

Nuclear Medicine Physics
Symposium 2008

***MonteCarlo Applications In
Nuclear Medicine and
Radiotherapy***

**A review of Monte Carlo
Applications in Radiotherapy
14:00-14:30**

Trevor Ackerly Chief Physicist

William Buckland Radiotherapy Centre

Alfred Hospital



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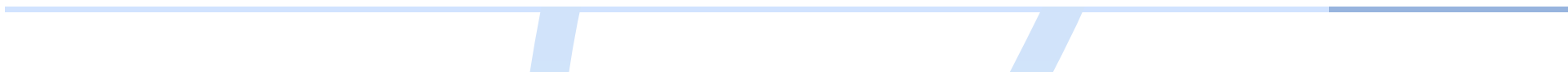
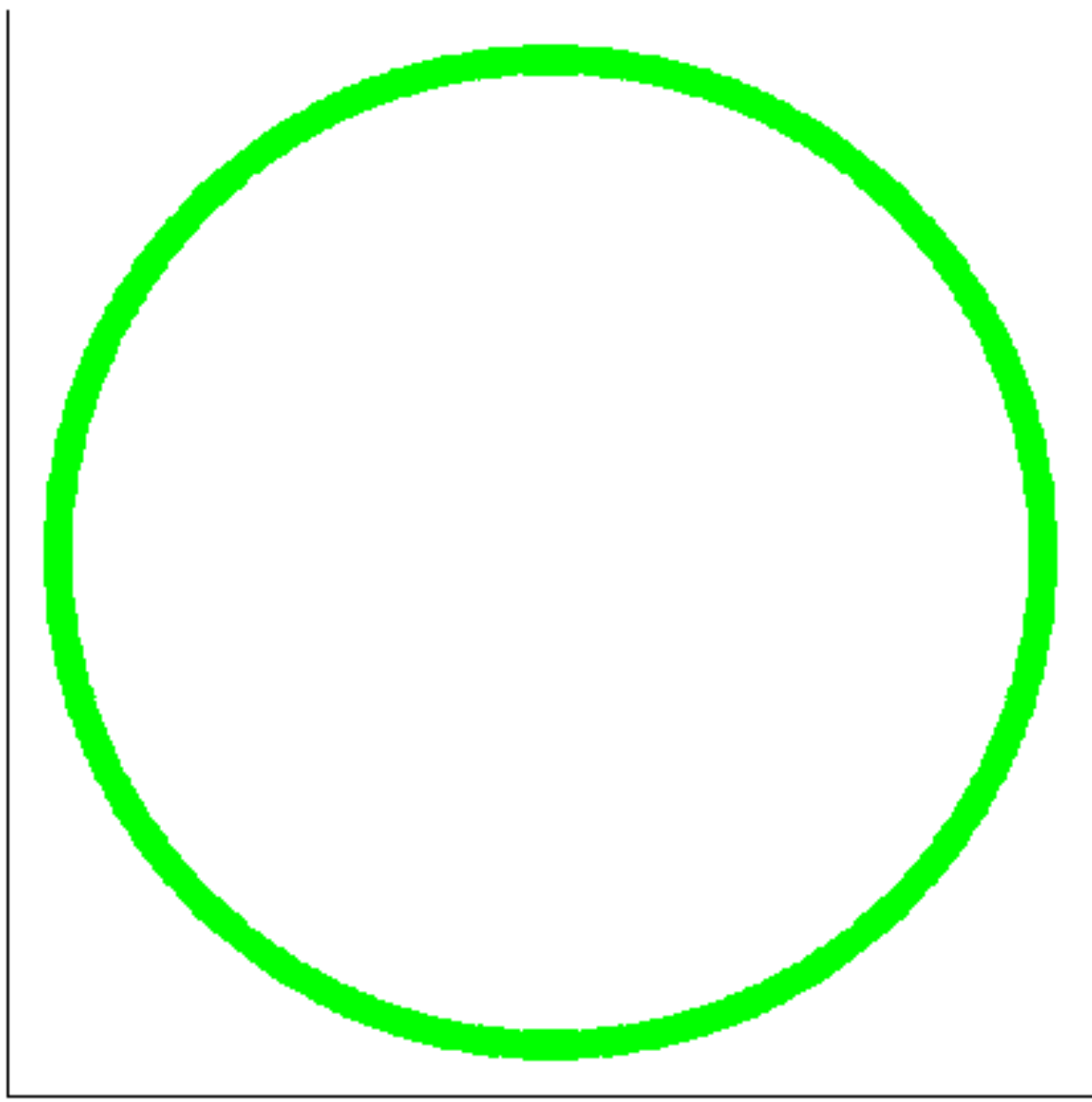
Monte Carlo Estimation of Pi

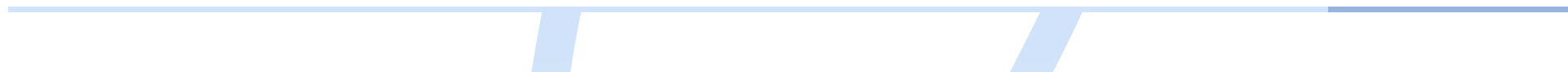
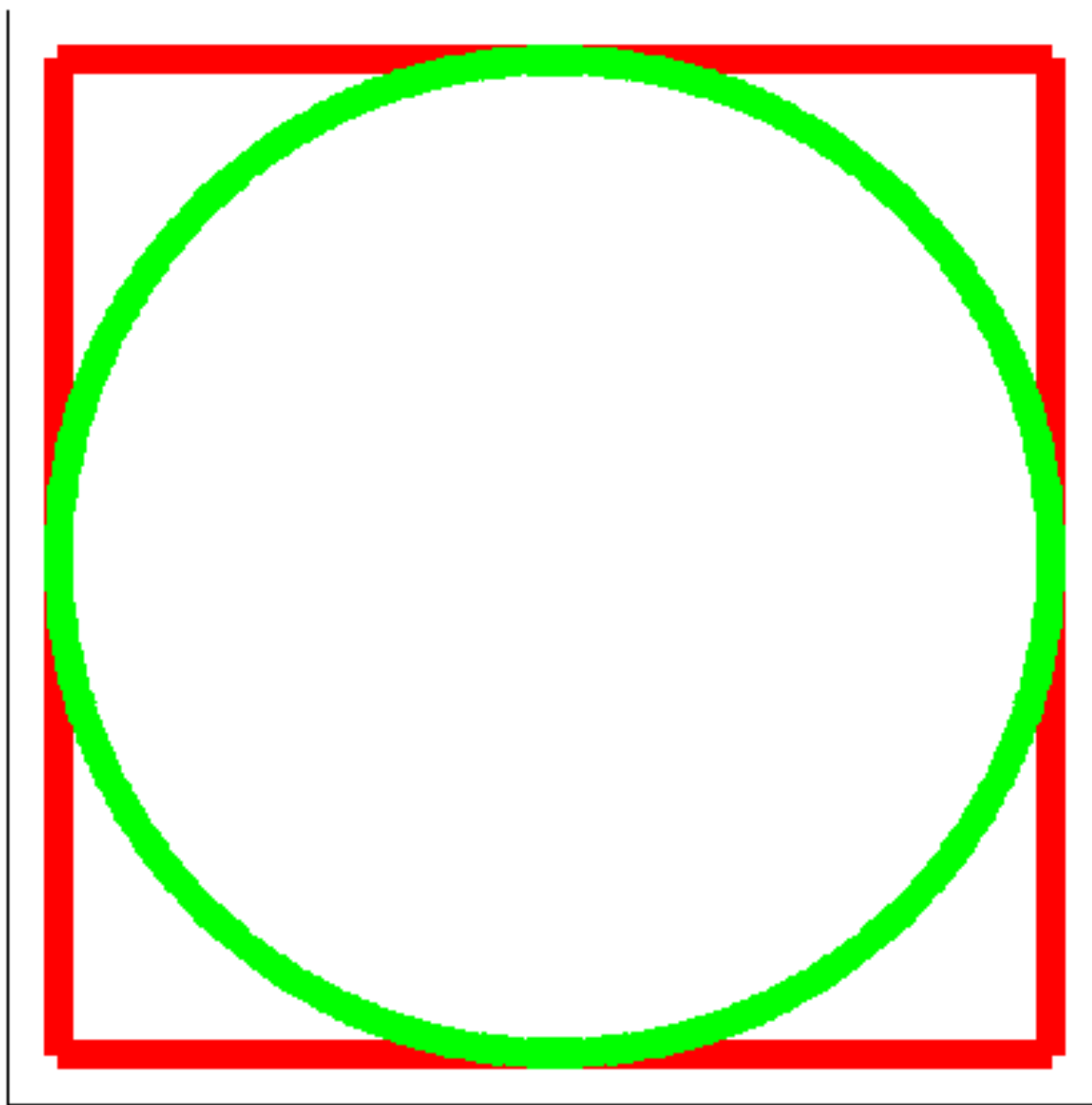
- ▶ Estimate Pi by randomly selecting points within a square of area 4, side length 2.
- ▶ Check if the points are inside or outside a circle of area Pi within the square.
- ▶ Number of points inside the circle divided by the total number of points is a statistical estimate of the area of the circle divided by the area of the square, $\text{Pi}/4$.
- ▶ Multiply ratio by 4 to get a statistical estimate of Pi.

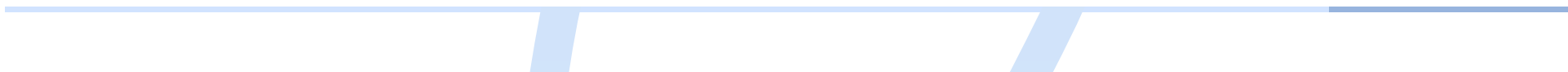
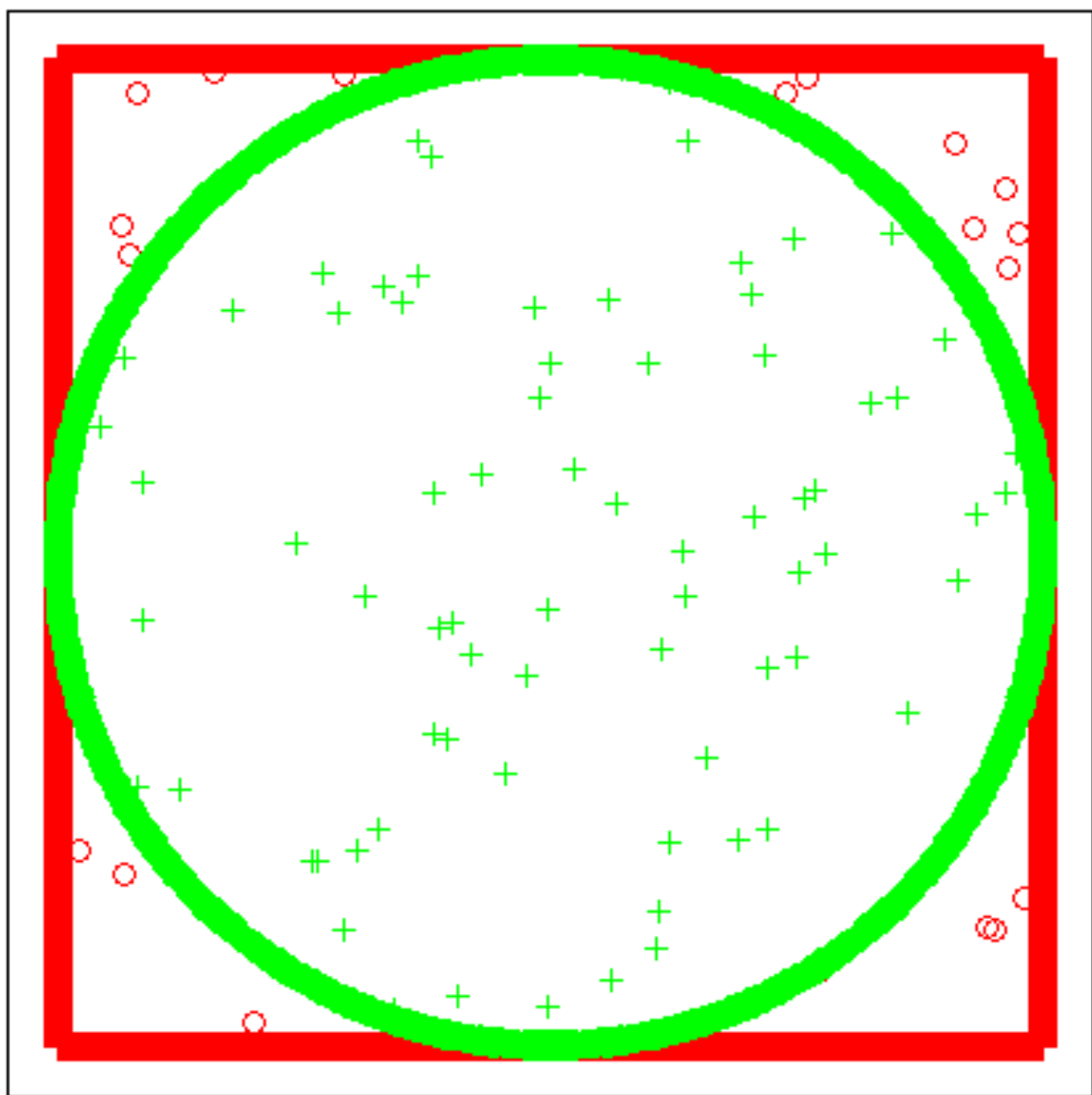


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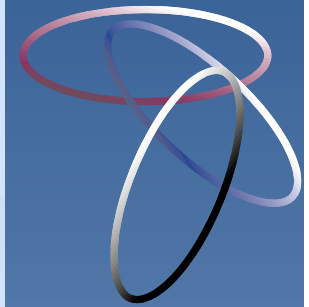






Statistical Estimate of Pi

- ▶ 100 points.
- ▶ 75 points in the circle.
- ▶ 25 points outside the circle.
- ▶ Estimate of Pi is $4 \times 75 / 100 = 3$
- ▶ Since we know the answer is $\text{Pi}=3.14$,
- ▶ Error is 0.14 after 100 points.



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How accurate is the estimate of pi?

5.4 Error estimation for binary scoring

In the special case where the scoring quantity is binary (*e.g.* a particle enters a detector's sensitive region or not, *e.g.* a particle backscatters or not) there is a significant simplification. Consider N events where the scoring variable x_i is either 0 or 1. The mean is calculated according to eq. 5.12. Starting from eqs. 5.12–5.14 it is easy to show that:

$$s_{\bar{x}}^2 = \frac{\bar{x}(1 - \bar{x})}{N - 1}. \quad (5.24)$$

Hence, knowing the mean value gives one knowledge of its estimated variance! One is not required to gather these events in statistical bins.

