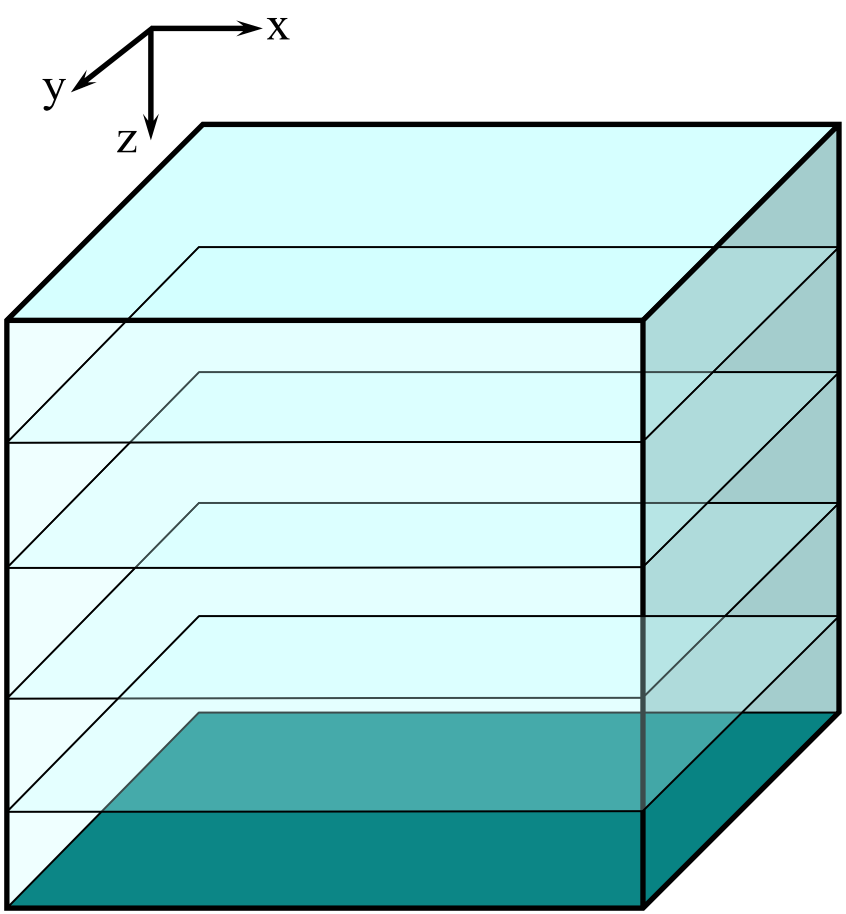

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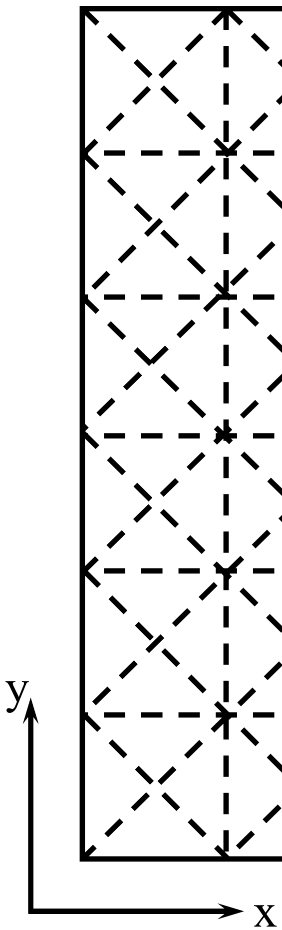
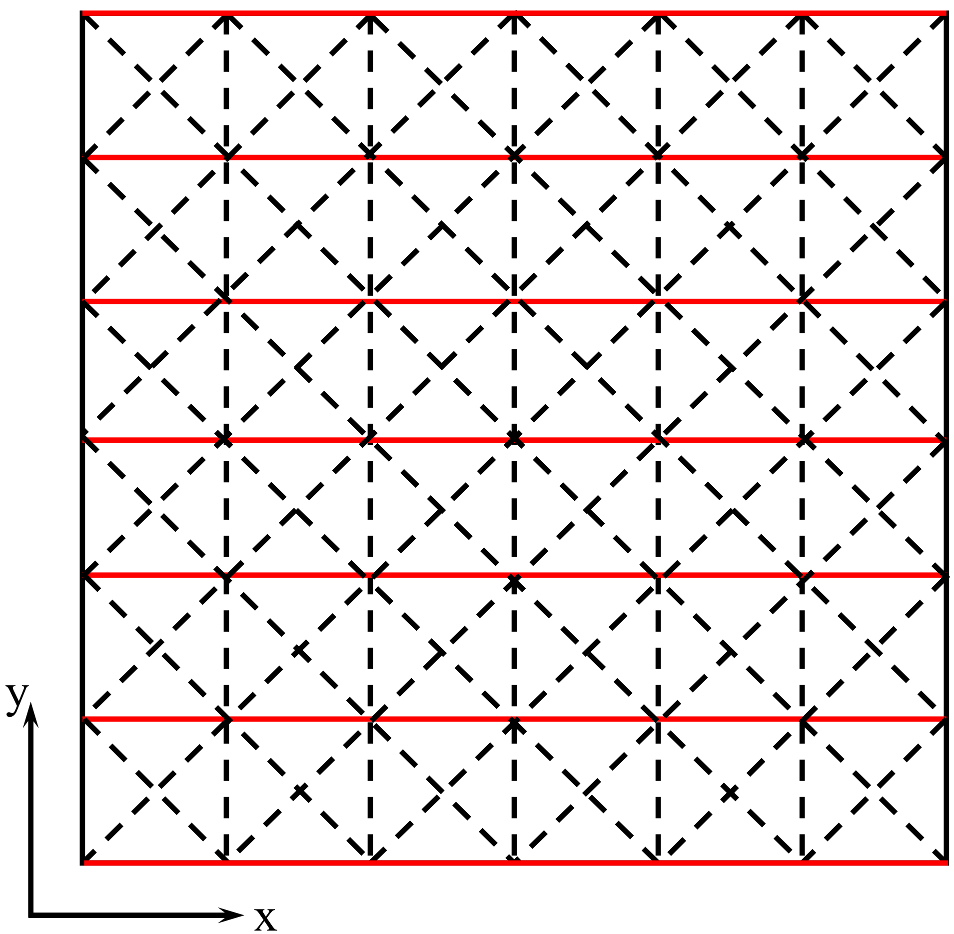


- **Evolution eqn uses**
  - Continued fractions
  - Operator splitting
  - ADI finite difference
- **Each depth step requires applying four operators**
  - Along x
  - Along y
  - Along x + y
  - Along x – y

