CUDA-based Geant4 Monte Carlo Simulation for Radiation Therapy

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The collaboration

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Special thanks to the CUDA Center of Excellence Program

20,000,000

radiotherapy treatments per year in US

Image: capitalmedical.com liver

kidney

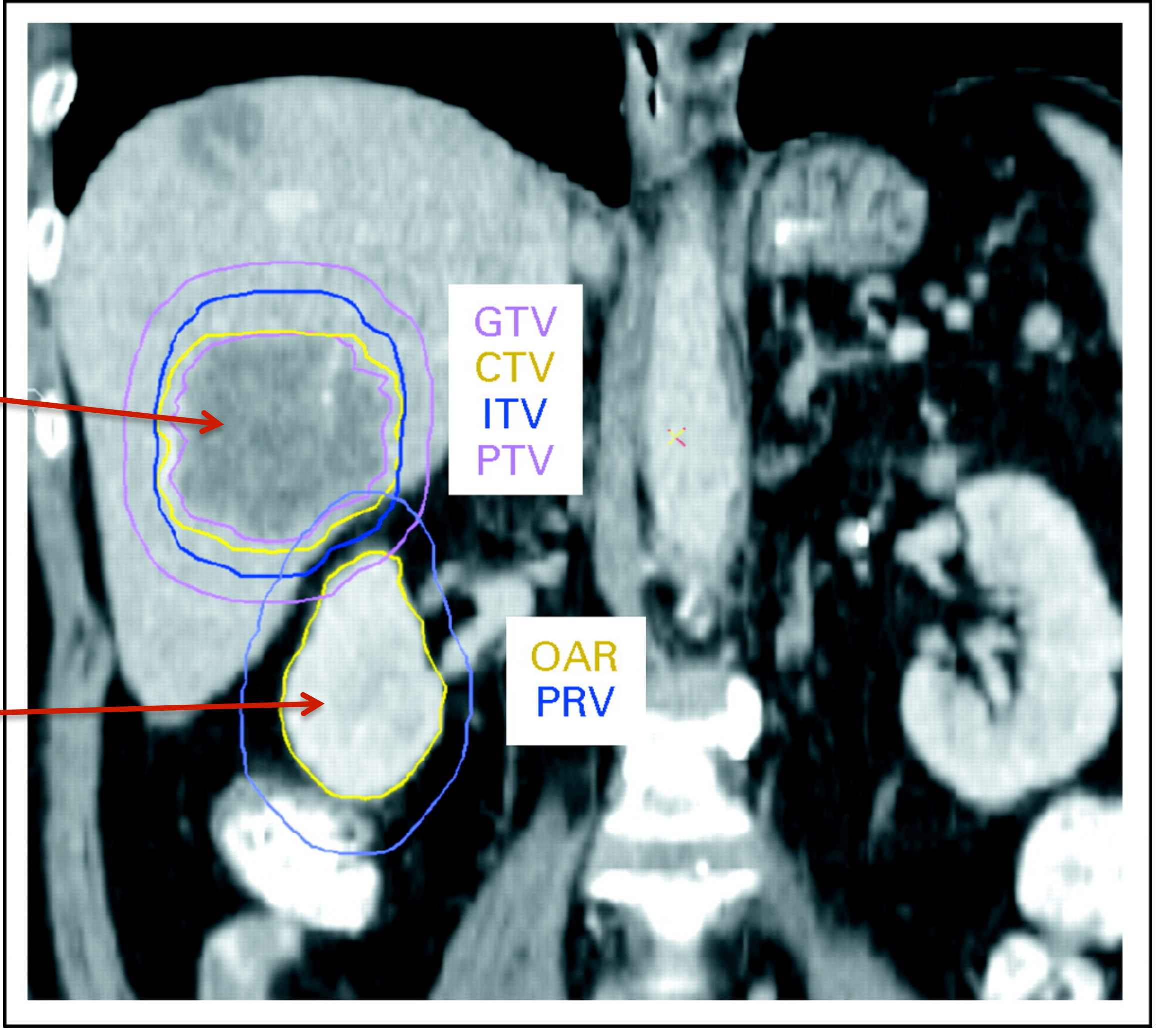


Image: James M. Balter and Marc L. Kessler, *JCO March 10, 2007 vol. 25 no. 8 931-937*