Combining the results of independent runs is particularly simple. The mean is calculated from eq. 5.12 but the use of the variance combination relation, eq. 5.20, is inaccurate unless the N_j are all “large” ($N_j \gg 1$). It is best to resort to eq. 5.24 which has no such restriction.

$$s_{\bar{x}}^2 = \frac{\bar{x}(1 - \bar{x})}{N - 1}$$

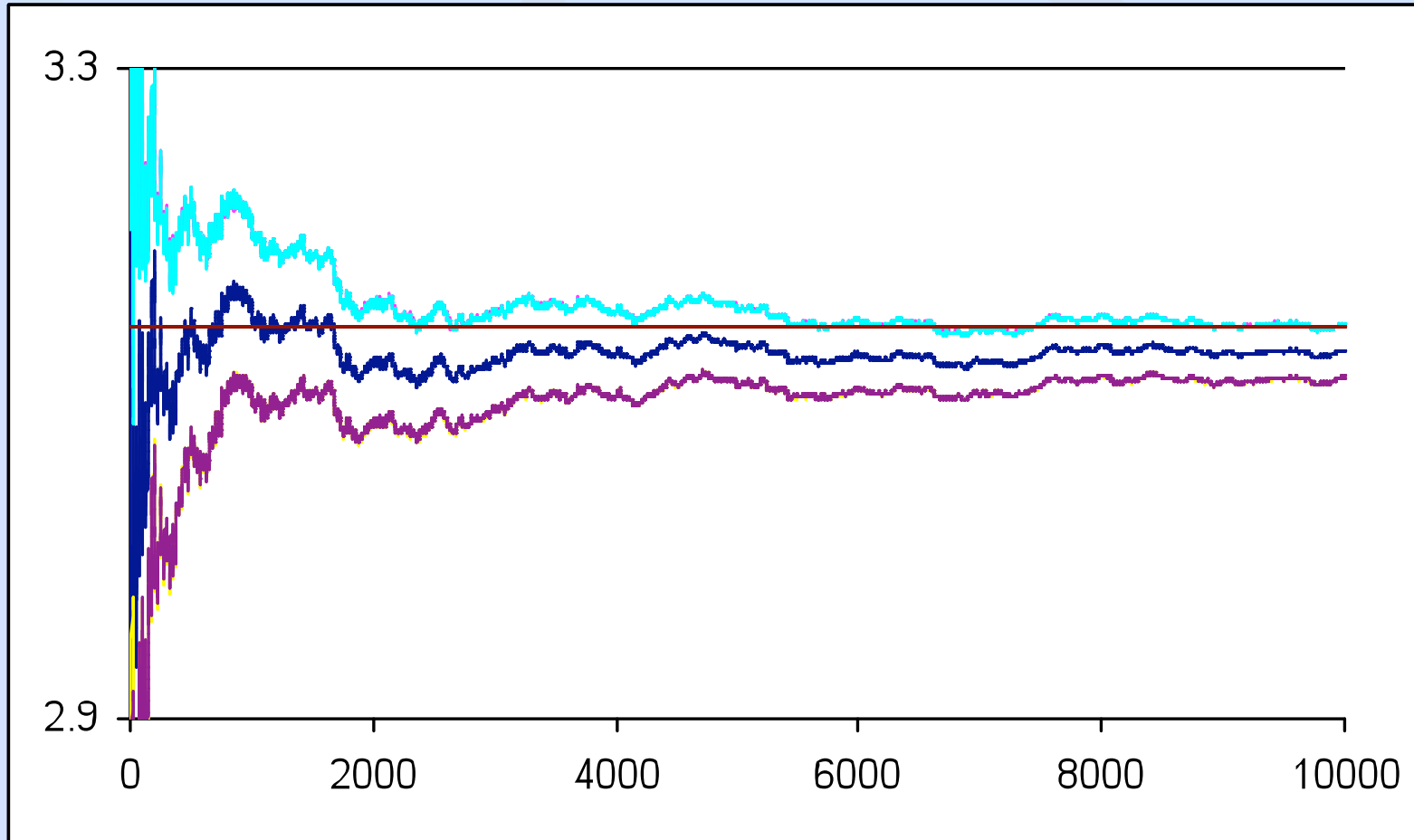
Is valid for estimates of pi/4, so for estimates of pi

$$s_{\bar{\pi}}^2 = \frac{\bar{\pi}(4 - \bar{\pi})}{N - 1}$$

And this has been used to Determine the error shown.



Error margins in practice, meaning of a statistical estimate.

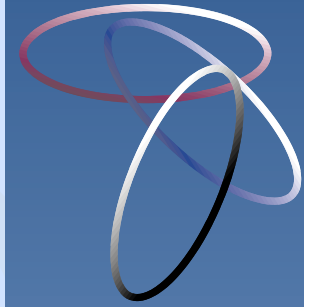


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How accurately can we estimate Pi?

- ▶ Age of Universe is 14.0 Billion years.
- ▶ On August 26, 2008, BOINC recorded a processing power of over 1,080 TFLOPS through over 550,000 active computers.
- ▶ If we got one point per floating point operation, and ran BOINC for the life of the Universe, we would obtain a statistical estimate of Pi that was 65% likely to be correct to 17 decimal places.



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<http://numbers.computation.free.fr/Constants/Pi/piclassic.html>

In 1699 Abraham Sharp (1651-1742) (England) used Gregory's series by Taking $x=1/\sqrt{3}$

$$\frac{\pi}{6} = \frac{1}{\sqrt{3}} \left(1 - \frac{1}{3.3} + \frac{1}{3^2.5} - \frac{1}{3^3.7} + \dots \right)$$

The first iterates are:

X1=3.(4641016151377545...)

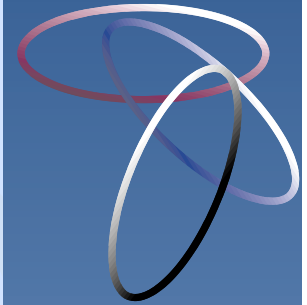
X2=3.(0792014356780040...)

X5=3.14(26047456630846)

X10=3.14159(05109380800...)

By computing x150, Sharp calculated pi to 72 digits.

And with series expansions it is usually possible calculate the margin of error.



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So what are
Monte Carlo
calculations
good for?!

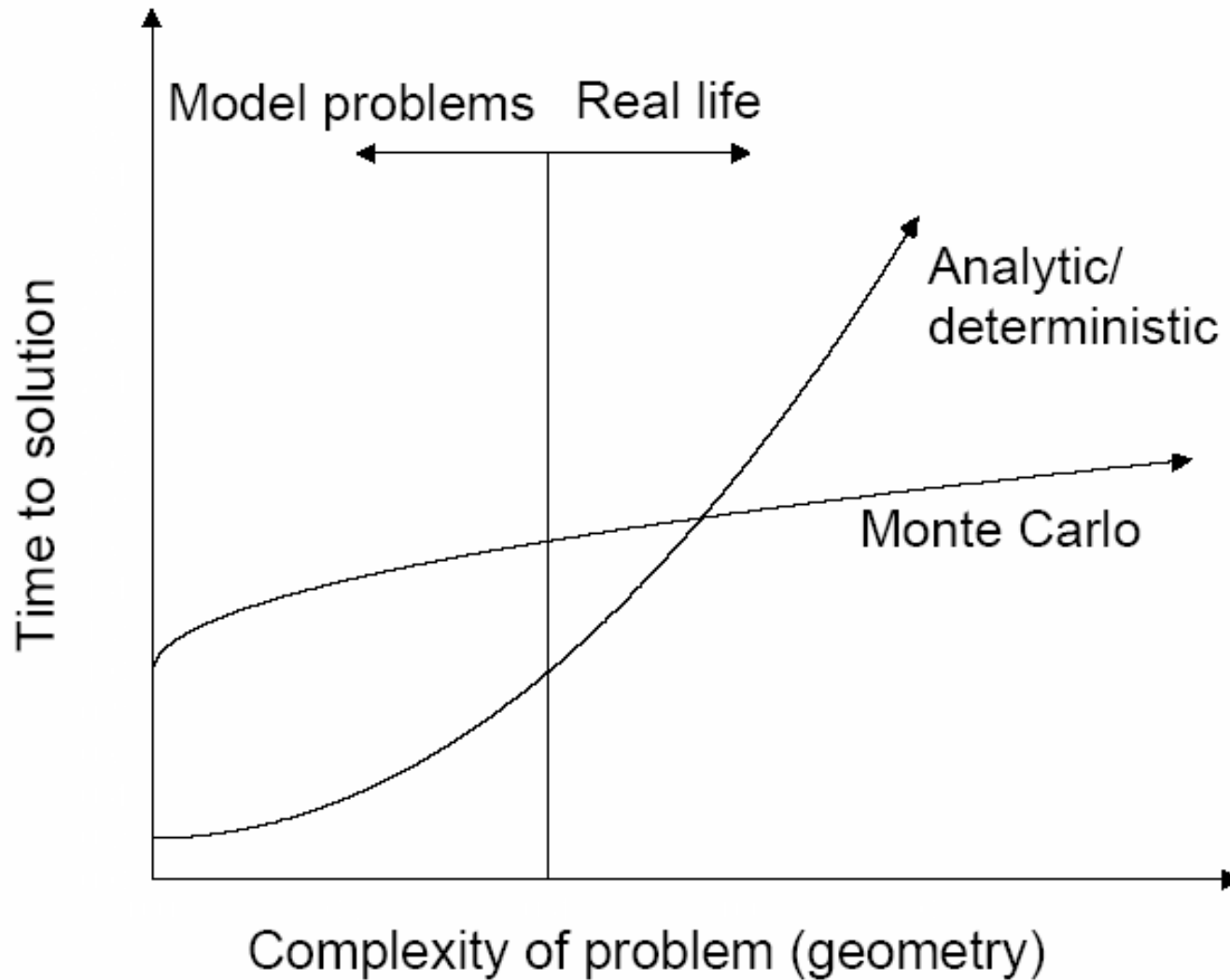


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The Monte Carlo method is very good for many-dimensional integrals.

Monte Carlo *vs* deterministic/analytic methods



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Monte Carlo Calculations

- ▶ “Monte Carlo is the method of choice for doing integrals of functions of MANY variables.” Professor Geoffrey Opat, University of Melbourne School of Physics.



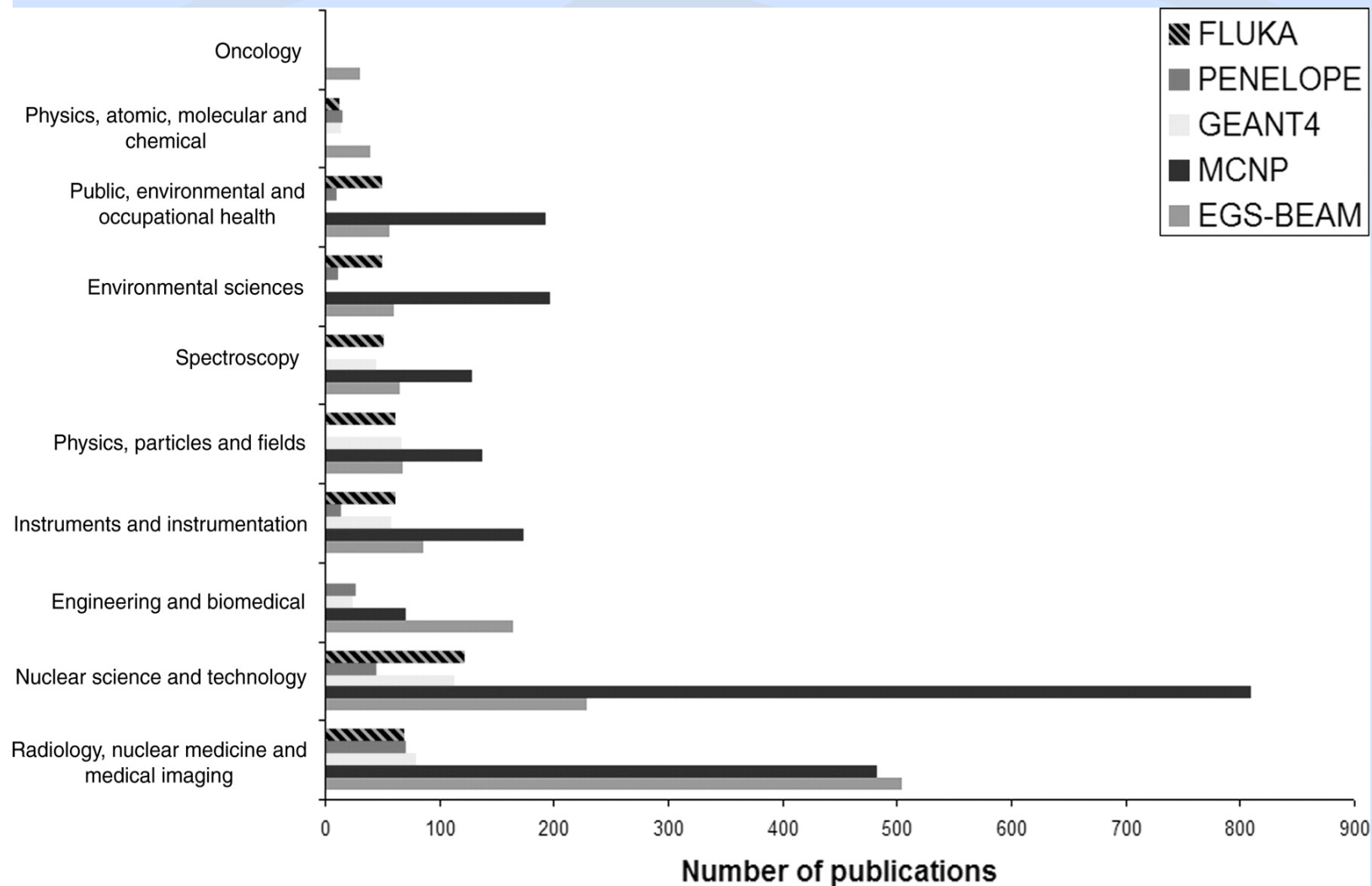
Geoffrey Opat
(1935-2002)



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Number of publications between 1985 and 2007 for main MC codes of interest in radiation therapy



Spezi, E. et al. Radiat Prot Dosimetry 2008 131:123-129; doi:10.1093/rpd/ncn277

Radiation Protection Dosimetry



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The Monte Carlo method:

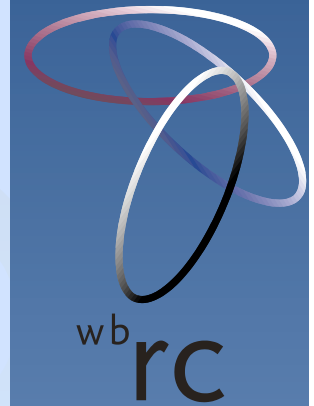
If you throw enough fair dice,
and interpret the results
correctly,
you can get a statistical
estimate,
of the correct answer.