"Wave-equation" Imaging

One-way propagation



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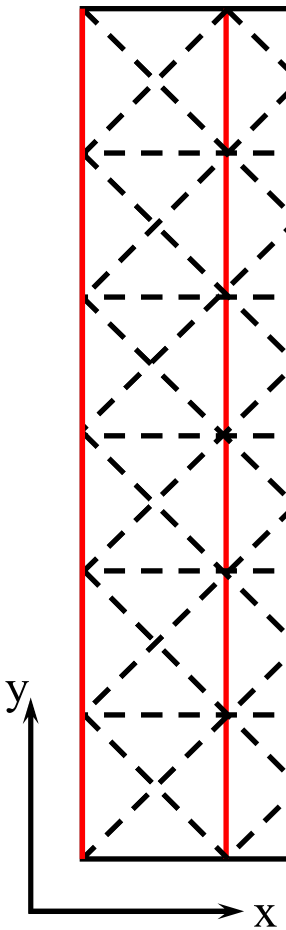

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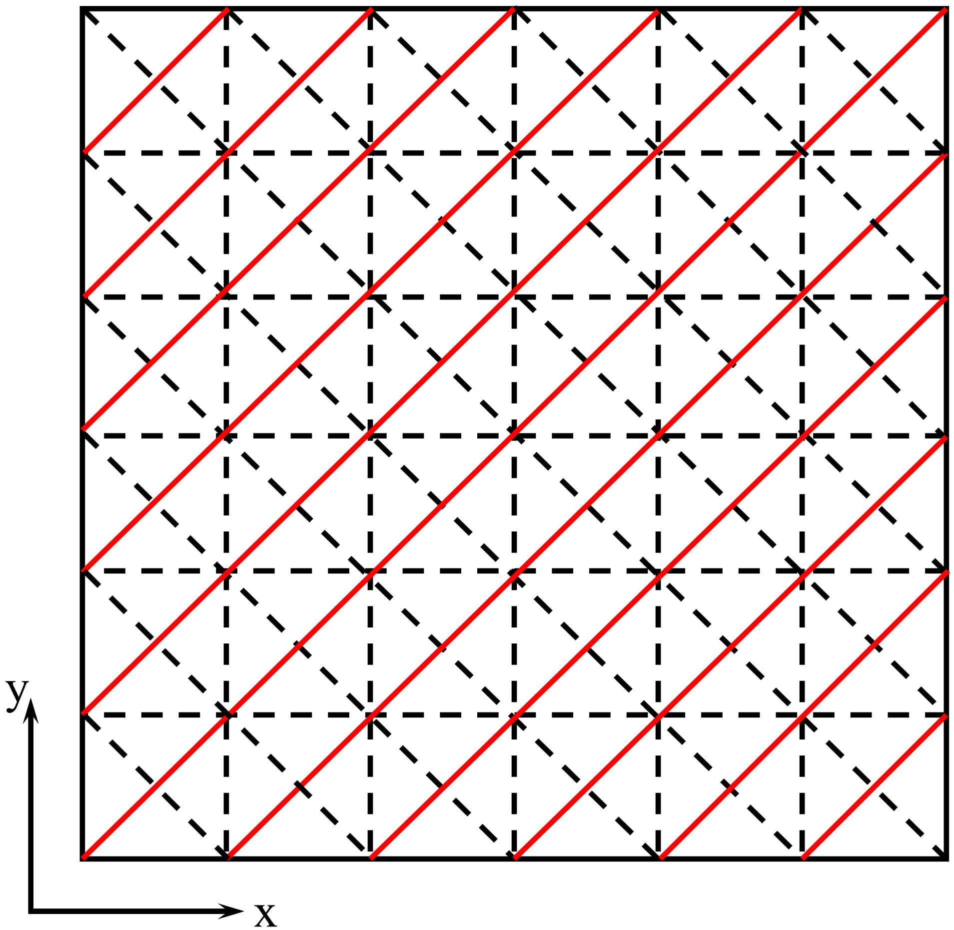

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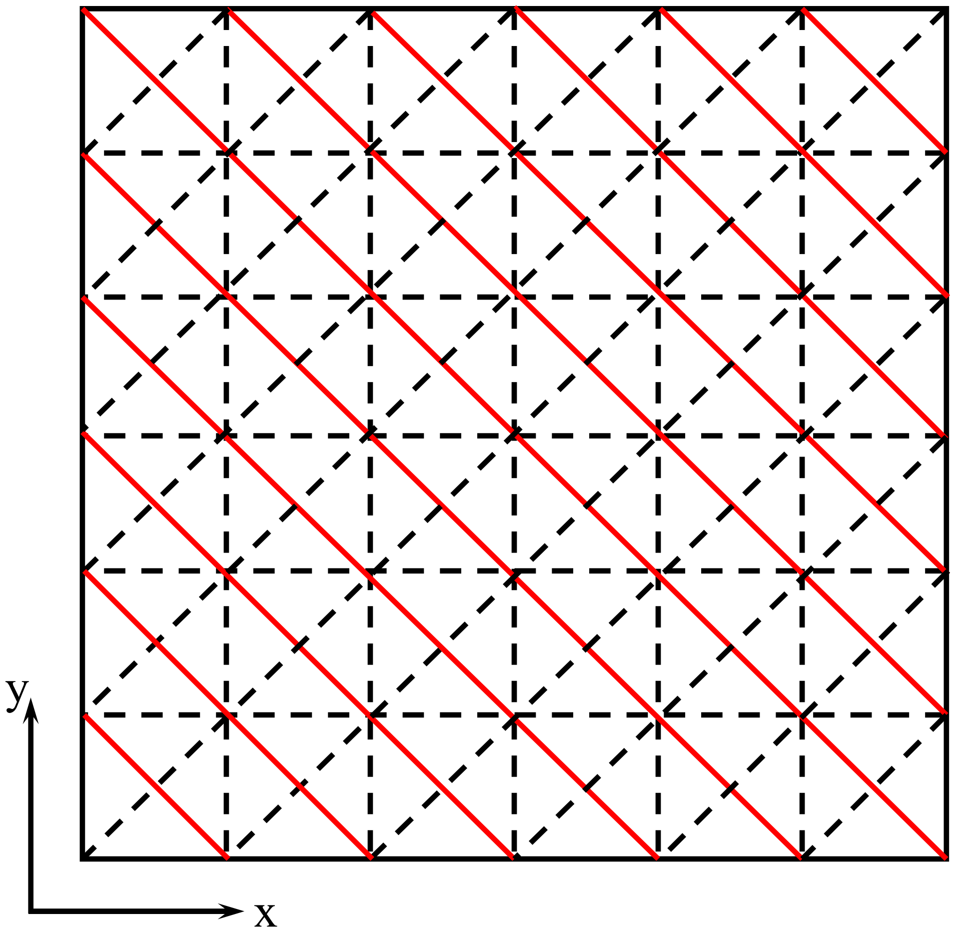