Simulation methods

Analytic

- time: seconds to minutes
- accurate within 3-5%
- used in treatment planning

Monte Carlo

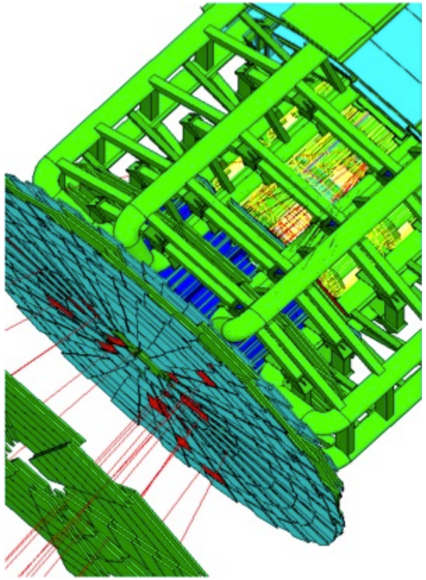
- time: several hours to days of CPU time
- accurate within 1-2%
- used to verify treatment plans in certain cases

Geant4 Toolkit

- Enables Monte Carlo simulation of particles travelling through and interacting with matter
- Allows modeling of complex geometries
- Covers all elementary particles and nuclei for a wide energy range

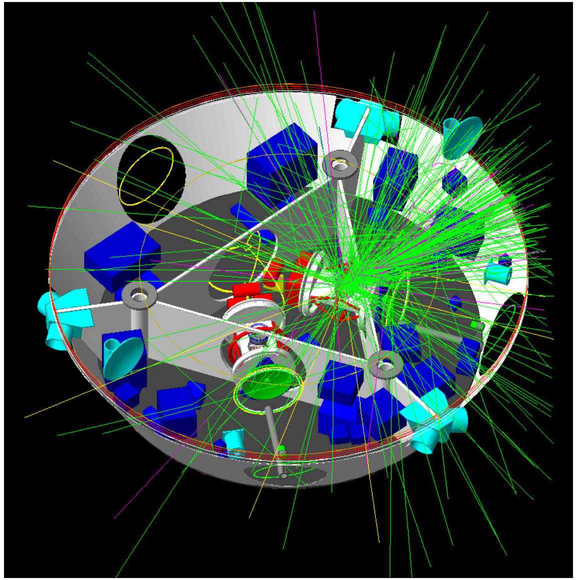
Geant4 Applications

High Energy Physics



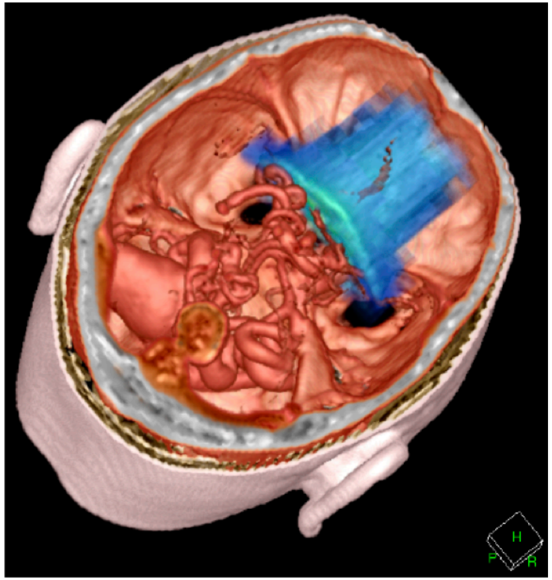
ATLAS

Space & Radiation



LISA

Medical Physics



gMocren

Images from: Geant4 gallery and gMocren

Geant4 101

- Geant4 simulates particles travelling through and interacting with matter
- Example: photoelectric effect