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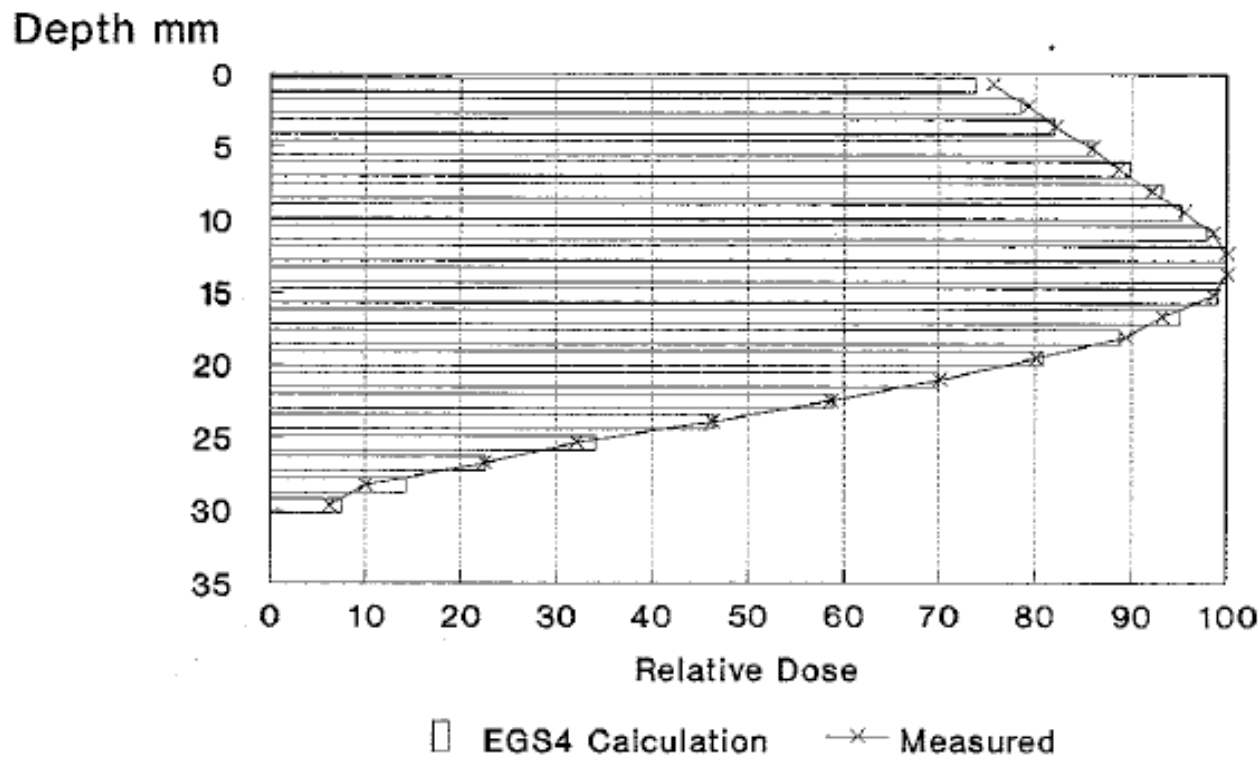
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EGS4 1990 Simulating Radiotherapy Electron Depth Dose



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6 MeV 2100C Depth Dose
E6E 10x10 Applicator



Landau Approx $E_p=6.4$ MeV, $E_0=5.80$ MeV

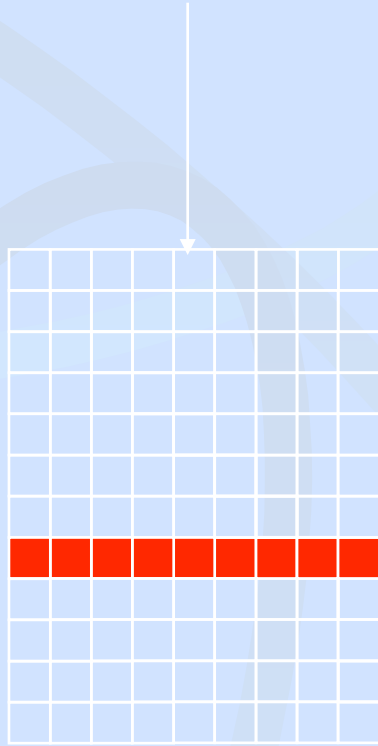
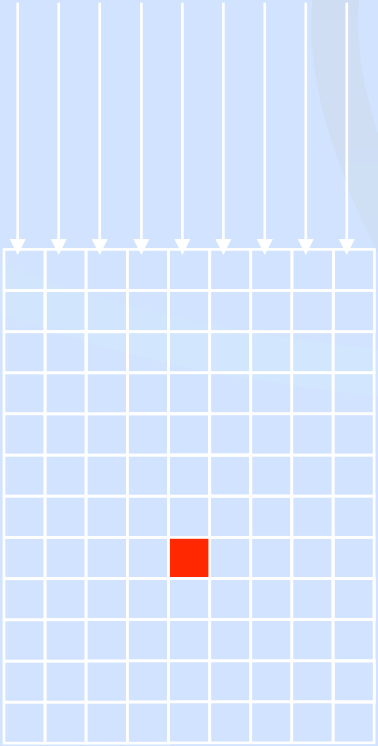
Reciprocity Theorem

- ▶ A broad parallel beam incident on a small detector...
- ▶ ...Is equivalent to...
- ▶ ...a narrow incident on a broad detector.
- ▶ See ICRU Report 35 Radiation Dosimetry: Electron Beams with Energies Between 1 and 50 MeV