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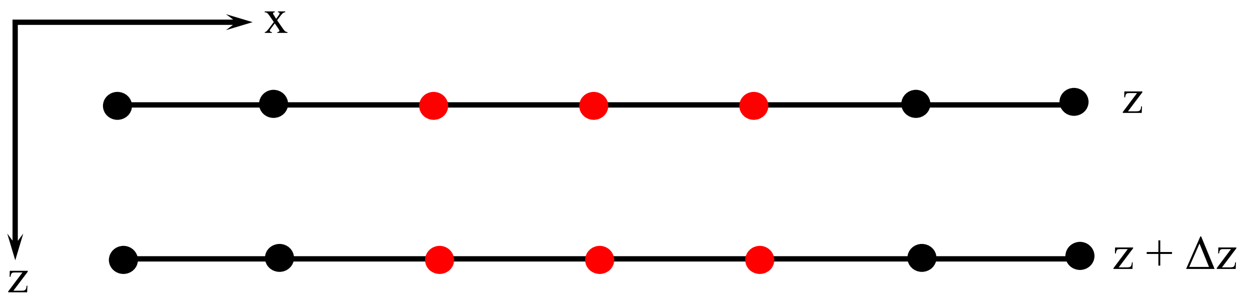
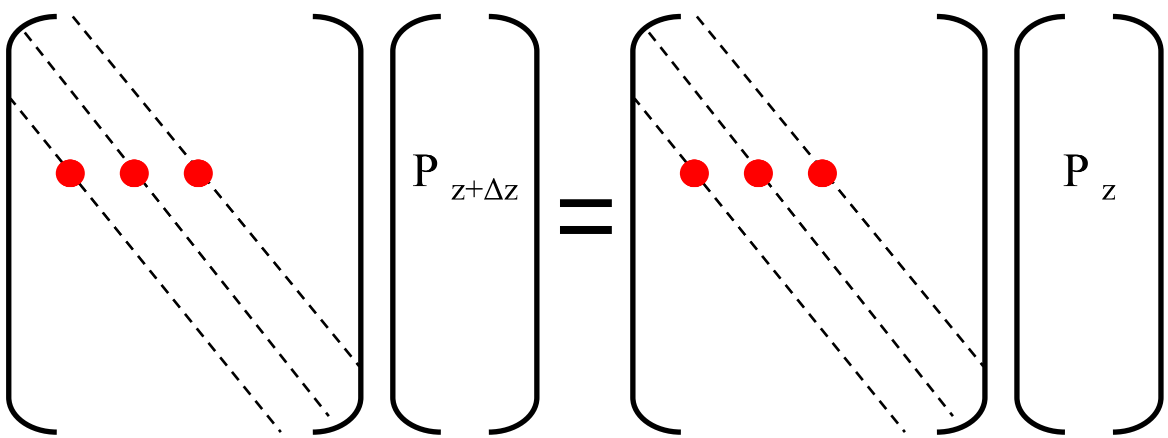
“Wave-equation” Imaging

Implicit complex tri-diagonal linear systems



$$A P_{x-\Delta x,y}^{z+\Delta z} + \left(1-2A\right) P_{x,y}^{z+\Delta z} + A P_{x+\Delta x,y}^{z+\Delta z} =$$
$$A^{*} P_{x-\Delta x,y}^{z} + \left(1-2A^{*}\right) P_{x,y}^{z} + A^{*} P_{x+\Delta x,y}^{z}$$



"Wave-equation" Imaging

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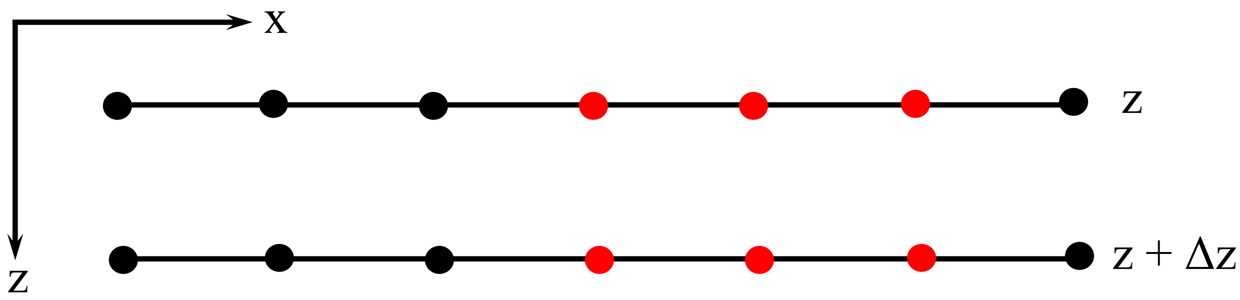

$$AP_{x-\Delta x,y}^{z+\Delta z} + (1-2A)P_{x,y}^{z+\Delta z} + AP_{x+\Delta x,y}^{z+\Delta z} =$$
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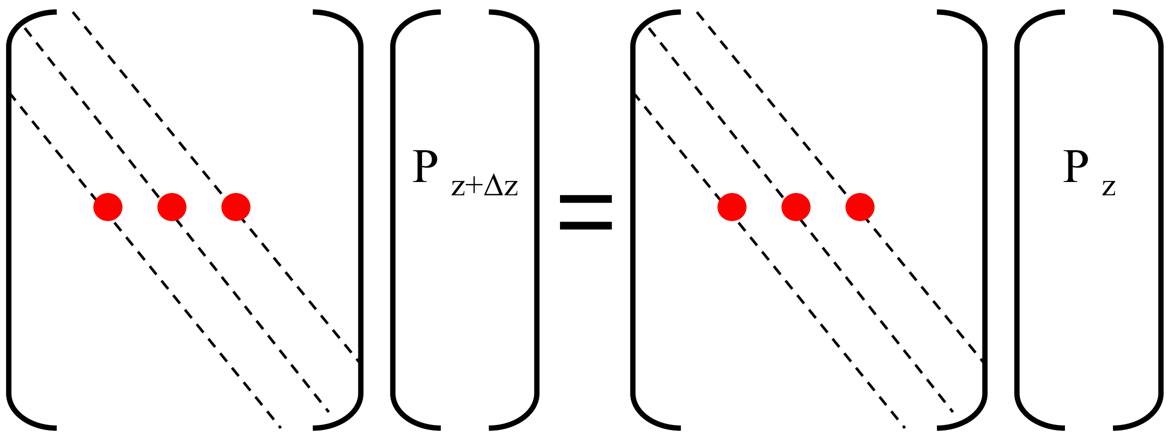
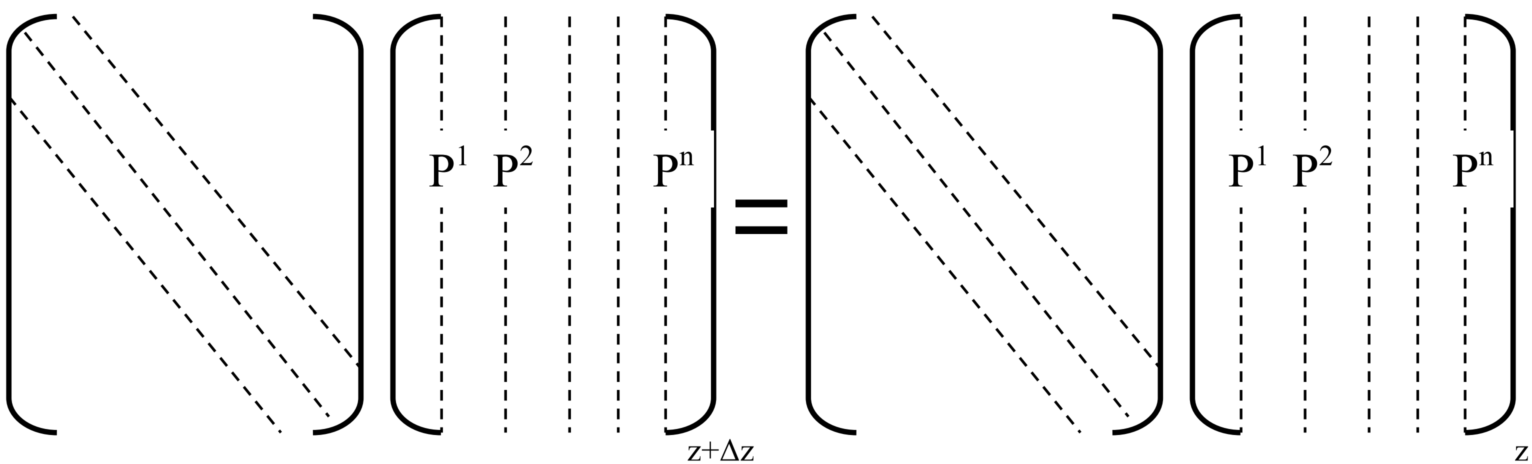