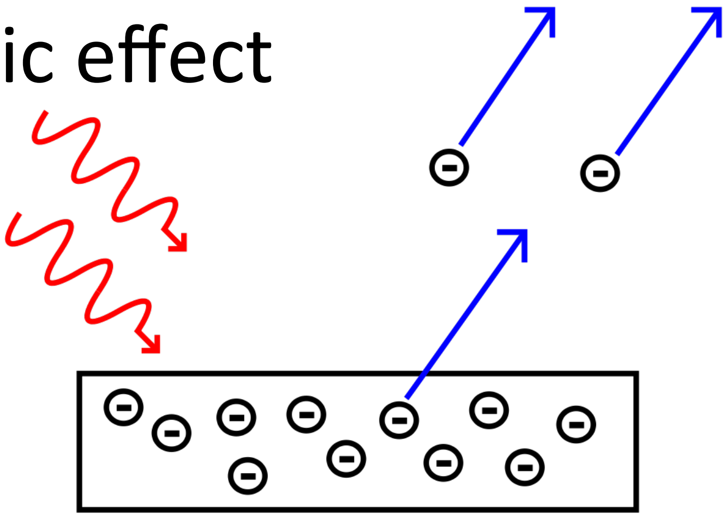


Image: CCSA by Wolfmankurd on Wikipedia

Parallelization challenges in Geant4

- Large and complex code base
- Sophisticated geometry framework
- Elaborate physics models
- Branching, look-up tables, single-thread optimizations

Thank goodness

The simulation is embarrassingly parallel!

(the particles are independent)

Requirements for X-ray Radiotherapy

- Geometry is a voxelized box
- Physics is limited to low-energy electromagnetics
- Material is modeled as water with different densities

Low energy electromagnetics

Gamma

- Compton scattering
- Photoelectric effect
- Gamma conversion

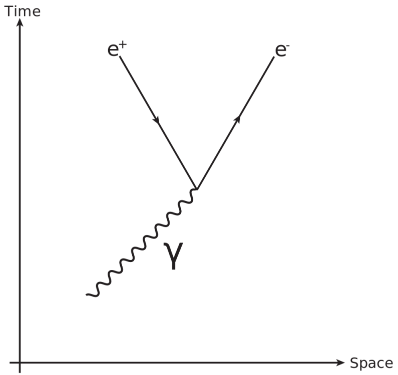


Image: CCSA by Manticorp on [Wikipedia]

Electron/positron

- Ionization
- Bremsstrahlung
- Positron annihilation
- Todo: Multiple scattering

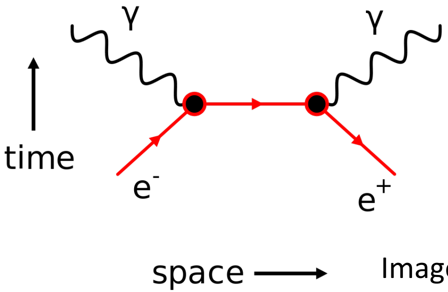


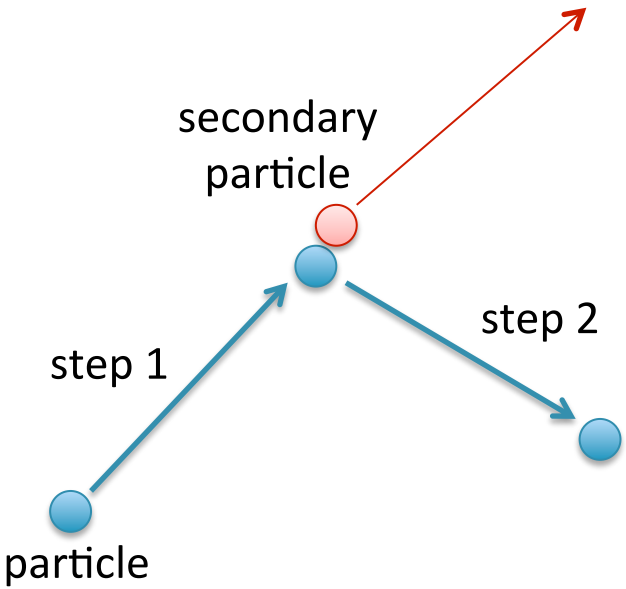
Image: public domain

What makes a physics process?

- Sample for angular and energy distributions of secondary particles
- Deposit energy to material
- Produce secondary particles that must be tracked at a later point