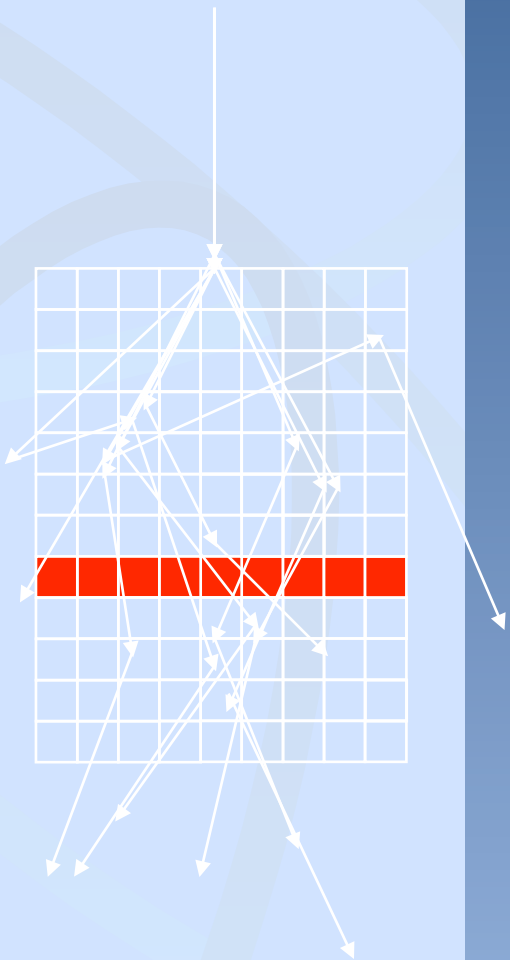
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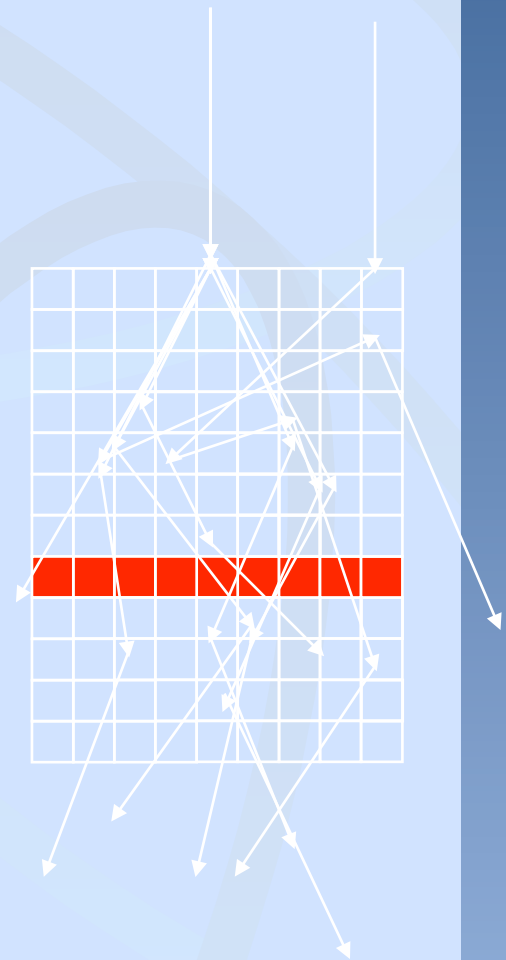
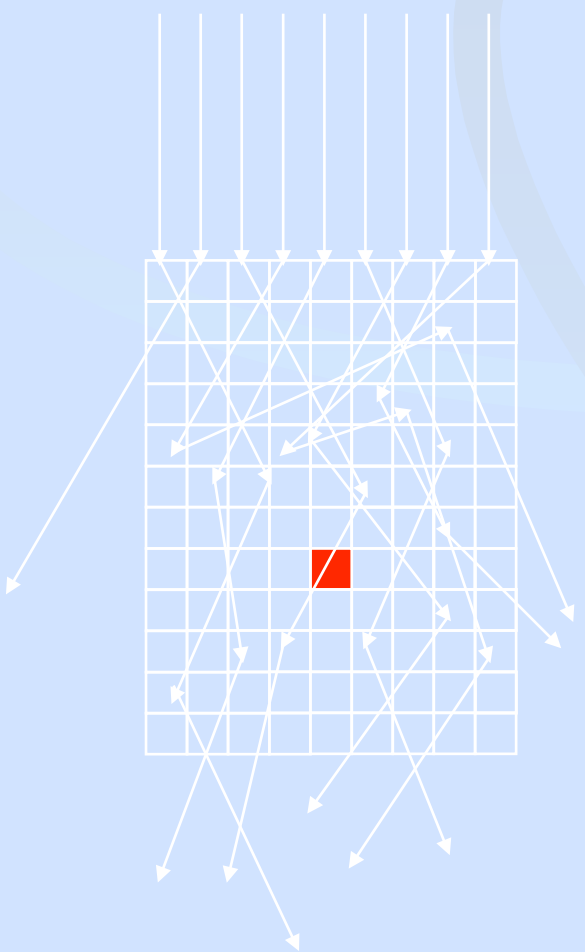
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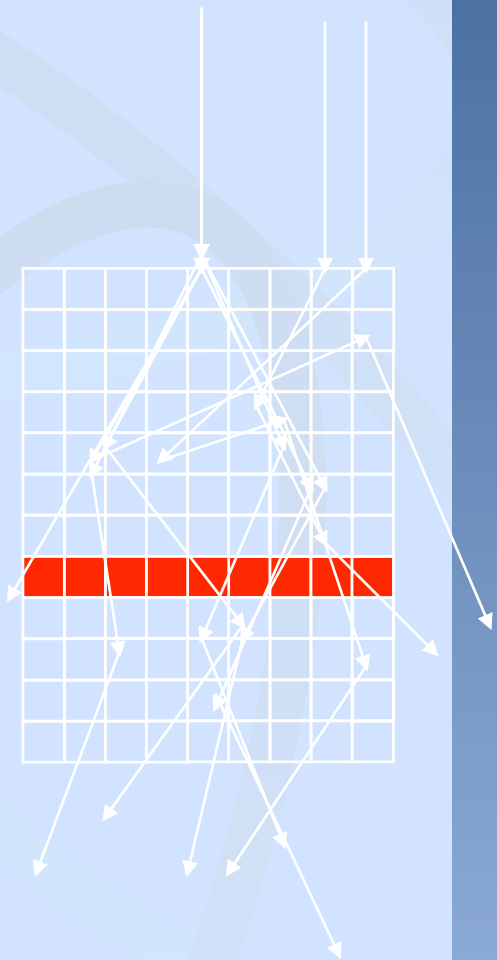
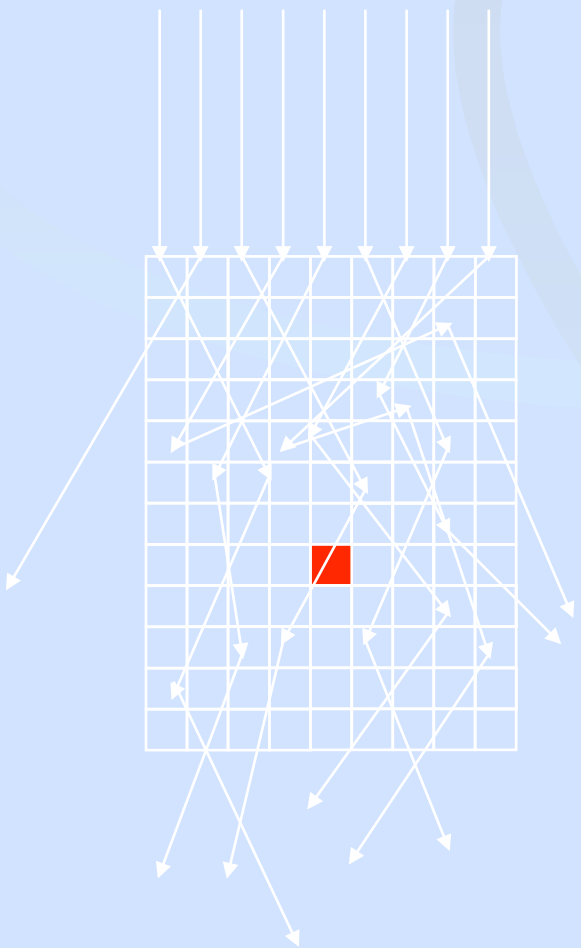
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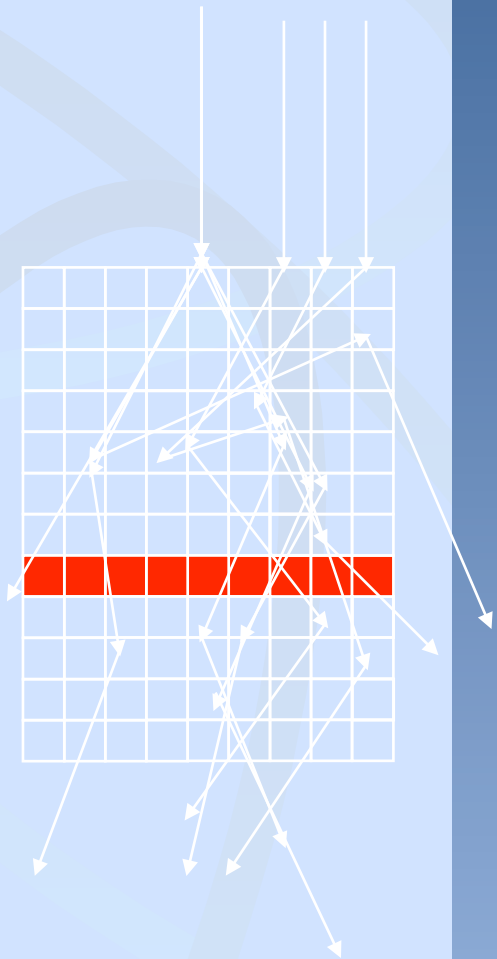
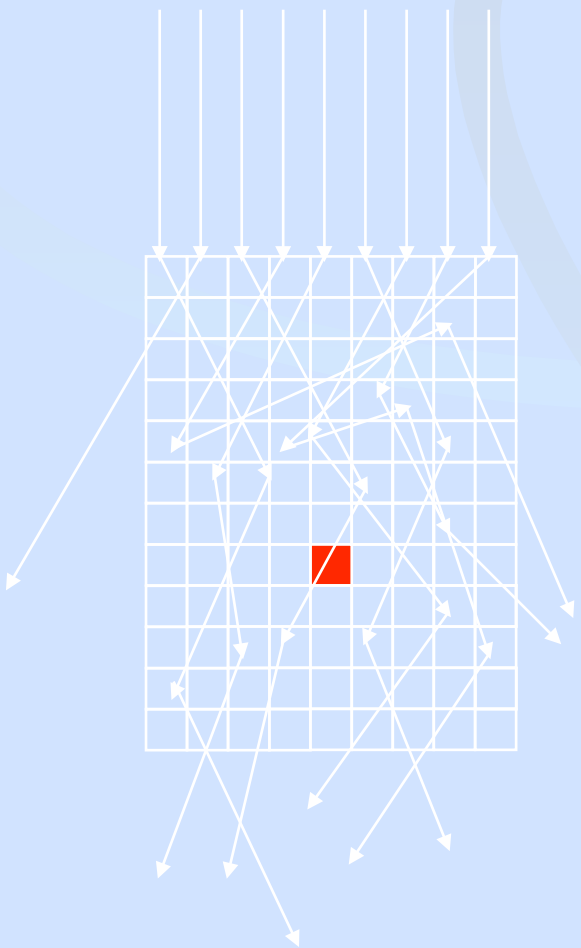
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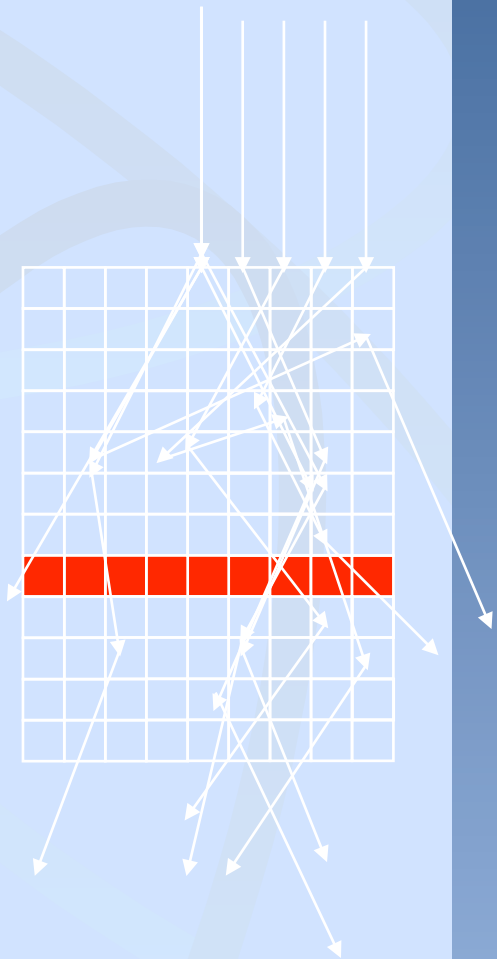
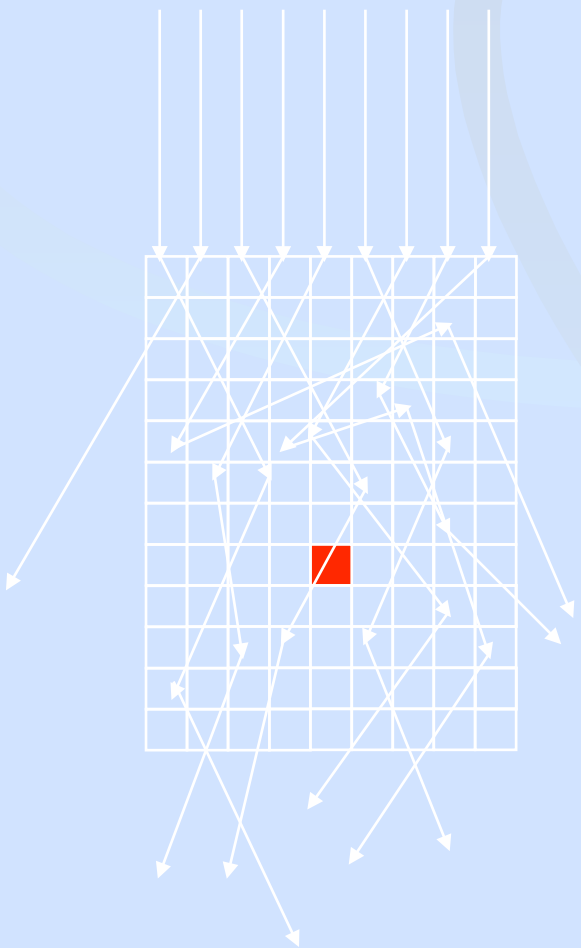
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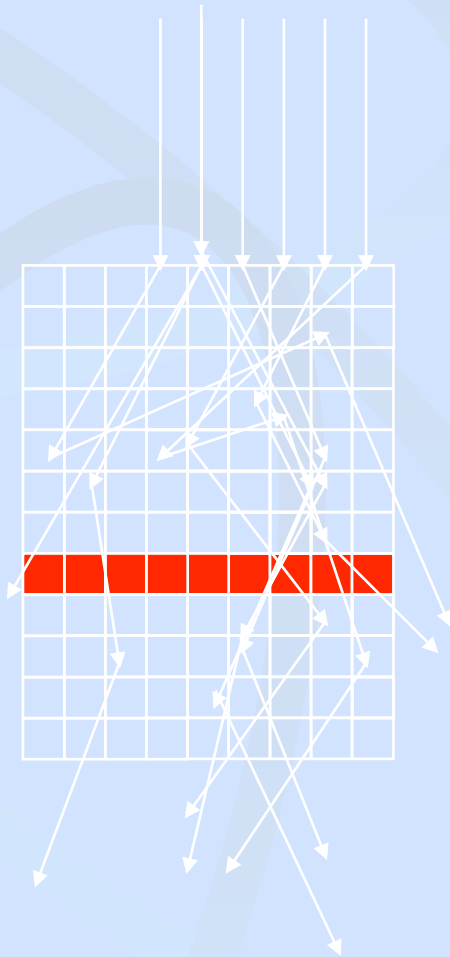
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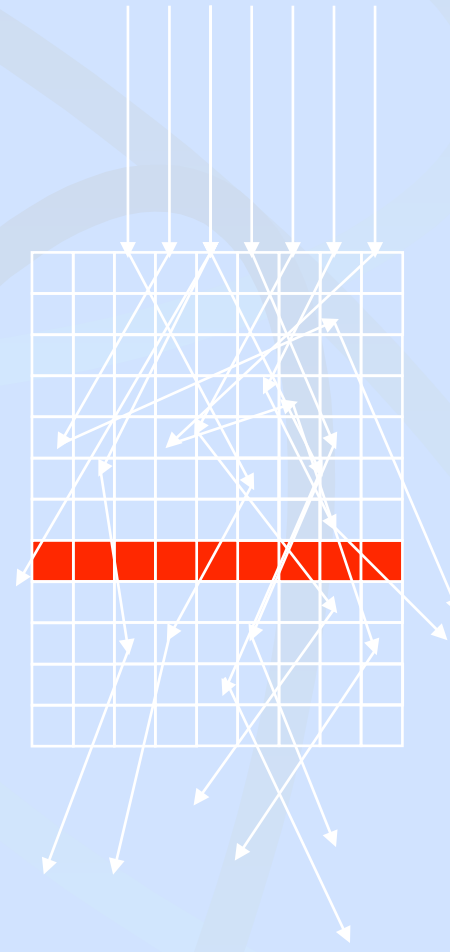
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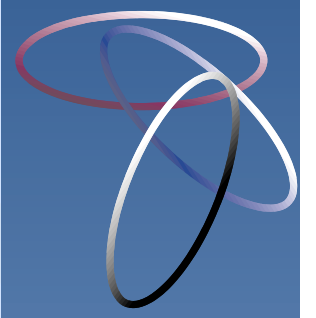
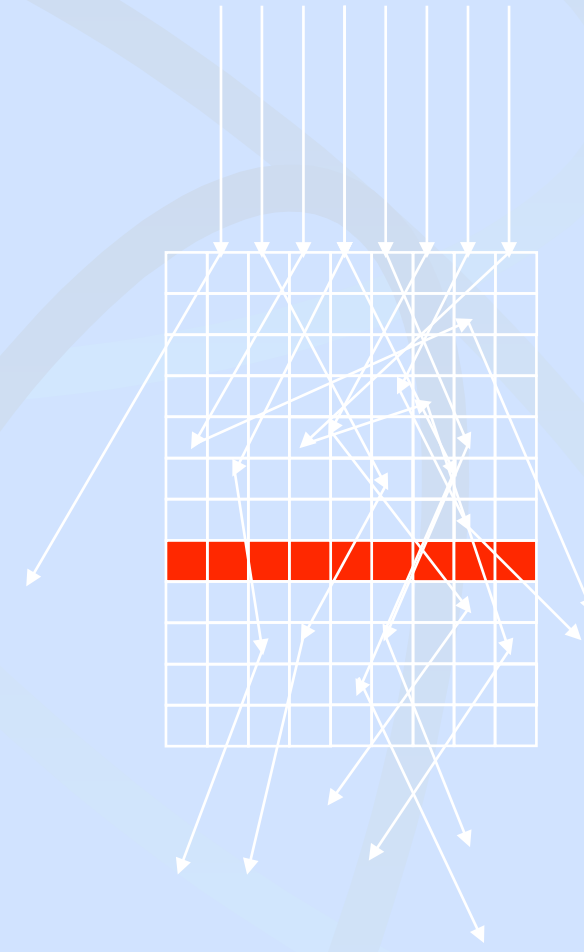
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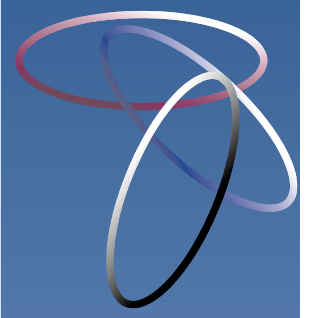
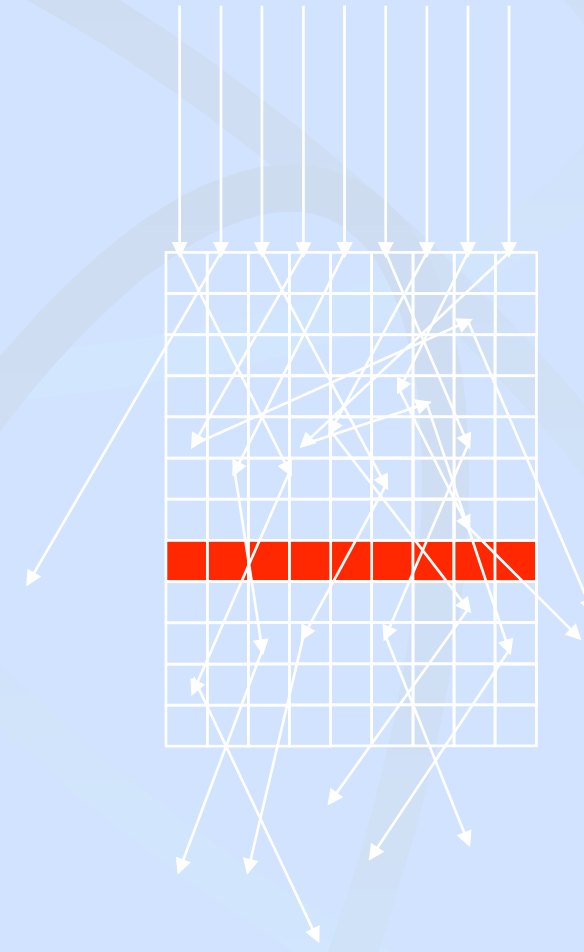
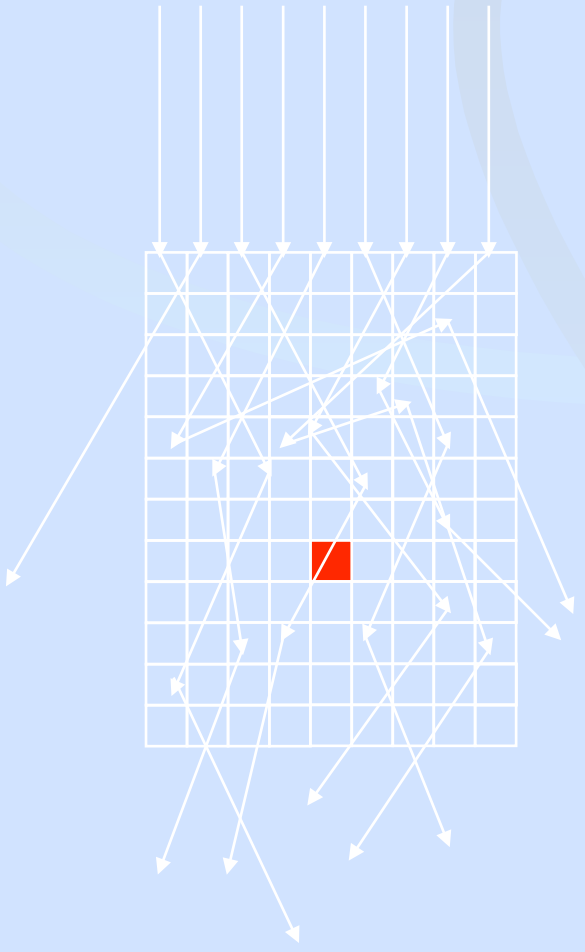
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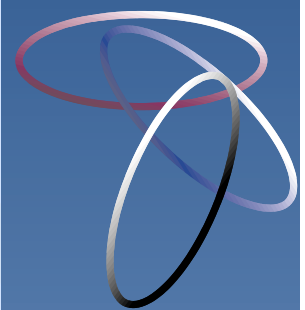
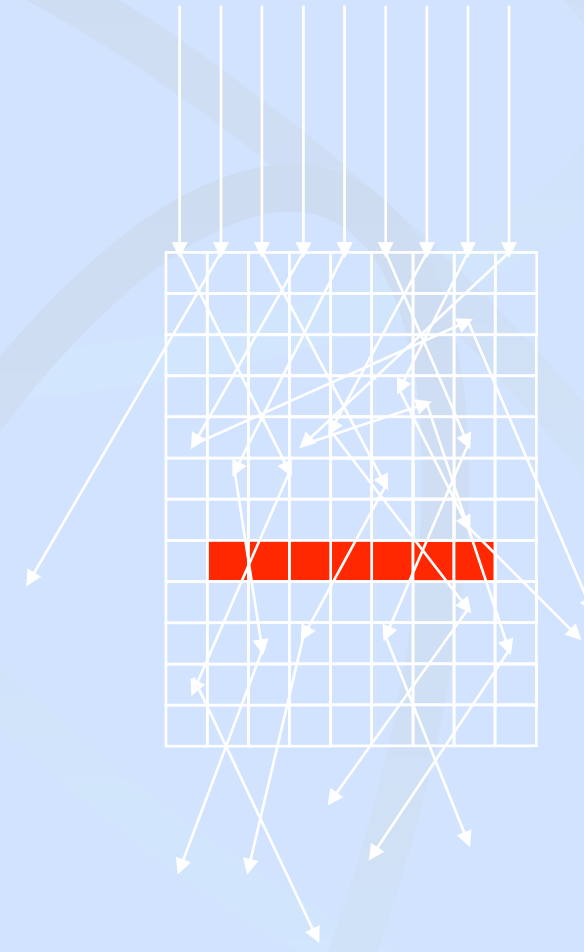
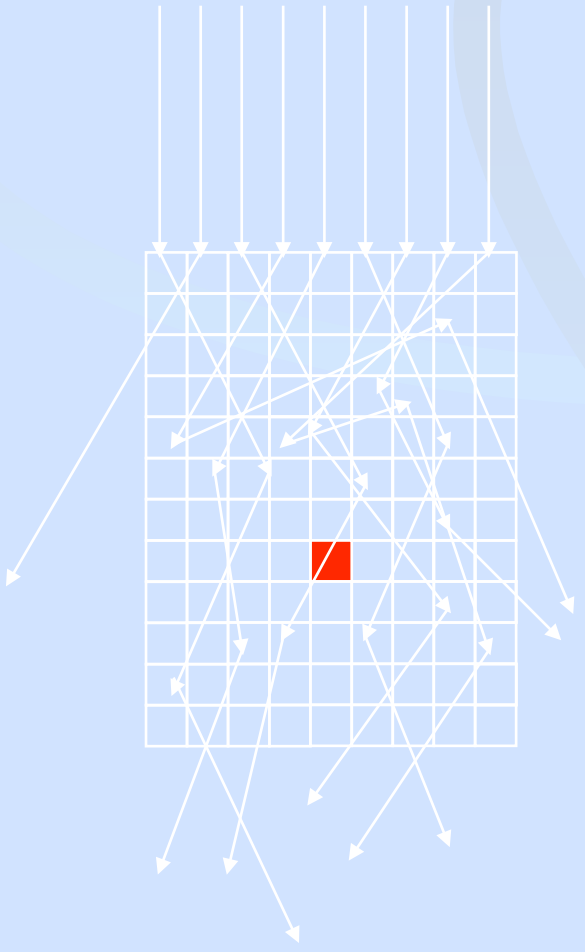
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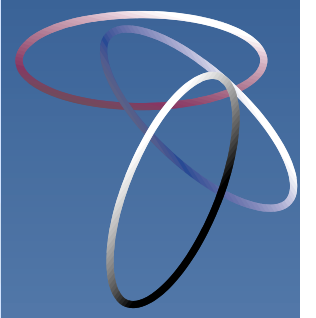
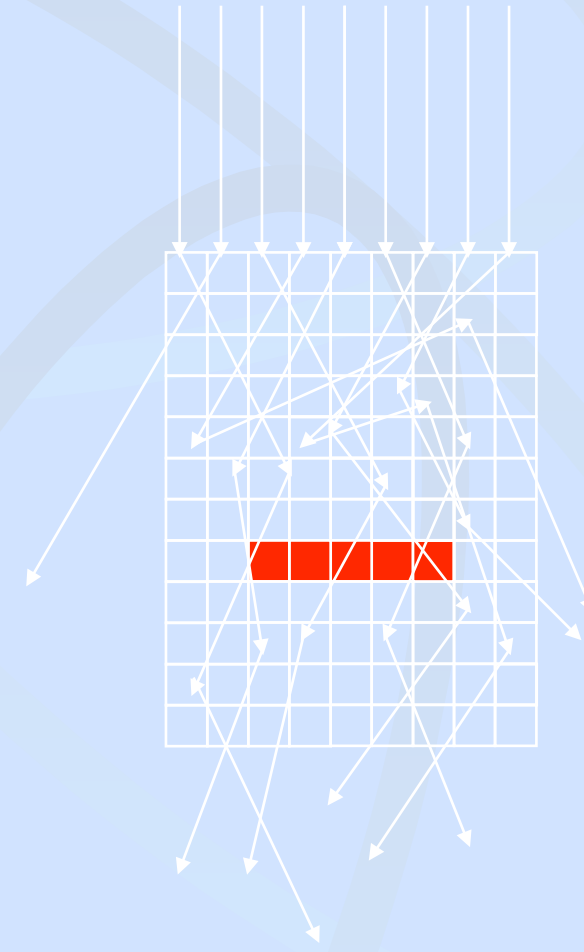
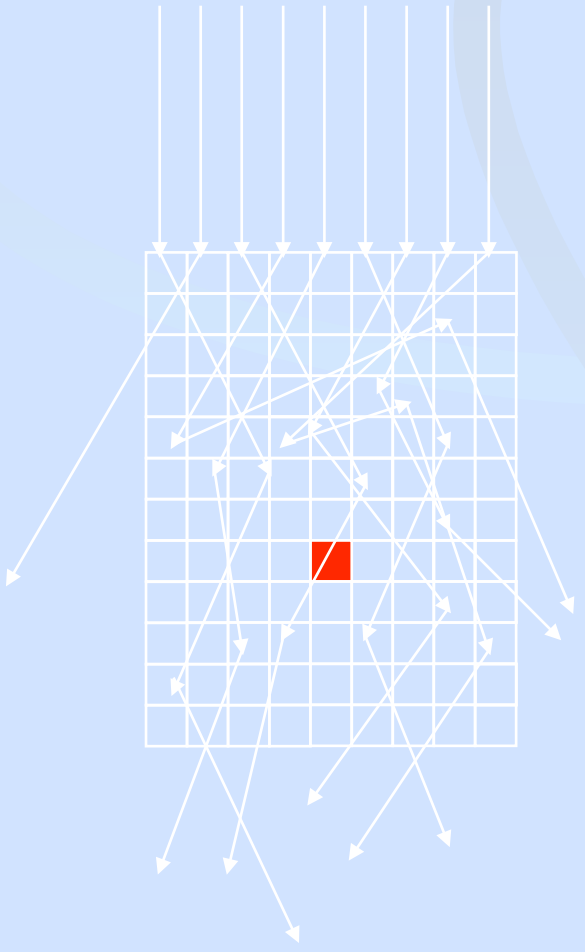
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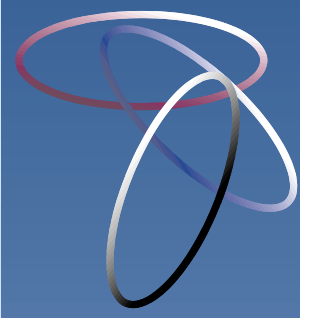
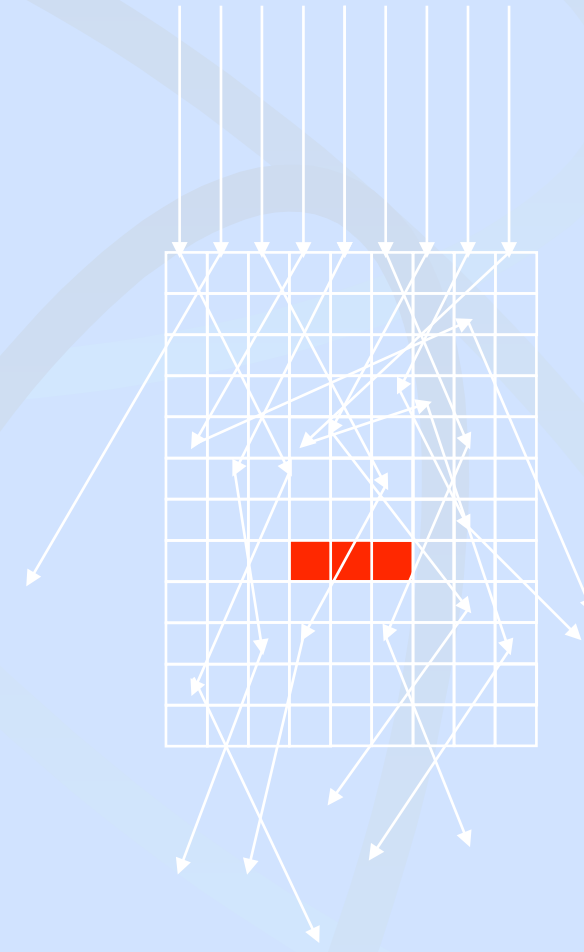
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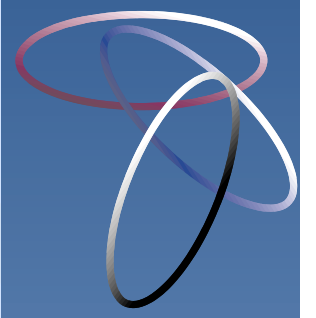
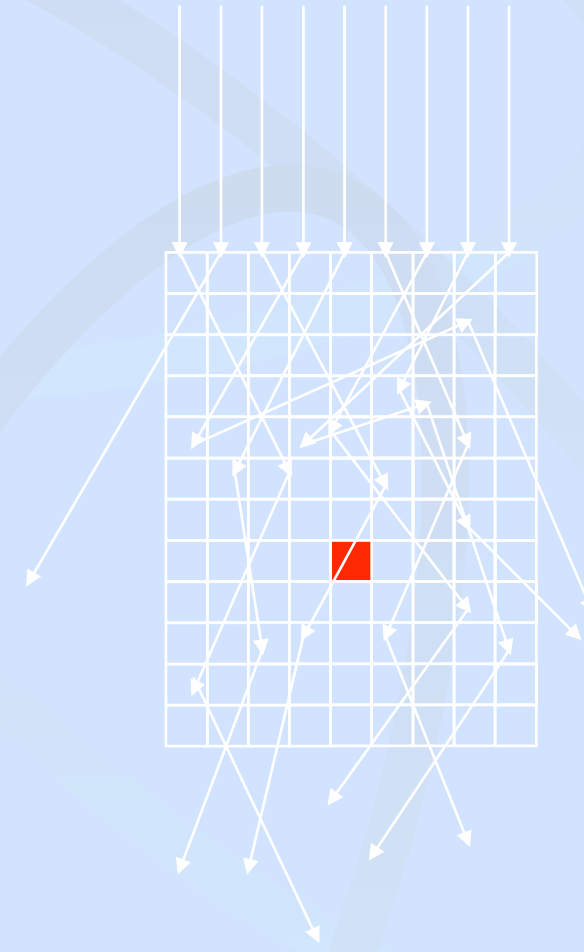
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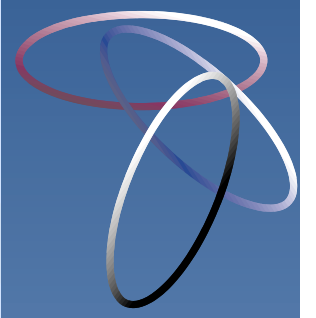
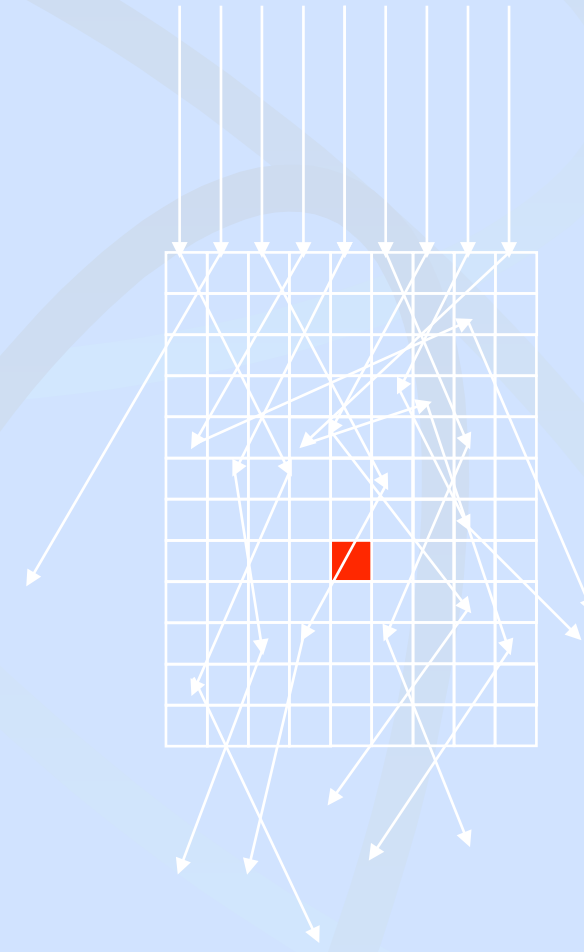
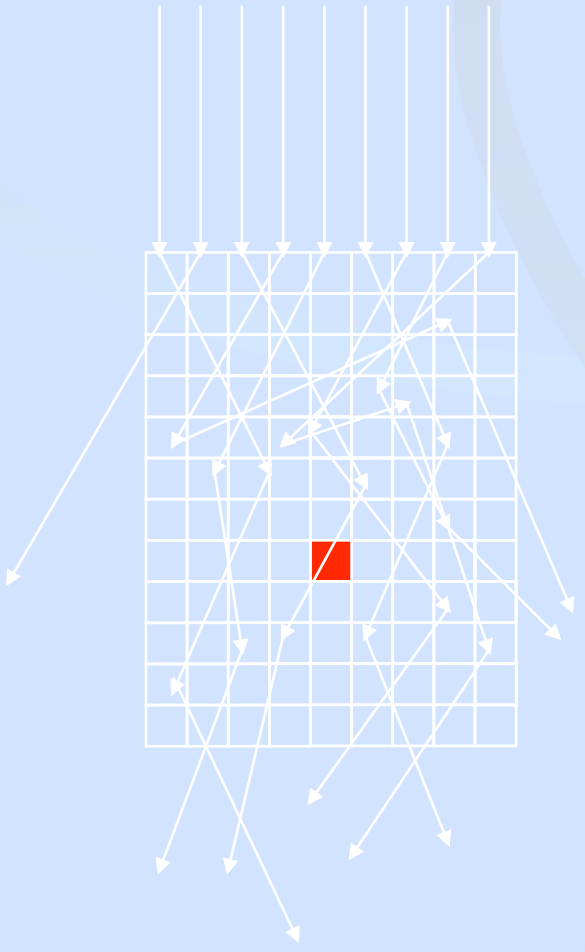
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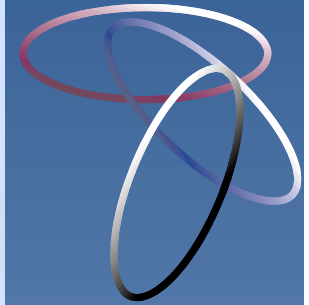
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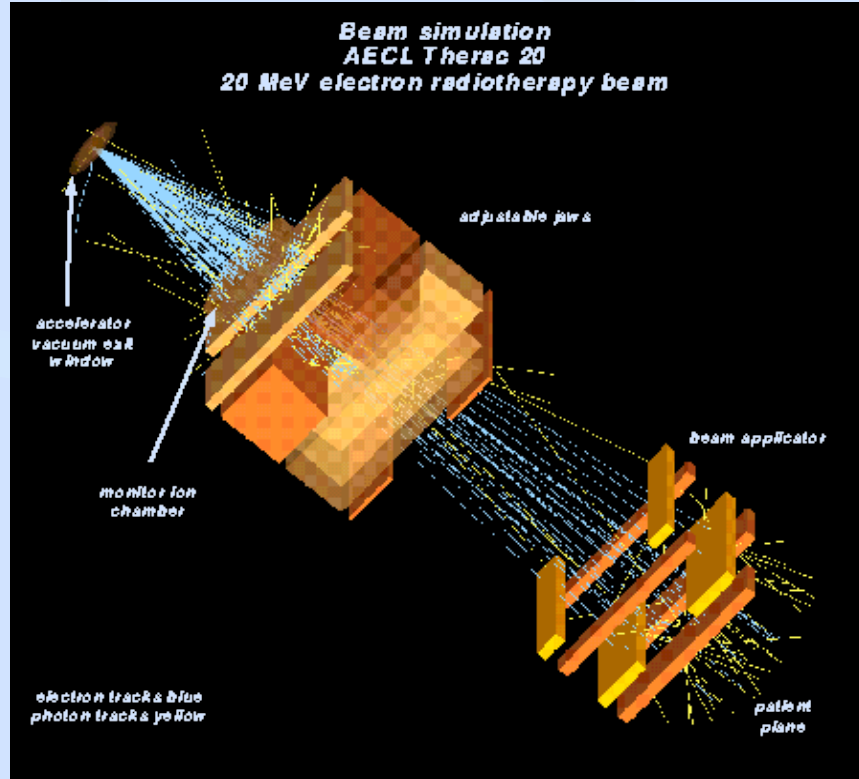