The evaluation and solution of these complex tri-diagonal systems dominates the computational cost of our wave-equation imaging code.

“Wave-equation” Imaging
Low level parallelism

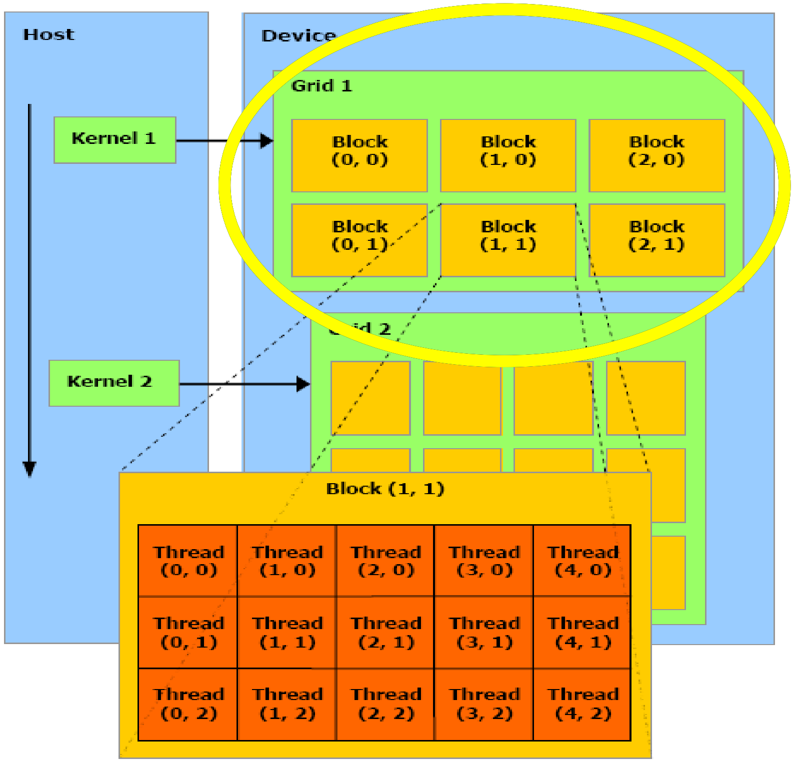
- **Common work between shot-records**
  - Calculating the coefficients of the matrices
    - Dependent on frequency & local velocity
  - Part of the solving of the tri-diagonal system
- **Parallelize over shot-records in the kernel**



“Wave-equation” Imaging

CUDA kernels

- **Separate kernels for each operator**
  - x, y, x+y and x-y



"Wave-equation" Imaging

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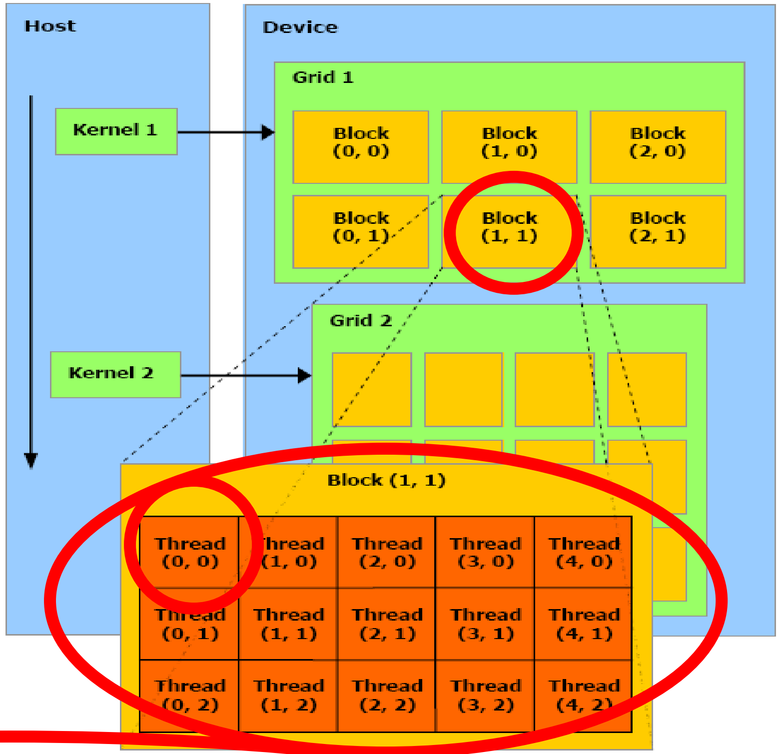