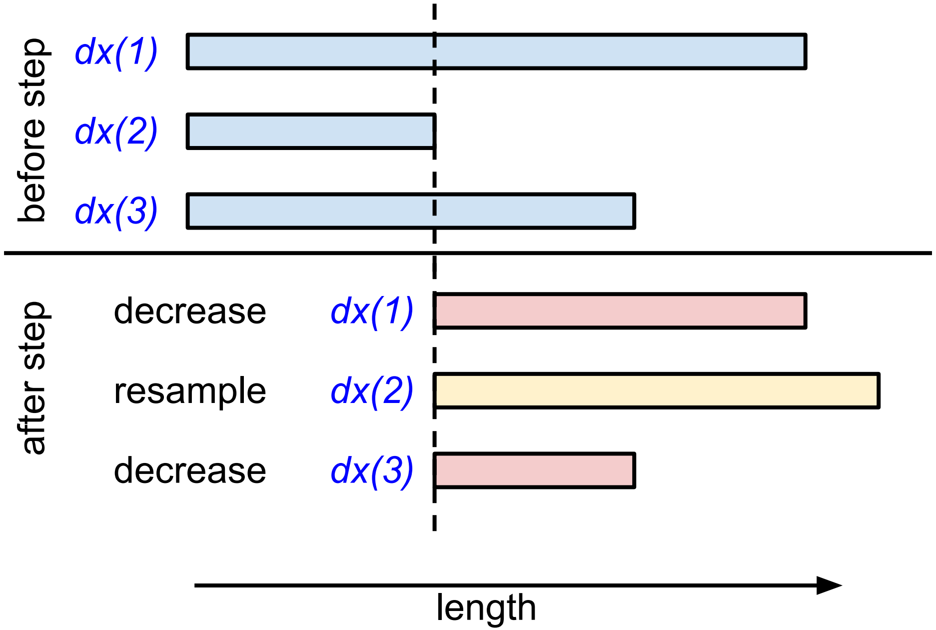
Tracking algorithm

- Particles are tracked through space
- Each discrete move is called a step
- Physics process may occur along step, after the step, or both



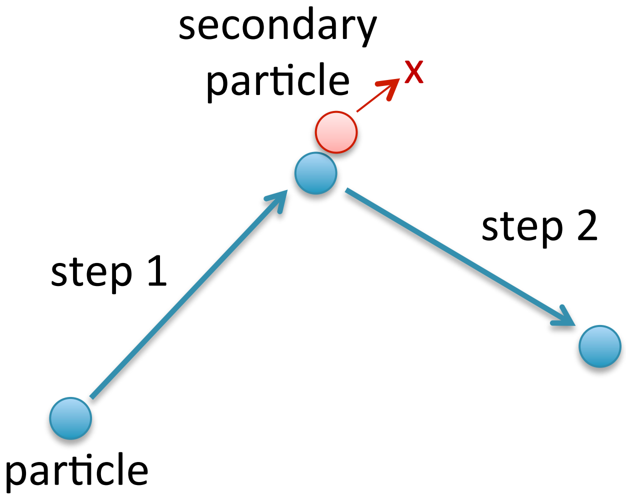
How are processes selected?

- Each process has an "interaction length" (dx)
- Process with shortest dx is selected
- After the step dx is decreased or resampled



Energy deposition

- Happens along the step for the ionization process
- May happen at the end of the step
- Secondary particles with too low energy are not generated, but treated as point-like energy depositions



G4CU: CUDA-base MC for RT

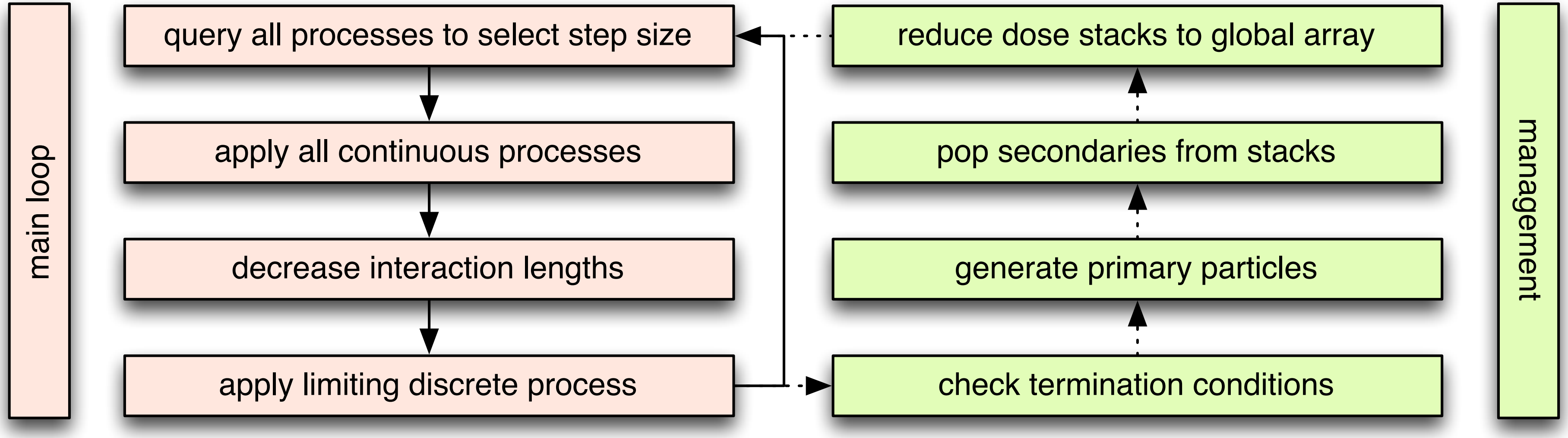
- Important data structures
- Algorithm summary
- Details
  - Parallel stack
  - Look-up tables