Welcome to the EGSnrc Distribution Site



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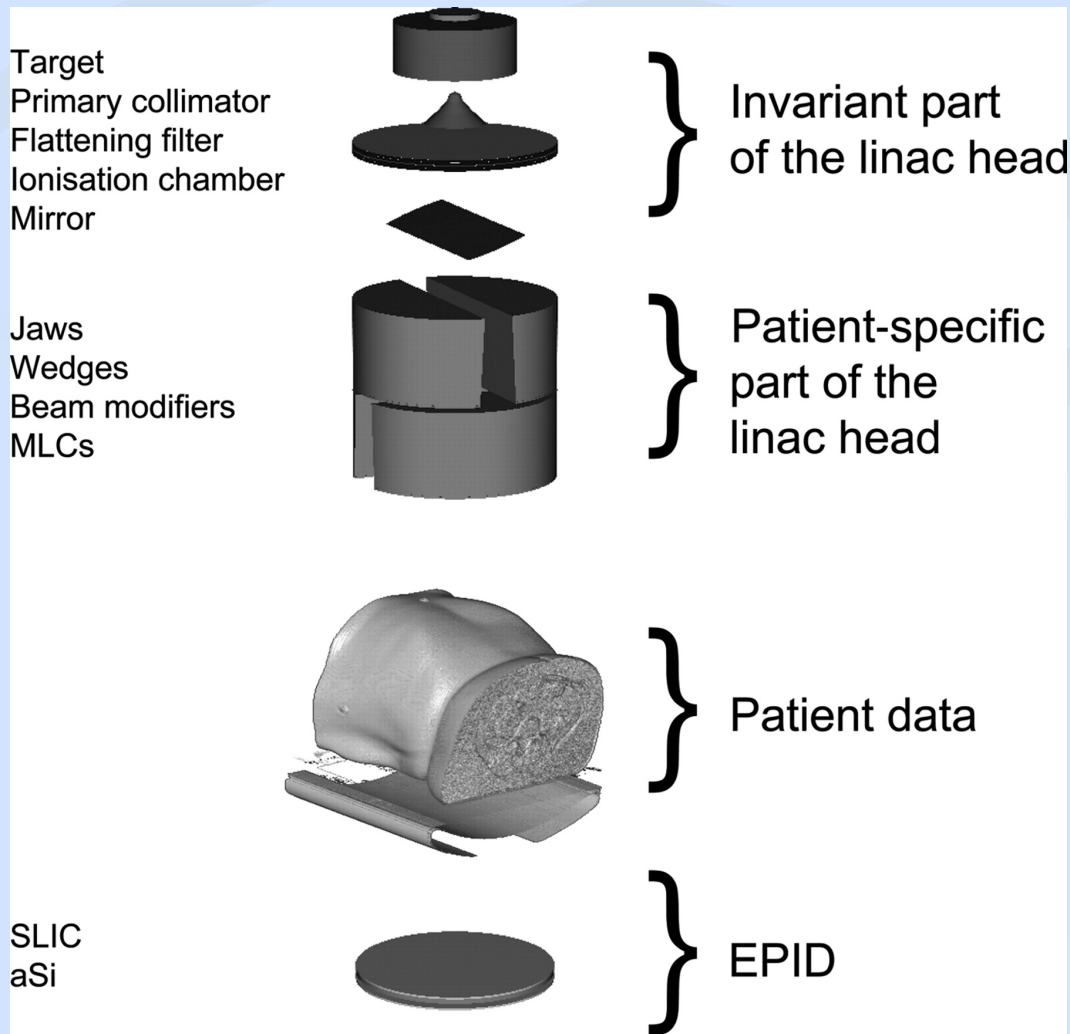
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Invariant and patient-specific parts of a radiotherapy linac



Radiation Protection Dosimetry

Spezi, E. et al. Radiat Prot Dosimetry 2008 131:123-129; doi:10.1093/rpd/ncn277

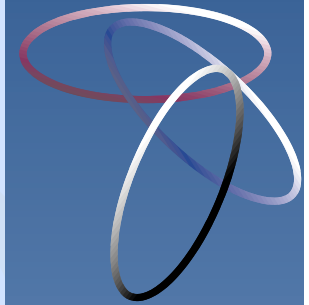


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Radiotherapy vs Nuclear Medicine

- ▶ Nuclear Medicine detects individual photons.
- ▶ Radiotherapy detects nano Coulombs of ionisation caused by 10^8 electrons/photons.
- ▶ The number of electrons passing through each square cm of the patient per second is of the same order of magnitude as the total number of annihilation photons per second emitted by the whole patient in a whole body FDG scan.
- ▶ What radiotherapy measures at one point, nuclear medicine measures for a whole patient over a longer time.
- ▶ 6 Gy/min versus 700 MBq
- ▶ Nuclear Medicine Radiation is isotropic, spectrum is from an isotope.
- ▶ Radiotherapy directional dependence is divergent geometry with complex perturbations. Spectrum is complex, derived more from simulations than measurements.