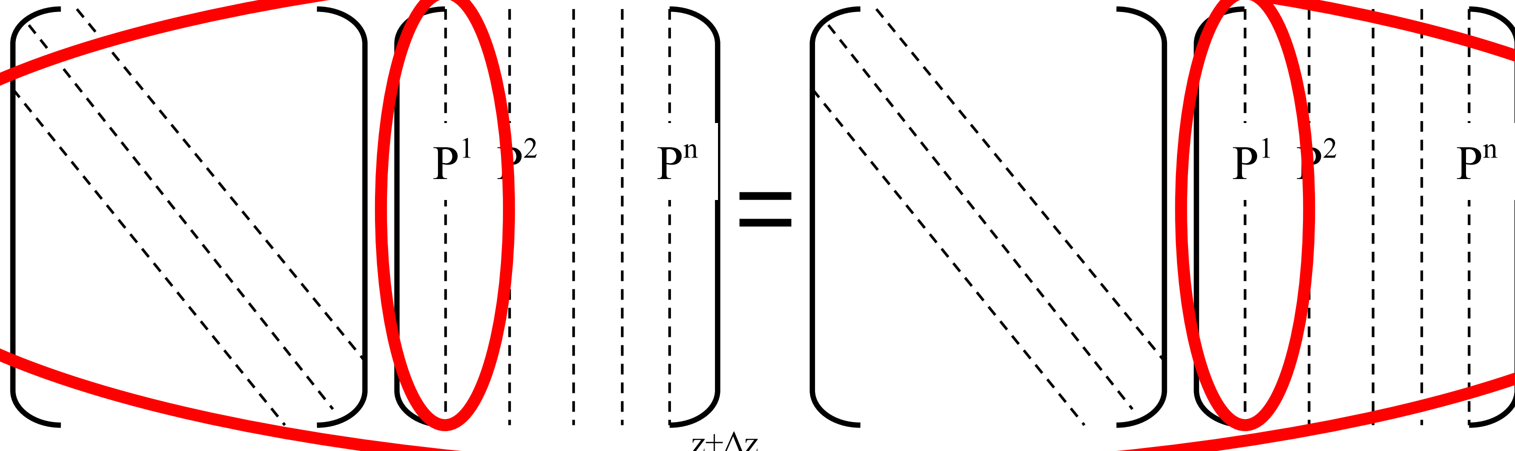

"Wave-equation" Imaging

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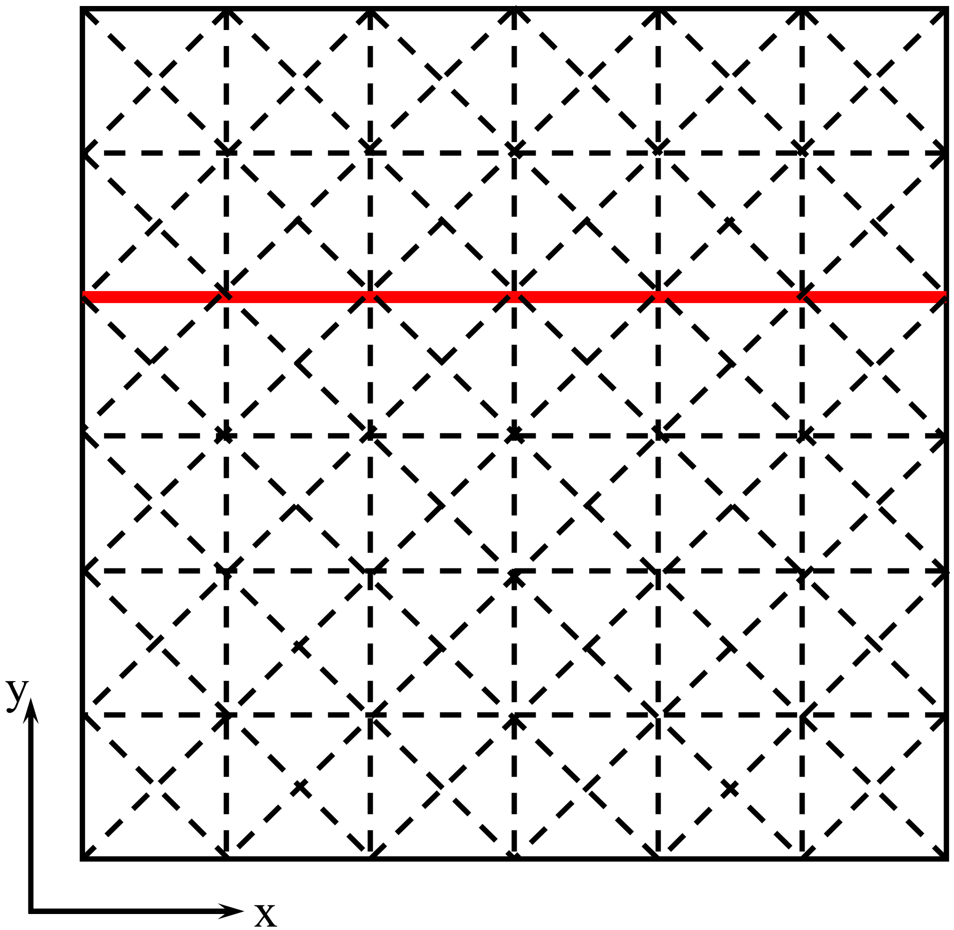