Struct-of-arrays data pattern

```
struct ParticleArray {
  // length of arrays
  int length;
  // kind of particle
  ParticleKind *kind;
  // position
  float *x, *y, *z;
  // direction
  float *dx, *dy, *dz;
  // particle energy
  float *energy;
  // voxel index
  int *vx, *vy, *vz, *vid;
};
```

- Common pattern in CUDA to allow for coalesced memory access
- Experiments with transport showed this to be 3-4x faster than AOS

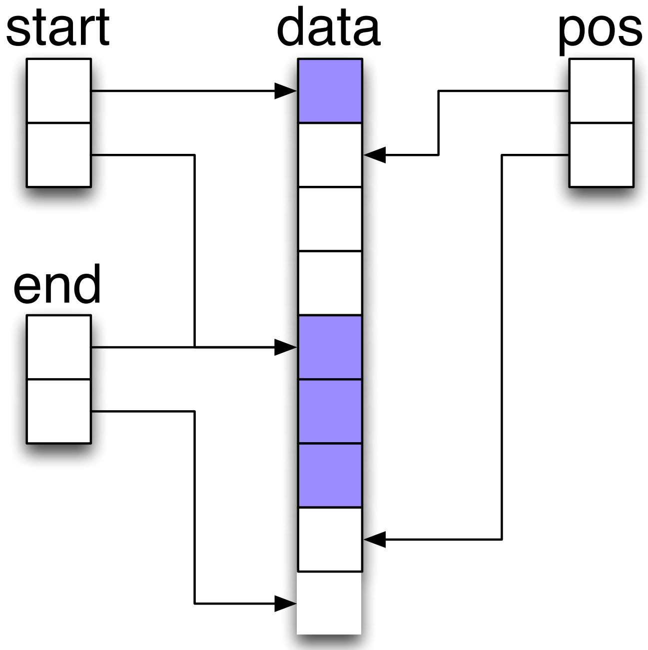
G4CU: algorithm



Some details

- A process does a few things:
  1. Changes direction and momentum of primary particle
  2. Generates secondary particles
  3. Deposits energy to the material
- We use thread local stacks to handle 2 and 3

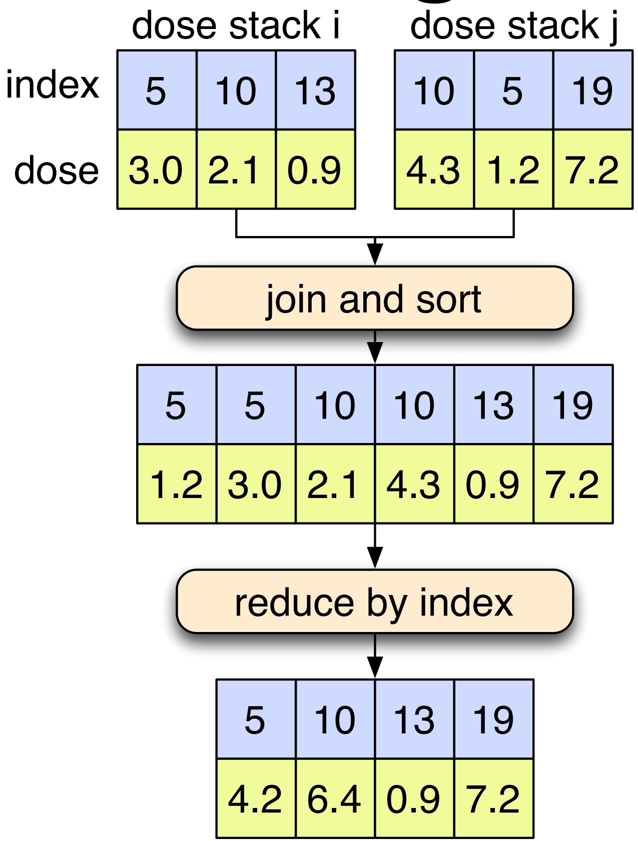
Parallel stacks




```
template <typename T>
struct pstack {
  // number of stacks
  int stack_num;
  // size of each stack
  int stack_size;
  // starts and ends of stacks
  int *start, *end;
  // stack positions
  int *pos;
  // stack data array
  T *data;
};
```