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Impact of Monte Carlo in Radiotherapy

- ▶ Scale: Microdosimetry (cell) to Bunker Shielding
- ▶ Scope: Universal, every radiotherapy determines dose using correction factors derived in part from Monte Carlo calculations.
- ▶ Speed: Weeks to minutes depending on the application. Universally too slow.



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EFFECT OF CT ELECTRON DENSITY IDENTIFICATION ON MONTE CARLO SIMULATIONS OF RADIOTHERAPEUTIC TREATMENTS

- ▶ T. Kairn, A.L. Fielding
- ▶ School of Physical and Chemical Sciences, Queensland University of Technology, Brisbane, Australia.
- ▶ EPSM ABEC 2008 Christchurch.

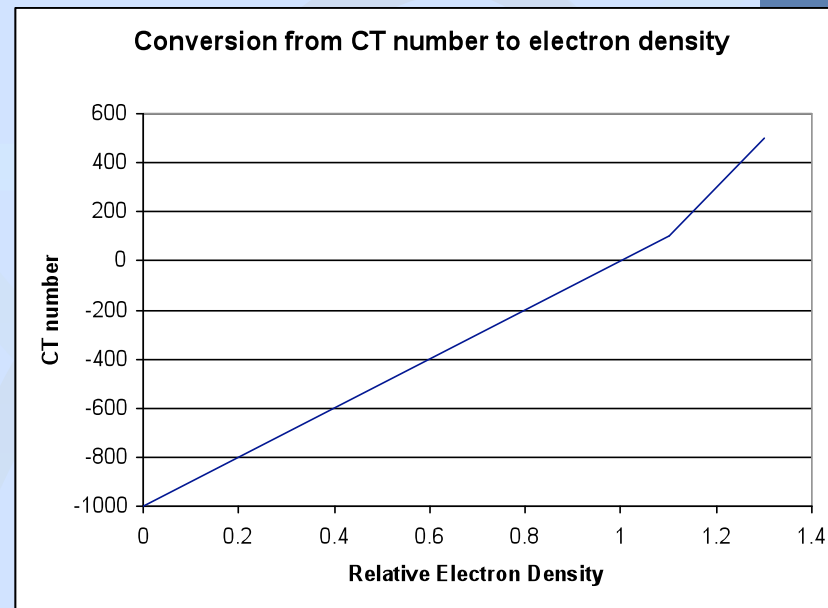


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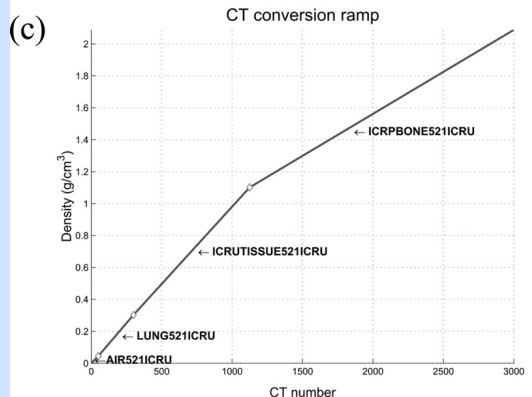
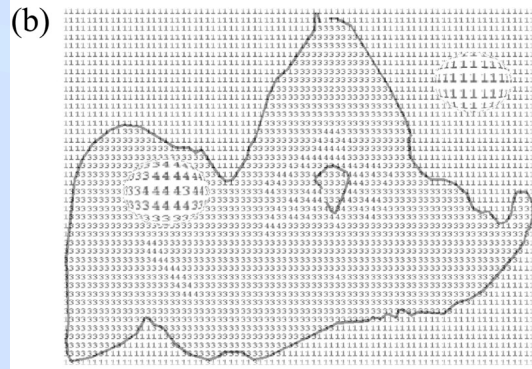
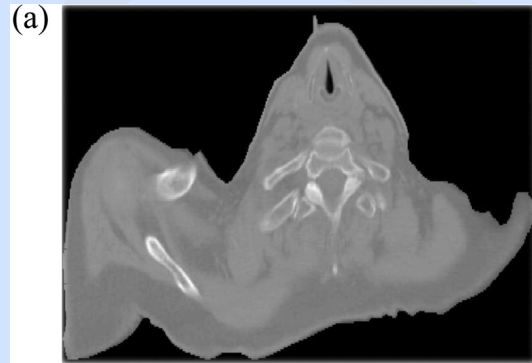
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CT ELECTRON DENSITY CORRECTION

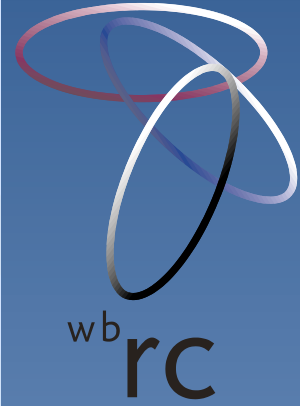
- ▶ CT create only allows a limited number of tissue types.
- ▶ Most are used to simulate an EPID,
- ▶ So not enough are available for the patient.
- ▶ Applications programming gone mad...
- ▶ ...or a work of deep relevance to radiotherapy treatment planning?



Patient modelling: conversion of Hounsfield numbers (a) into materials and densities (b) using a predefined CT conversion function (c)

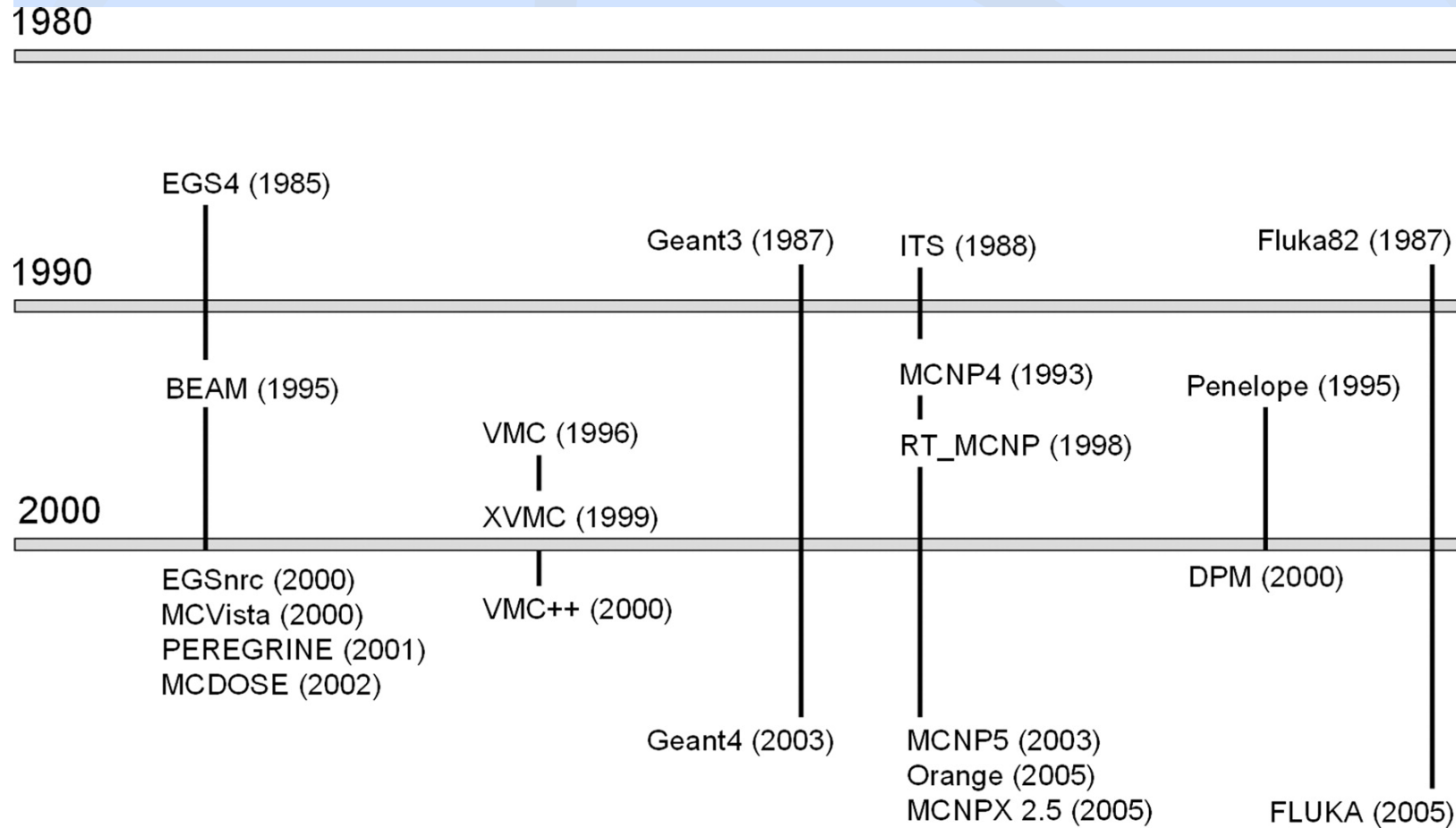


Radiation Protection Dosimetry



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Timeline of the release of major versions of MC codes used in medical radiation physics from the 1980s to the present



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Radiation Protection Dosimetry

Commercially Available Electron Monte Carlo Treatment Planning Systems

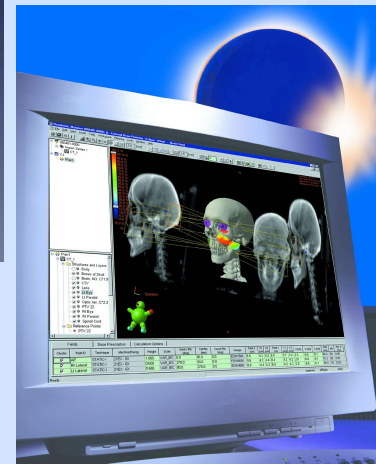
▶ NOMOS PEREGRINE



▶ ONCENTRA
MASTERPLAN VMC++



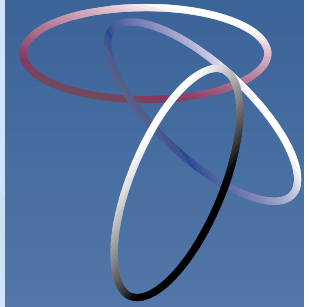
▶ ECLIPSE eMC (MMC)



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- ▶ 6 Gy/min versus 700 MBq



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VMC++ Nucletron Oncentra Masterplan 2001

- ▶ Avoid complexity: Voxel Monte Carlo. Model only down to the level of CT voxels, not individual particles. Initially not practical due to large amount of storage required for voxel transport lookup tables.
- ▶ Algorithm: Kawrakow I 2001 VMC++, electron and photon Monte Carlo calculations optimized for radiation treatment planning Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proc. Monte Carlo 2000 Meeting (Lisbon) pp229-36
- ▶ Verification: Cygler et. al. Evaluation of the first commercial Monte Carlo dose calculation engine for electron beam treatment planning Med. Phys. Volume 31, Issue 1, pp. 142-153 (January 2004)
- ▶ 50 to 100 times faster than EGSnrc, agrees with EGSnrc to within 1%
- ▶ Known deficiency: EGSnrc expected to underestimate electron backscatter from high atomic number materials.



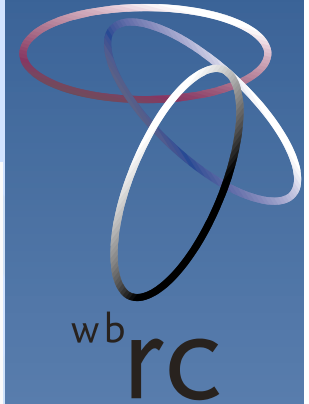
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PEREGRINE



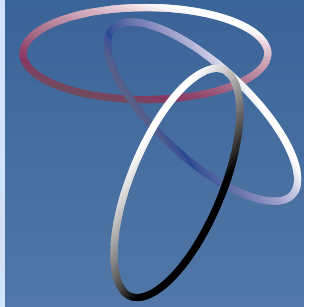
- ▶ PEREGRINE is a software/hardware system that implements the Monte Carlo method for the specific purpose of simulating medical radiation delivery <http://cnwm.berkeley.edu/courses/classes/NE39/Vujic-cancer.ppt#8>



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PEREGRINE

- ▶ Adaptive variance reduction techniques to reduce calculation time.
- ▶ Commercialised by NOMOS
- ▶ Hartmann Siantar C L et. Al. 2001
Description and dosimetric verification of the PEREGRINE Monte Carlo dose calculation system for photon beams incident on a water phantom Med. Phys. 28 1322-37