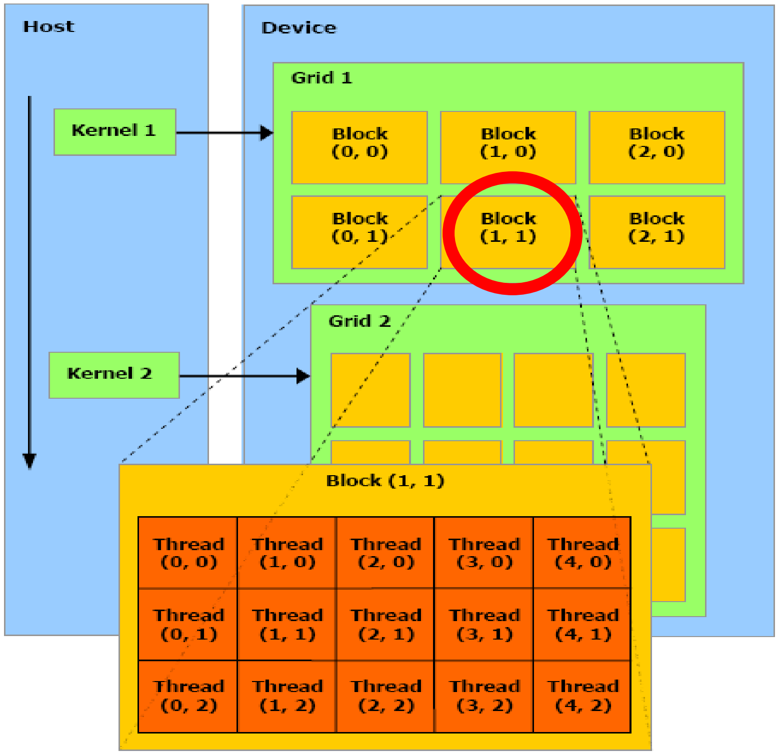

“Wave-equation” Imaging

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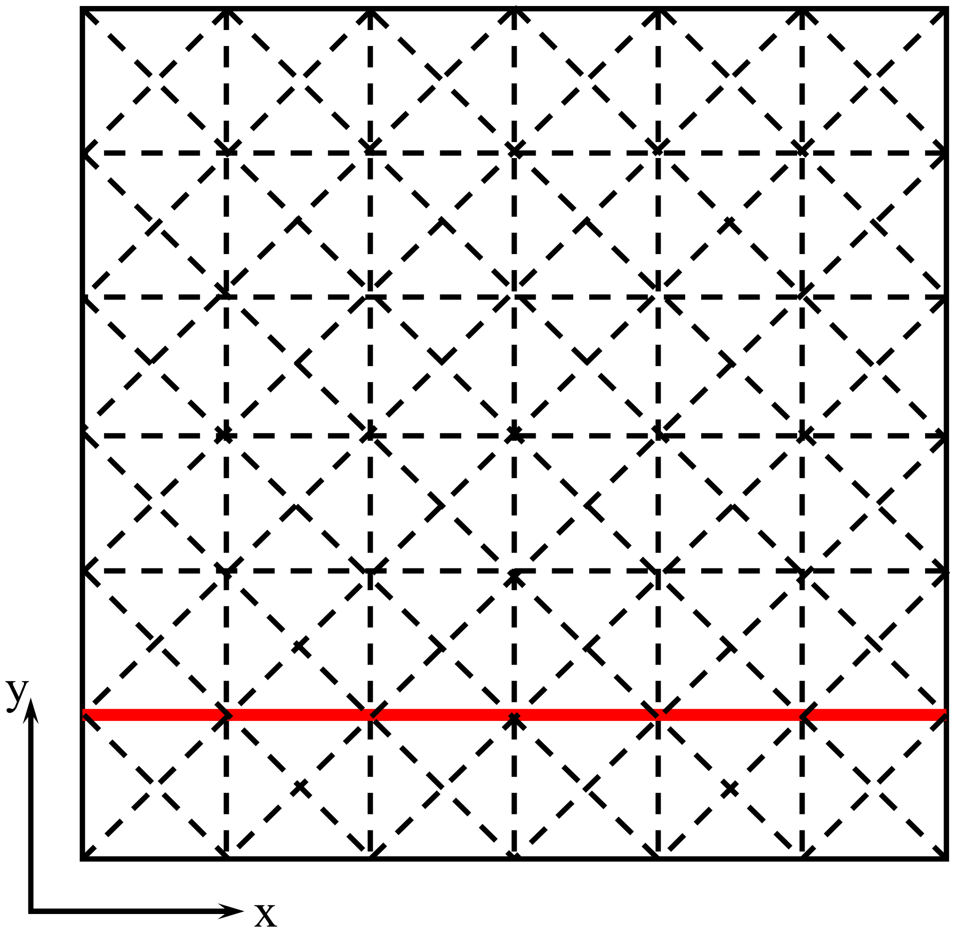
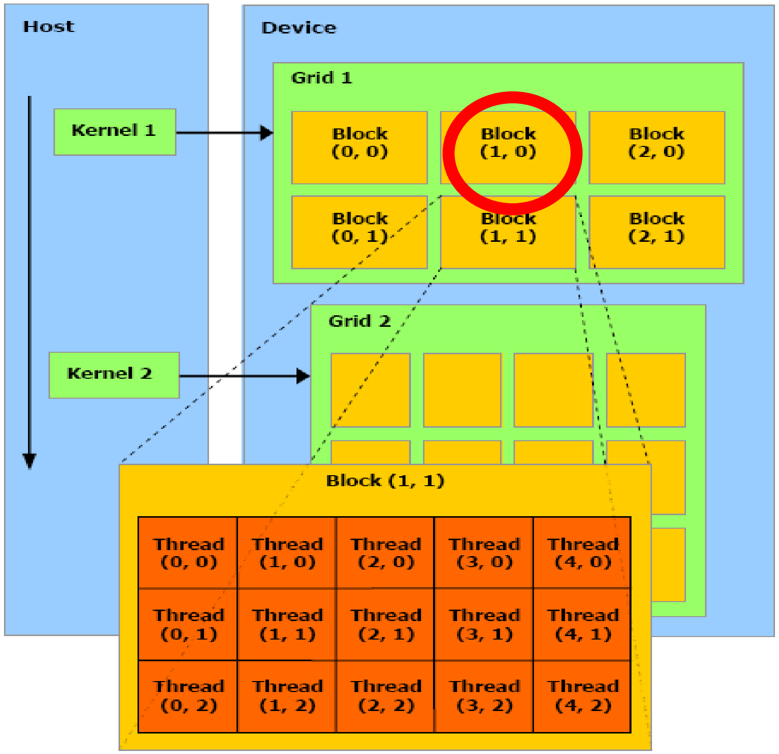




“Wave-equation” Imaging
Performance

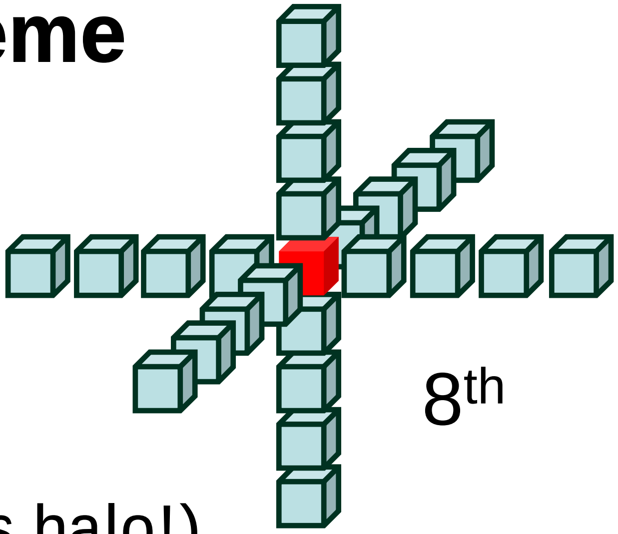
- **Production CPU kernel**
  - Performance: 15 – 50 Mpoints/sec
- **Prototype CUDA kernel**
  - Single tri-diagonal system
  - Constant coefficients
  - Performance: 700 Mpoints/sec
- **Production CUDA kernels**
  - Single kernel handles x, y, x+y & x-y operators
  - Several kernels calculate coefficients
  - Performance: 300-500 Mpoints/sec