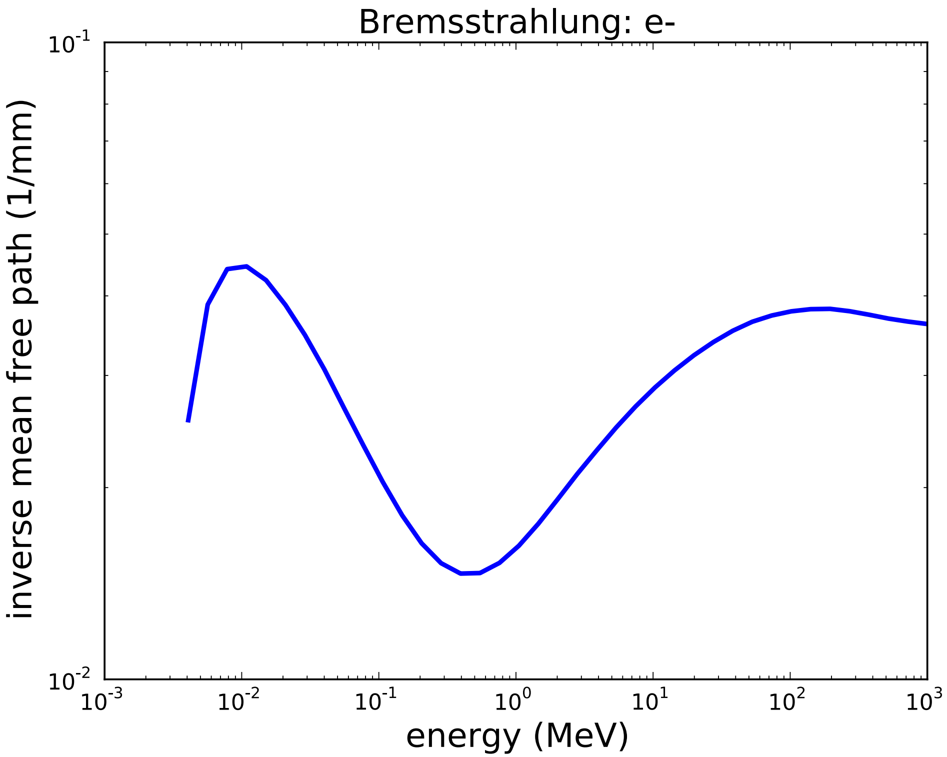
Dose reduction & storage

- Energy dose is stored in a thread local variable
- When particle moves to new voxel, dose is pushed onto stack
- Dose reduction is performed periodically
- We use Thrust



Look-up tables

- Used for interaction length computation
- 40 bins, log spaced
- Linear and spline interpolation
- Bremsstrahlung also uses 2D interpolation



Benchmarks

Configuration:

- Geometry: 512 x 512 x 256 voxels
- Dose reduction frequency: every 200 iterations
- 128 blocks with 256 threads
- Primary particle is a 6 MeV gamma
- Tesla C2070

Simulation time

- 100 million primary particles
- Time: 72 minutes
- ~ 23.1 primary particles per ms
- ~ 50-60x speedup over Geant4 on 1 CPU