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Eclipse eMC 2004

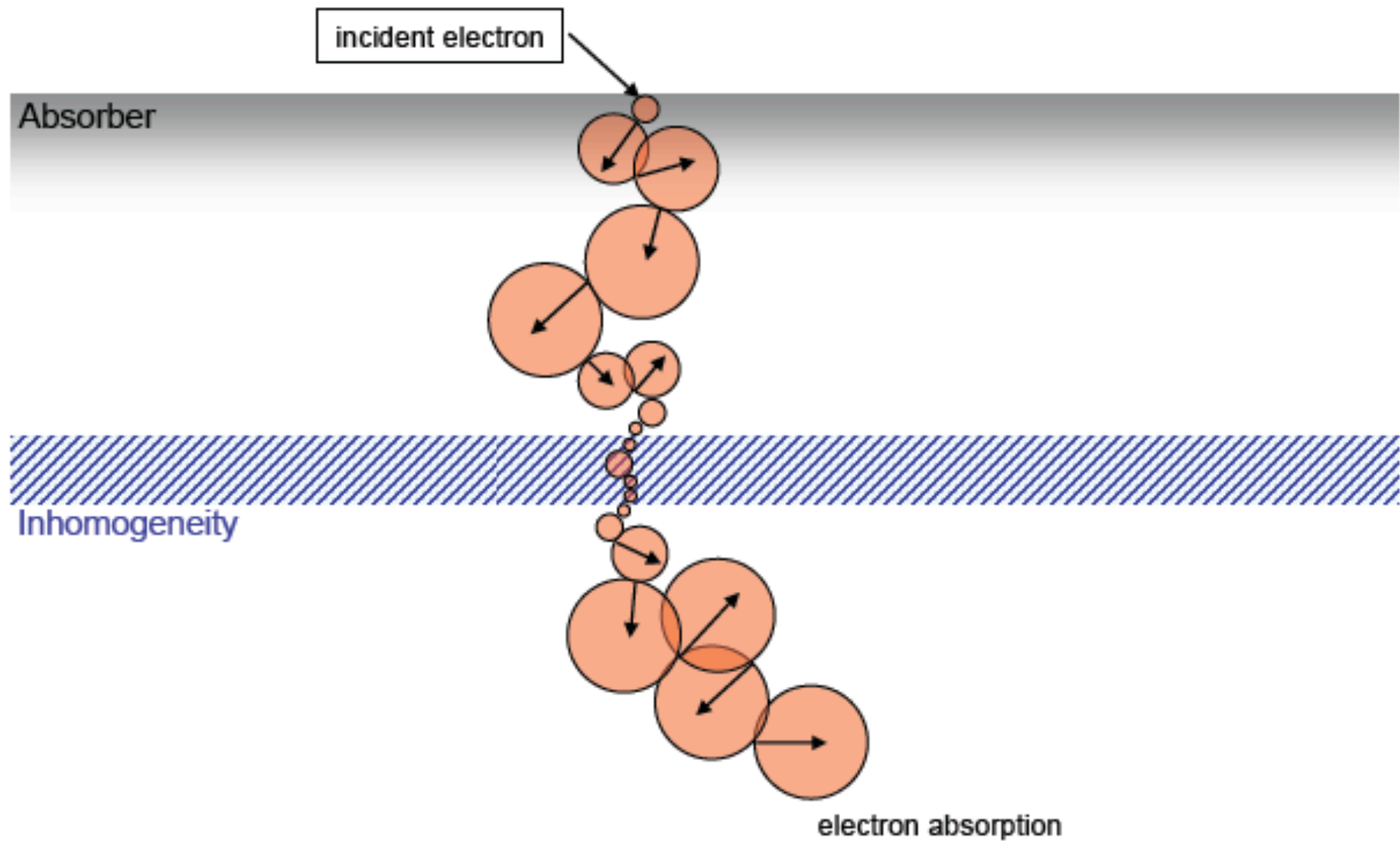
- ▶ Algorithm: Macro Monte Carlo
- ▶ Neuenschwander, H., Mackie, T.R. Reckwerdt, P.J., 1995, Phys. Med. Biol., 40:543-574
- ▶ Verification
- ▶ Popple et. al. Med Phys. 33(6):1540-1551
- ▶ Ding et. al. Phys. Med. Biol. 51:2781-2799
- ▶ Pемler et. al. 2006 Z. Med. Phys., 16:313-329
- ▶ See also Claridge Mackonnis poster 24 and Fogg poster 28 from ABEC 2008.



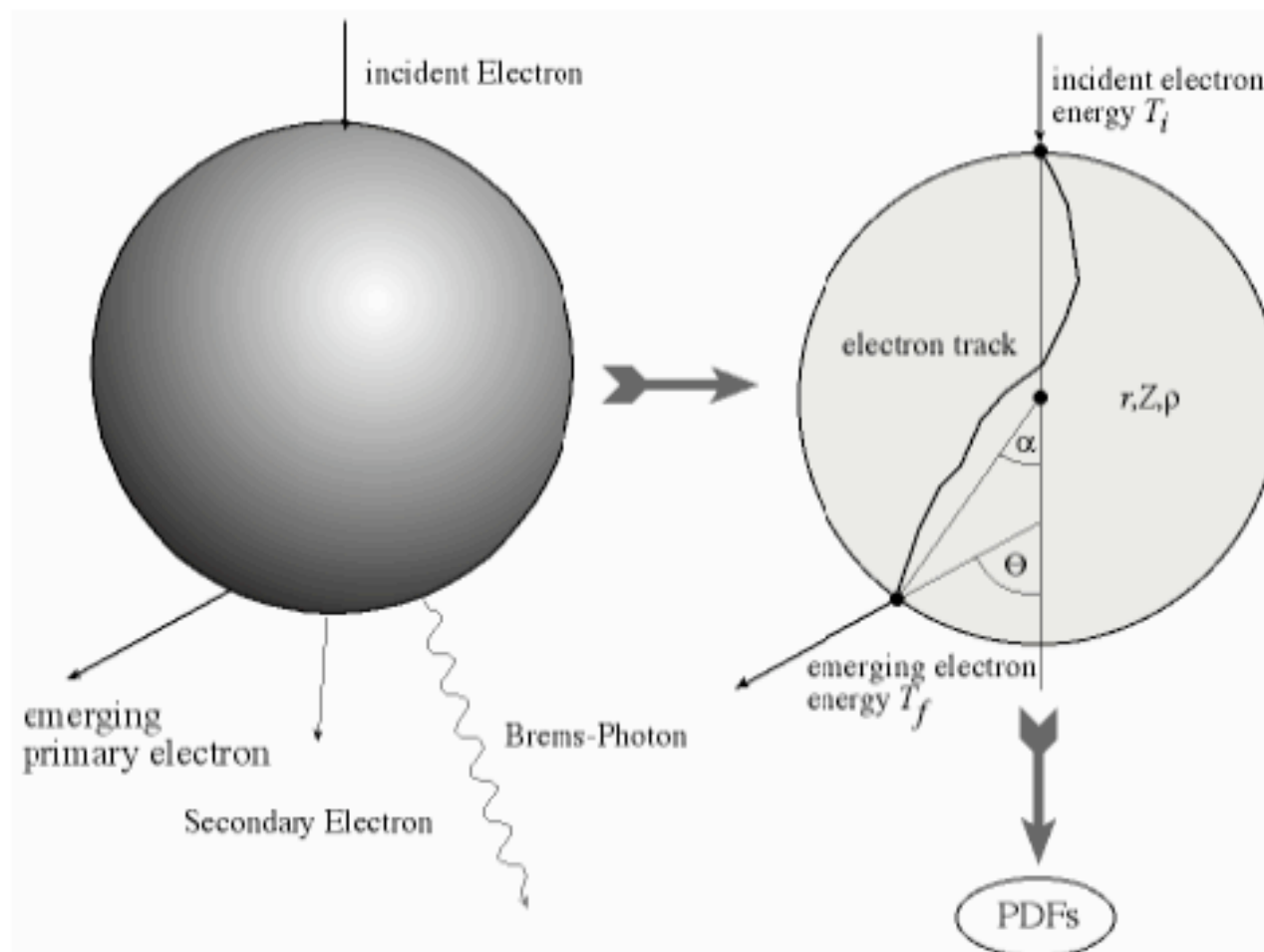
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Electron Transport



Primary Particle Transport Probability Distribution Function (PDF)



Local Geometry Calculations

- Local geometries are spheres of various sizes, material compositions and incident electron energies:
 - 5 materials: air, lung, water, lucite and solid bone
 - 5 sphere radii: 0.5, 1.0, 1.5, 2.0 and 3.0 mm
 - 30 incident energy values, between 0.2 and 25 MeV
- 200 000 electrons per sphere were simulated using Monte Carlo with EGSnrc Code System
- Results from simulations were collected to probability distribution functions (PDFs):
 - Exit point and direction of primary electron
 - Energy of primary electron
 - Secondary particles (e^- & γ) and their energies

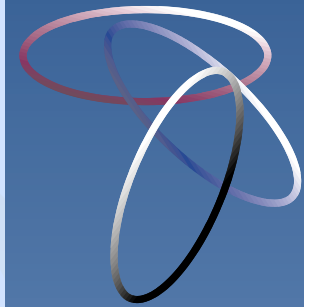


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EFFECT OF CT ELECTRON DENSITY IDENTIFICATION ON MONTE CARLO SIMULATIONS OF RADIOTHERAPEUTIC TREATMENTS

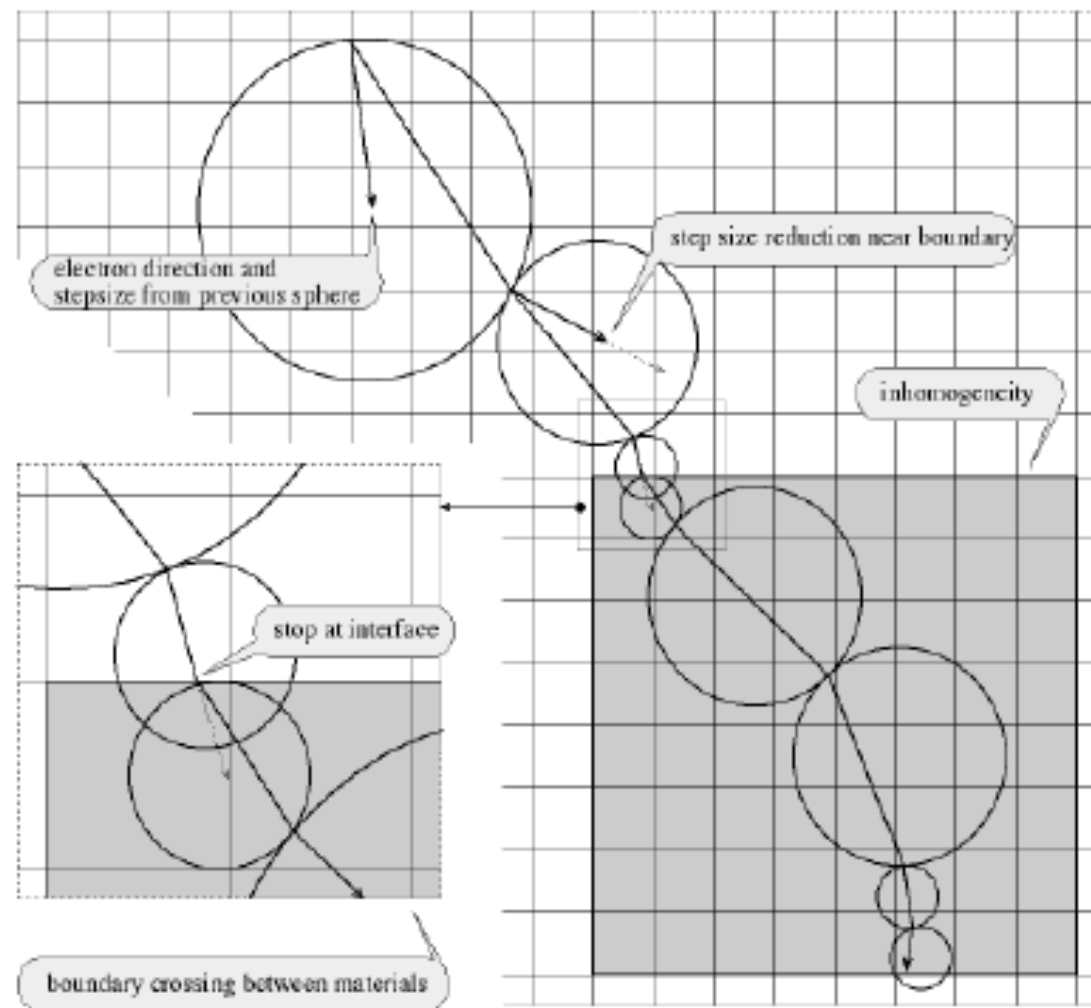
- ▶ T. Kairn, A.L. Fielding
- ▶ School of Physical and Chemical Sciences, Queensland University of Technology, Brisbane, Australia.
- ▶ EPSM ABEC 2008 Christchurch. What an important study!
- ▶ eMC five materials air, lung, water, lucite, and solid bone.



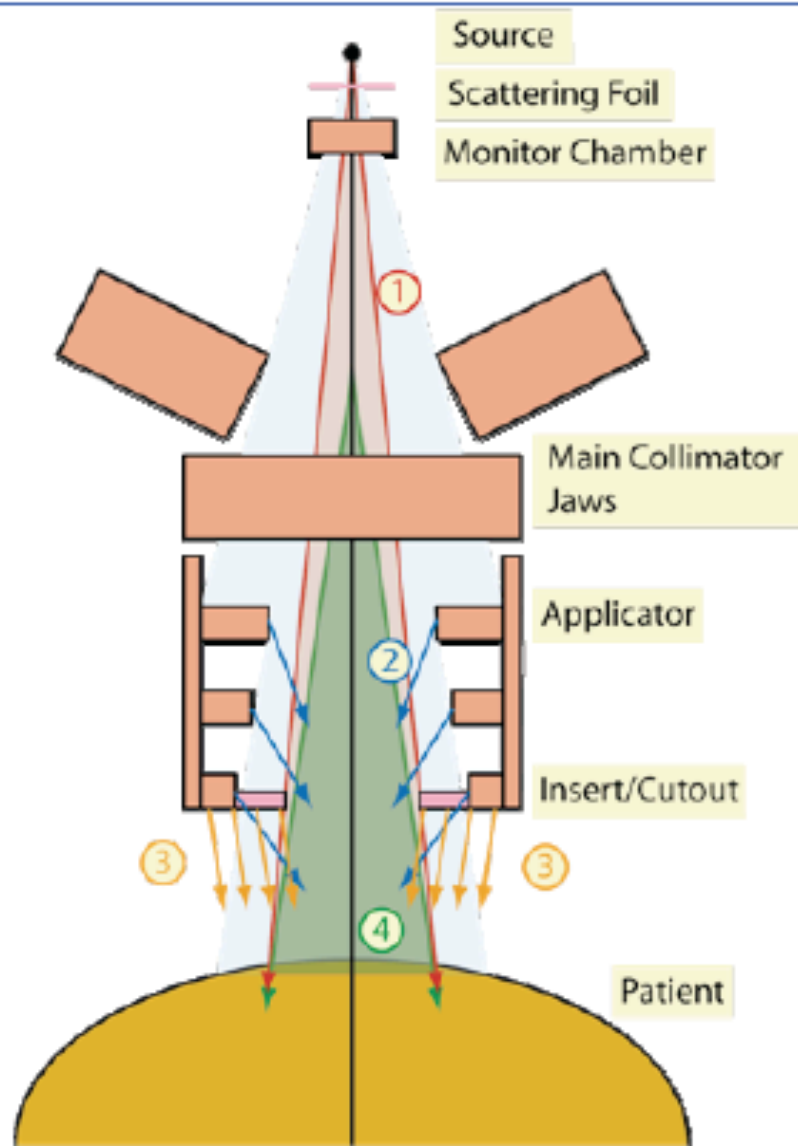
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Primary Particle Transport

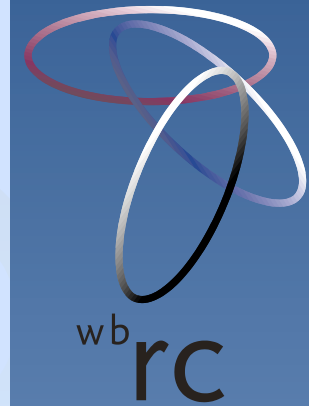


Initial Phase Space (IPS)



Four particle sub-sources:

1. electrons and photons from the main source
2. electrons scattered from the edges of an applicator, cutout or shield
3. photons going through or generated in an applicator, cutout or shield
4. virtual source for electrons and photons



Measurement Requirements

- For each electron energy, without an applicator, collimator jaws wide open (40x40):
 - Depth dose curve in water at SPD=100cm
 - Absolute dose in water [cGy/MU] at a specified depth
 - Profile in air at 95cm
- For each electron energy and applicator:
 - Depth dose curve in water at SPD=100cm
 - Absolute dose in water [cGy/MU] at a specified depth

Normalization and MUs

- Dose is normalized to 100% at D_{\max}
- MUs are calculated based on number of particle histories, D_{\max} and configuration factor

But where and what is D_{\max} ?