“Reverse-time” Imaging
Two-way propagation

- **Based on the scalar wave equation**

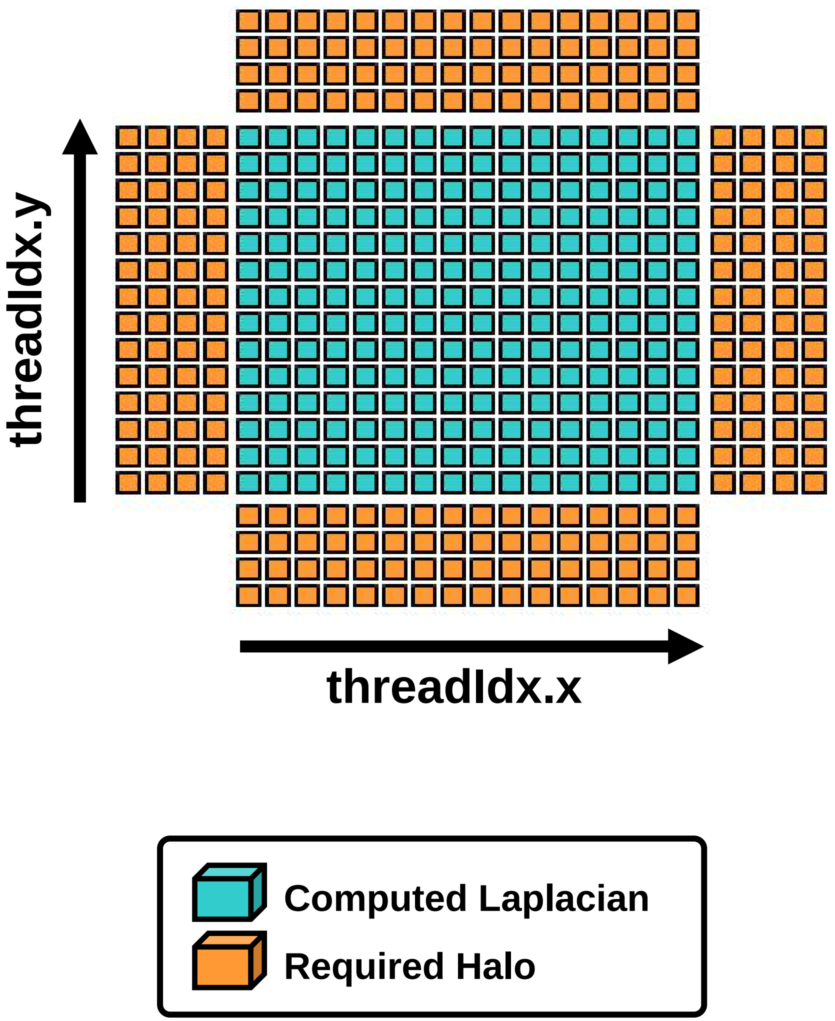
$$\frac{1}{V(\mathbf{x})^2}\frac{\partial^2 P}{\partial t^2} = \nabla^2 P$$

- **Explicit finite-difference scheme**
  - 2nd order in time
  - Variable order in space: 6th - 16th
    - Most of the computation
  - Bandwidth
    - Read *P(x,t)*, *P(x,t-dt) & V(x)* (plus halo!)
    - Write *P(x,t+dt)*
    - Max performance is 4+ Gpt/s



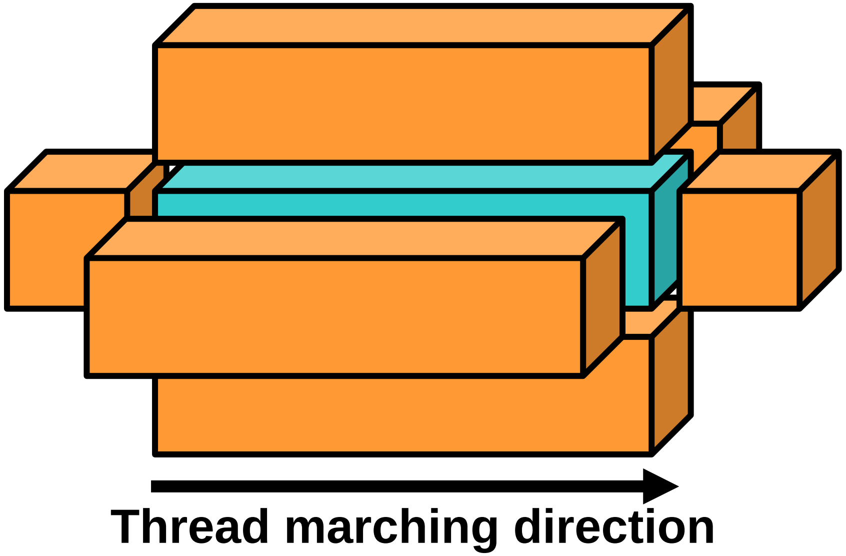
"Reverse-time" Imaging
CUDA algorithm

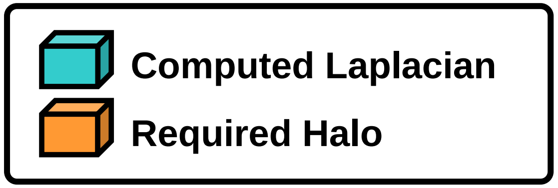
- **Paulius's algorithm**
  - Each thread specifies an (x,y) point, marching in z.
  - Each thread block handles a 2-D rectangle.
  - Each 2-D slice + halo is read into shared memory.
  - Threads in a block re-use these values.



“Reverse-time” Imaging
CUDA algorithm

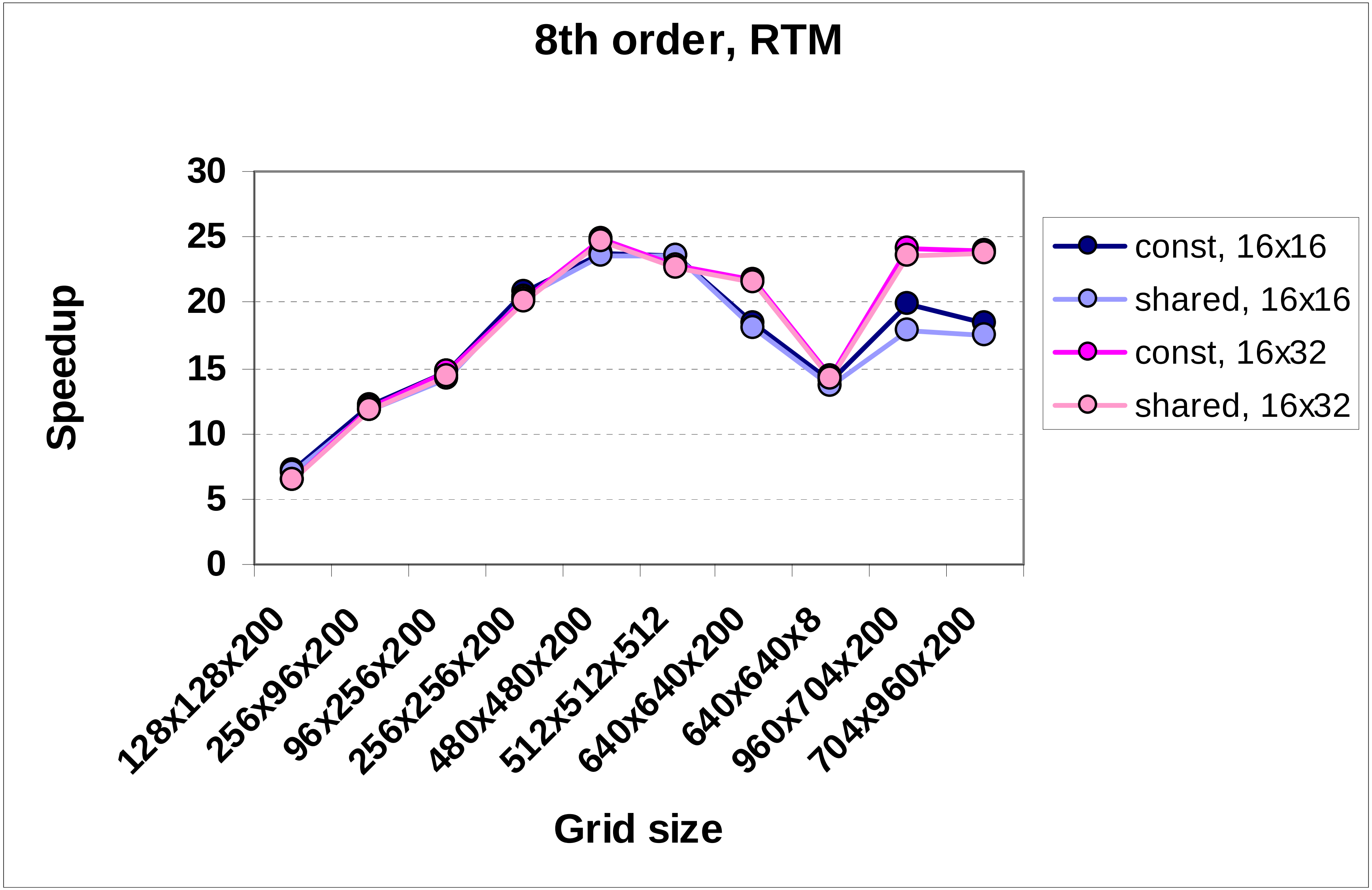
- **Paulius’s algorithm**
  - Threads in a block march in z, storing values “in-front” & “behind” in registers.
  - Number of registers limits the block size and the core-to-halo ratio.
  - GPU performance is predictable: 2.5 – 3 Gpt/s.