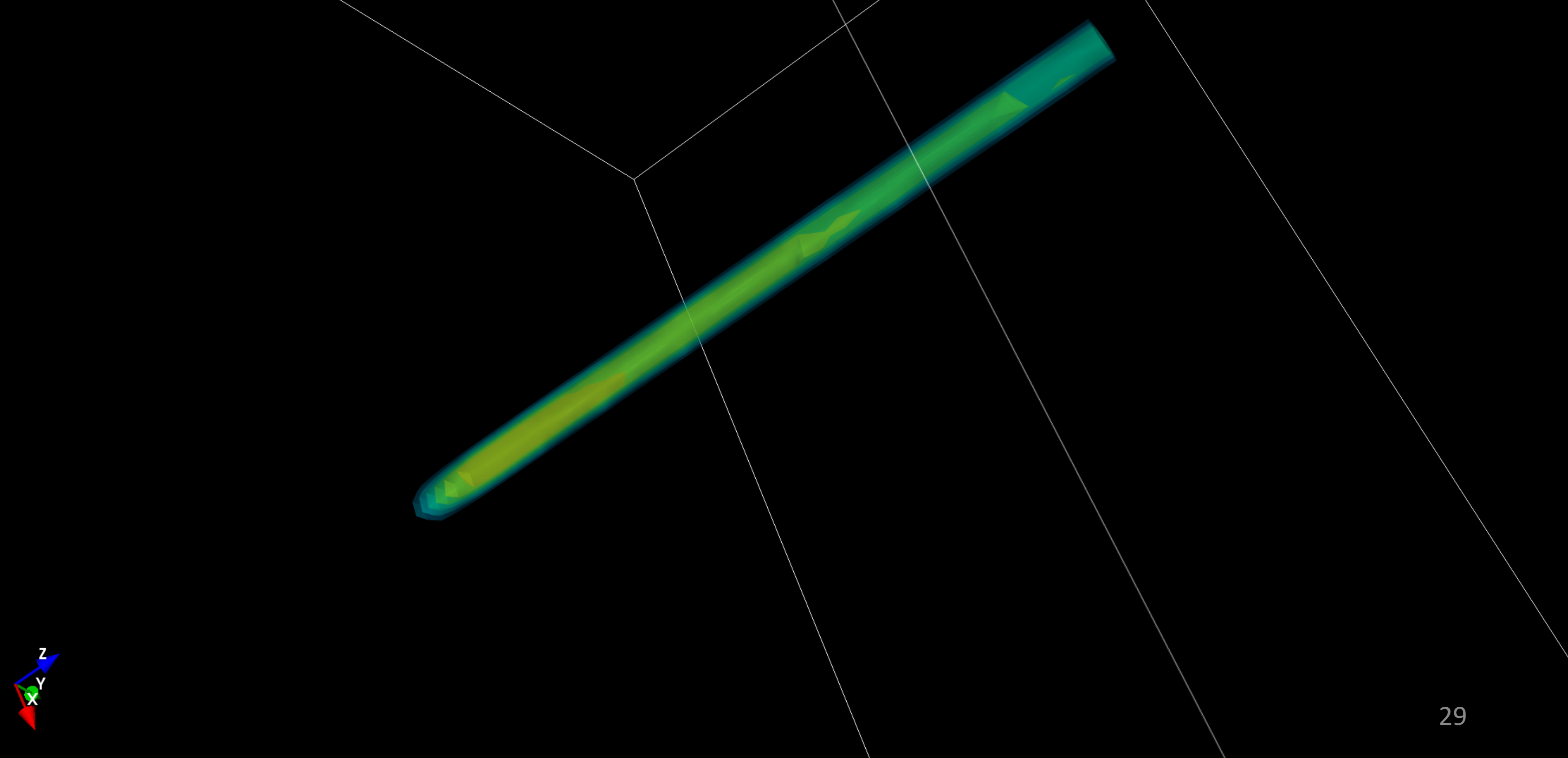
Profile

Component	Percentage of overall time
Physics processes	50
Energy dose reduction	30
Interaction length	18
Run management	2

Physics process breakdown

Process	Particle	Percentage of overall time
Bremsstrahlung	e- / e+	23
Pair production	γ	7.5
Transport	all	7
Photoelectric effect	γ	7
Ionization	e- / e+	3
Compton scattering	γ	1.5
Positron annihilation	e+	1

Dose distribution



Acknowledgements

Geant4 Collaboration, see

- **Geant4—a simulation toolkit,** *Nuclear Instruments and Methods in Physics Research* A 506 (2003) 250-303
- **Geant4 developments and Applications**, *IEEE Transactions on Nuclear Science* 53 No. 1 (2006) 270-278

NVIDIA & CCOE Program

People:

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