“Reverse-time” Imaging

Kernel performance



“Reverse-time” Imaging

Inter-GPU communication

- **High frequency requires**
  - Dense sampling
  - Large memory
  - Multiple GPUs
  - Halo exchange
  - Inter-GPU communication
- **Device ⇔Host**
  - Use pinned memory
  - PCIe bus predictably yields ~ 5 GB/s
  - ~ 10 % of kernel time
  - Easily hidden

"Reverse-time" Imaging

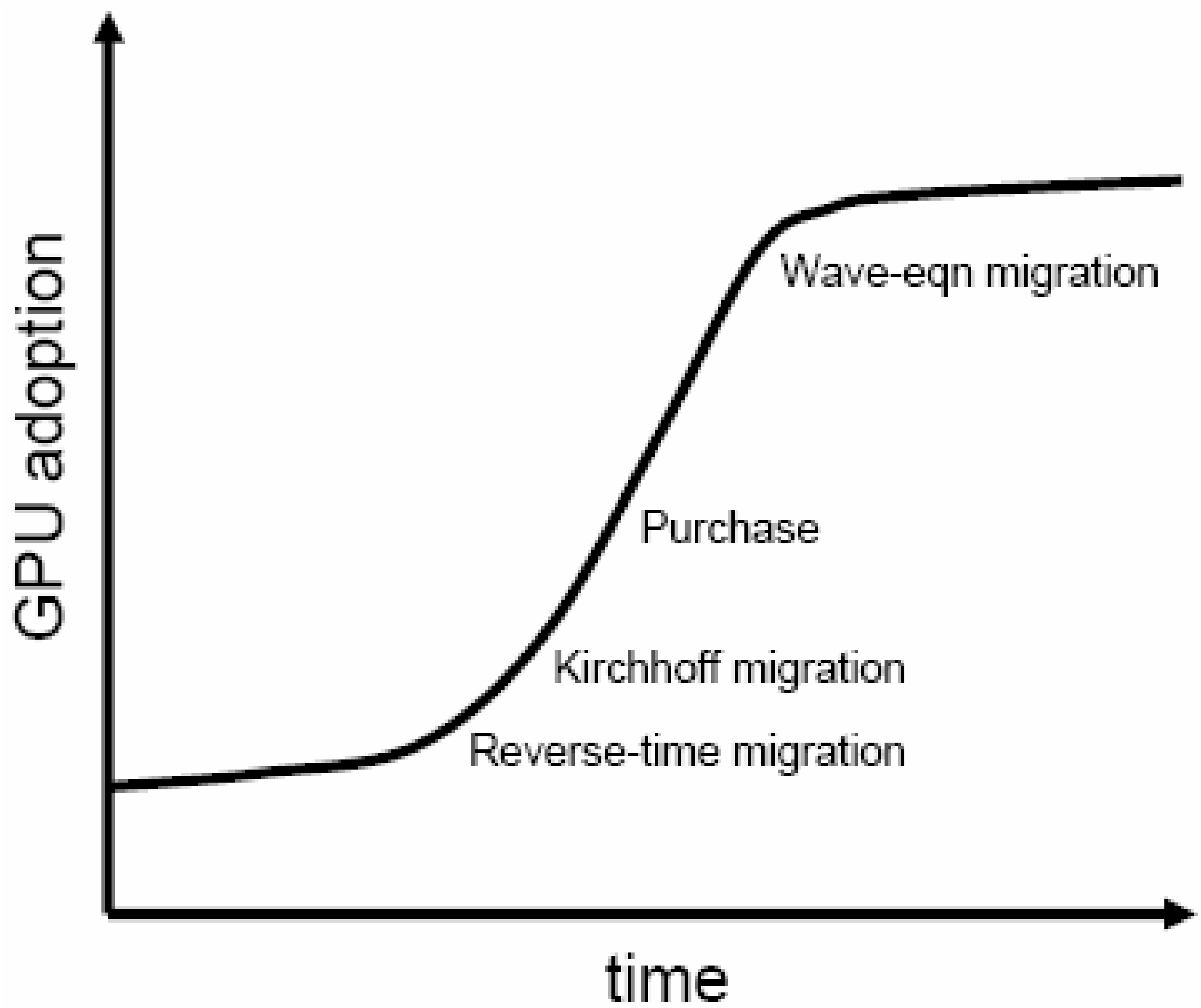
Inter-GPU communication

- **CPU process ⇔process**
  - Currently using MPI
    - From legacy code
  - Performance variable
  - Comparable to kernel time
  - Solutions
    - OpenMP?
    - single controlling process?
- **Node ⇔node**
  - Currently Gigabit Ethernet
  - Solution? Infiniband? 10-GigE?

Seismic Imaging
Summary

- **Seismic imaging CUDA codes**
  - All 3 main codes written & verified
    - Two in production
    - One in production testing/optimization
  - All done with about two-man years of effort
  - Kernel speed-ups vary from 10 – 80 X on GT200
  - 456-GPU cluster out-performs 3000-CPU cluster
- **GPU cluster**
  - Jan 2008: bought 32-nodes (128 G80 GPUs)
  - Dec 2008: upgraded & expanded to 456 GT200s
  - Nov 2009: expanding to 1200 GT200s

Seismic Imaging
Summary



Seismic Imaging
Acknowledgements

- **Code co-authors/collaborators**
  - Thomas Cullison (Hess & Colorado School of Mines)
  - Paulius Micikevicius (NVIDIA)
  - Igor Terentyev (Hess & Rice University)
- **Hess GPU systems**
  - Jeff Davis, Mac McCalla
- **NVIDIA support & management**
  - Ty Mckercher, Paul Holzhauer, Jeff Saunders, Philip Nenon
- **Hess management**
  - Jacques Leveille, Vic Forsyth, Jim Sherman