Absolute D_{\max} is always an overestimate, because of the noise in the dose distribution.

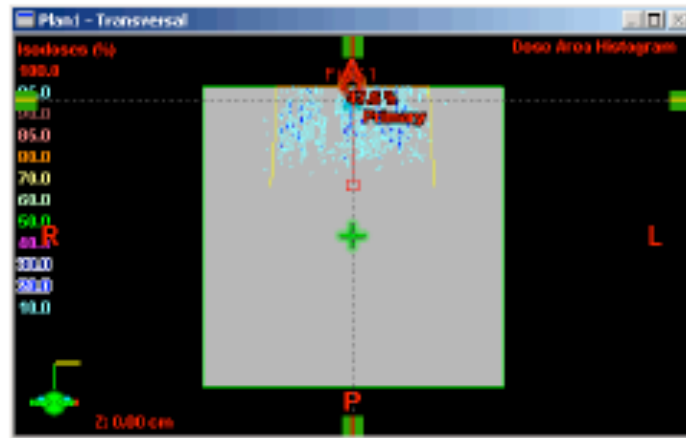
Therefore, a “ D_{\max} ” is used that is more descriptive by using a smoothed dose distribution.



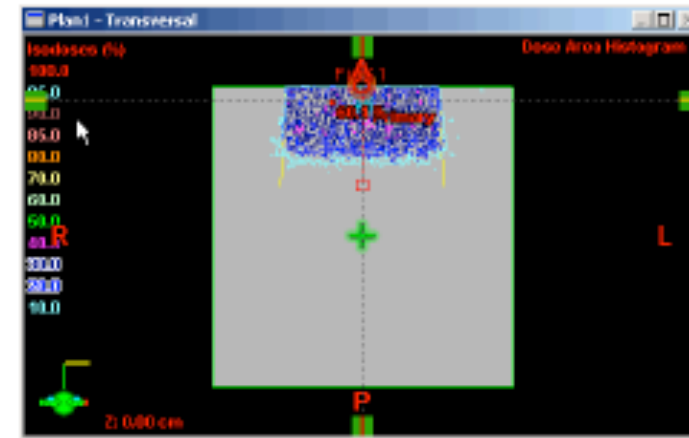
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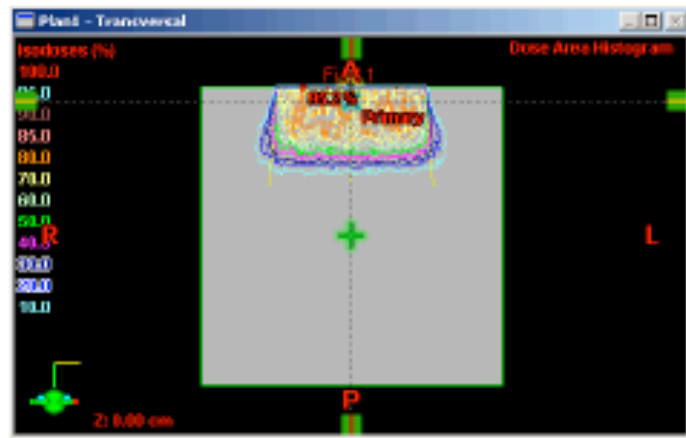
Dose Calculation Accuracy



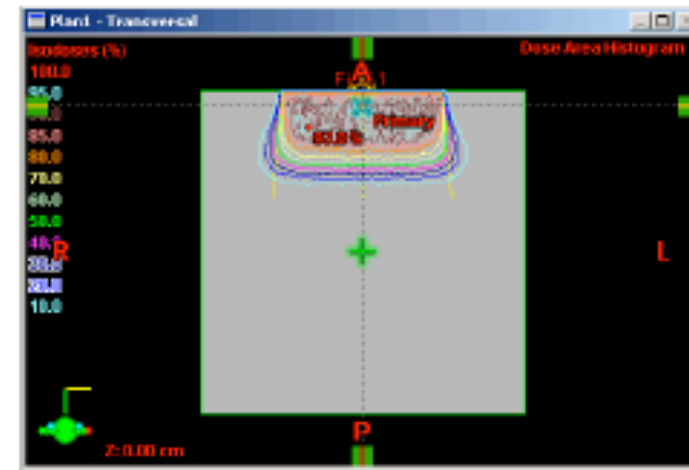
10'000 particles



100'000 particles

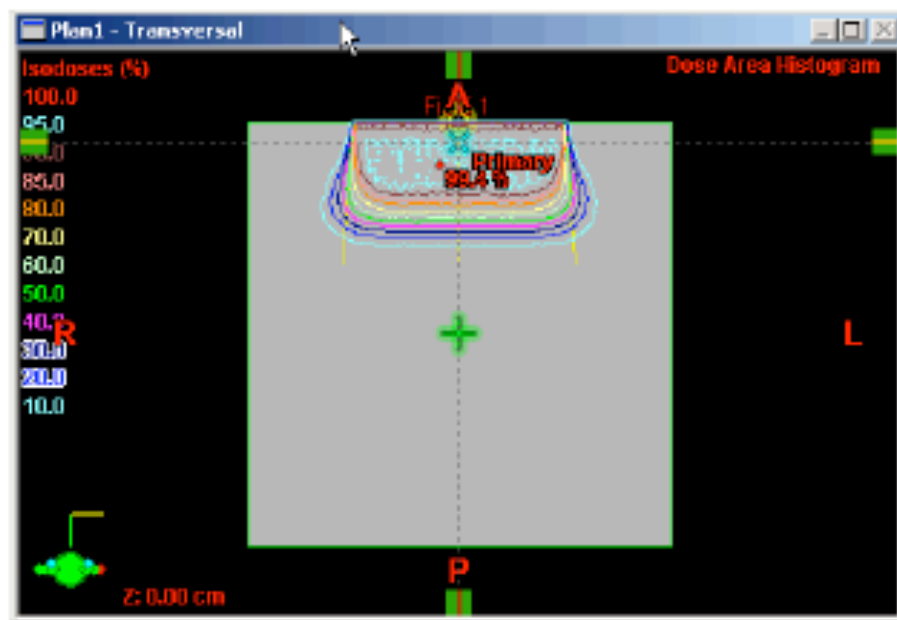


1'000'000 particles



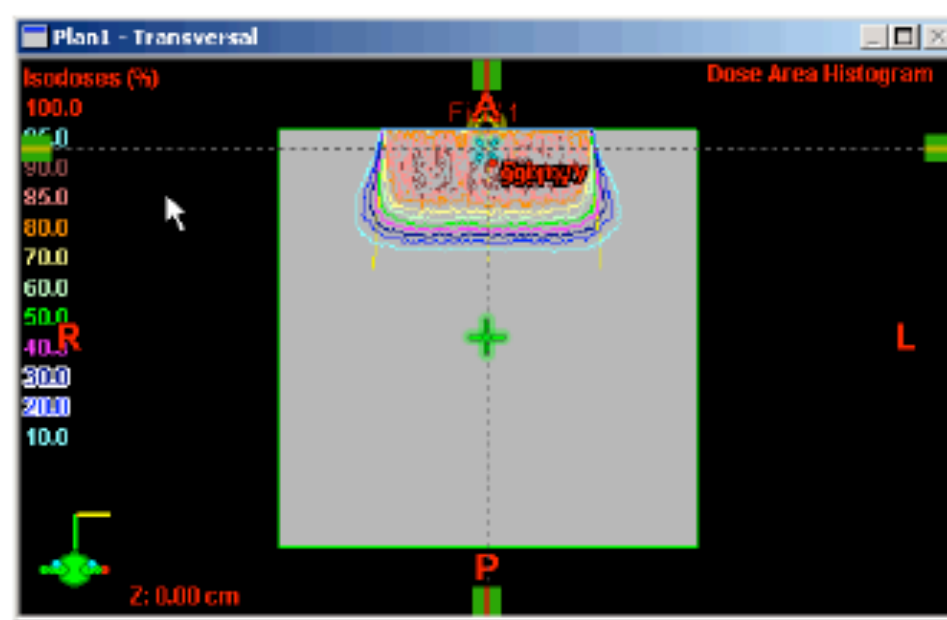
4'800'000 particles

Smoothing



No smoothing

- 1% Accuracy
- 52 Mio particles
- 1.5 hours (5503 seconds)

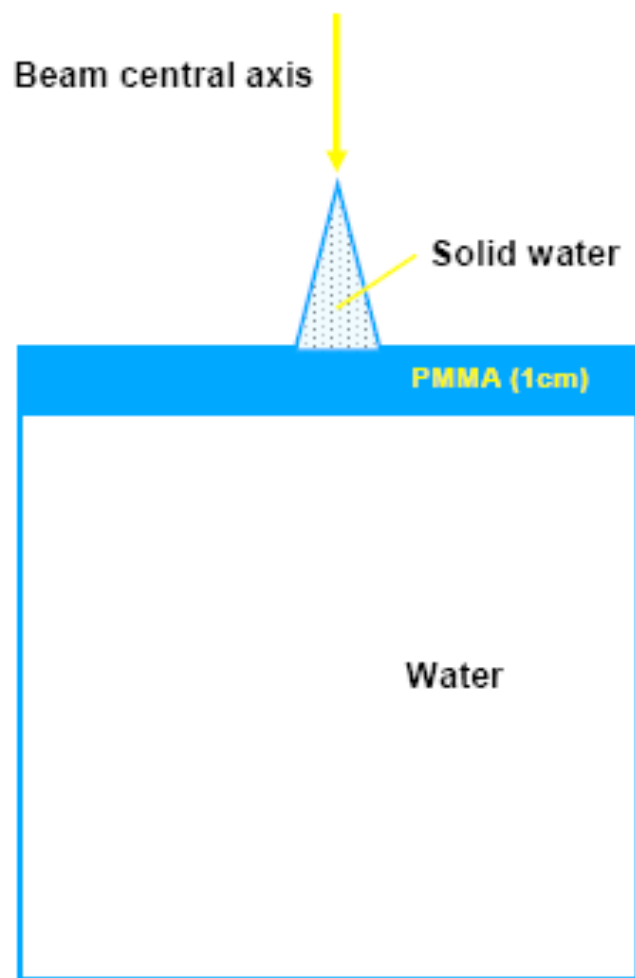


Smoothing

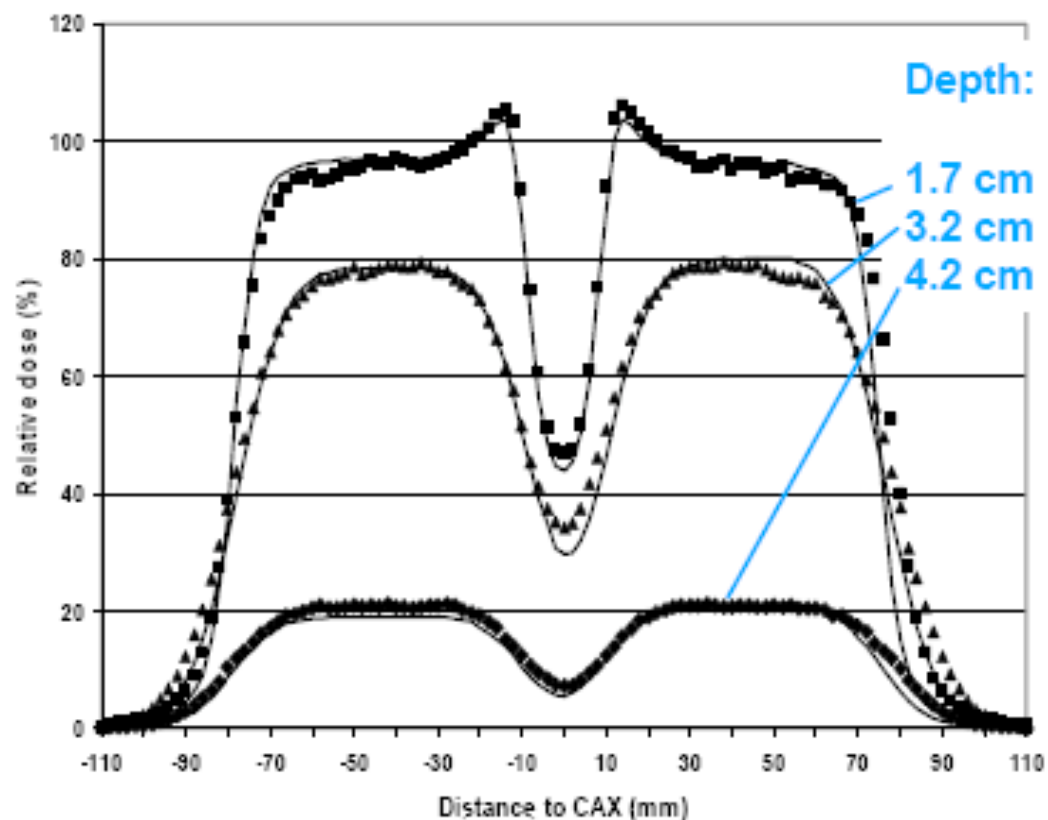
- 3% Accuracy
- 4.8 Mio particles
- 7 minutes (416 seconds)

Clinical validation

“Nose“ Phantom, Clinac 2300C/D, 9 MeV, 15cm x 15cm dose profiles



Measurements (lines) vs. Calculation (dots, statistical uncertainty 1.5%)



Clinical Experience

- ▶ Depth dose match good for 12 MeV, 15 MeV, 18 MeV
- ▶ Depth dose match not as good for 9 MeV
- ▶ Depth dose match worst for 6 MeV
- ▶ For the 6MeV beam, the 90% isodoses match pretty well, 80% not too bad, then gradually drifts off so (for example) the 40% measured isodose overlays the 50% Eclipse isodose, 10% measured overlays approx 22% Eclipse. Obviously, as the curve is so steep for 6MeV, the differences in isodose position are only 2-4mm but it makes a big difference to dose.
- ▶ Consequence of discrete energy binning.

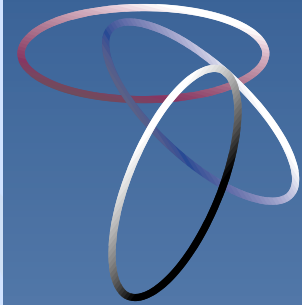


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Cultural Shift

- ▶ We had used PLATO, and used un-normalised dose distributions.
- ▶ With eMC, without normalisation, discrepancies of 10-15% were observed.
- ▶ By choosing an arbitrary normalisation point at approximately d_{max} on central axis, we reduce this discrepancy to less than 5%.
- ▶ Our action level for investigation is 5%.
- ▶ Ungureanu (Fogg) warns to keep reference point out of bone, and that eMC does not accurately model the effect of the electron applicator and insert at 3% level.



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Accessory factor problem, no one answer

Large Base Board Combination 0.970

Component1 Base Board 0.993

Component 2 neck shape 0.995

Component 3 Couch top 0.985

Product 0.973

The 0.3% difference is not significant, but
the supervisor cannot check the answer numerically.

Planning requested a single correct procedure.



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Clinical Example

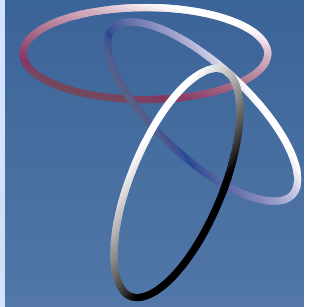
- ▶ Backscatter from lead under lip at Traralgon
- ▶ Measurement is difficult.
- ▶ Eclipse eMC available at Traralgon.
- ▶ Wax thickness selected from spreadsheet based on slab geometry and measurement.
- ▶ Eclipse eMC significantly underestimated lead backscatter to the extent that the clinical decision would have been different.



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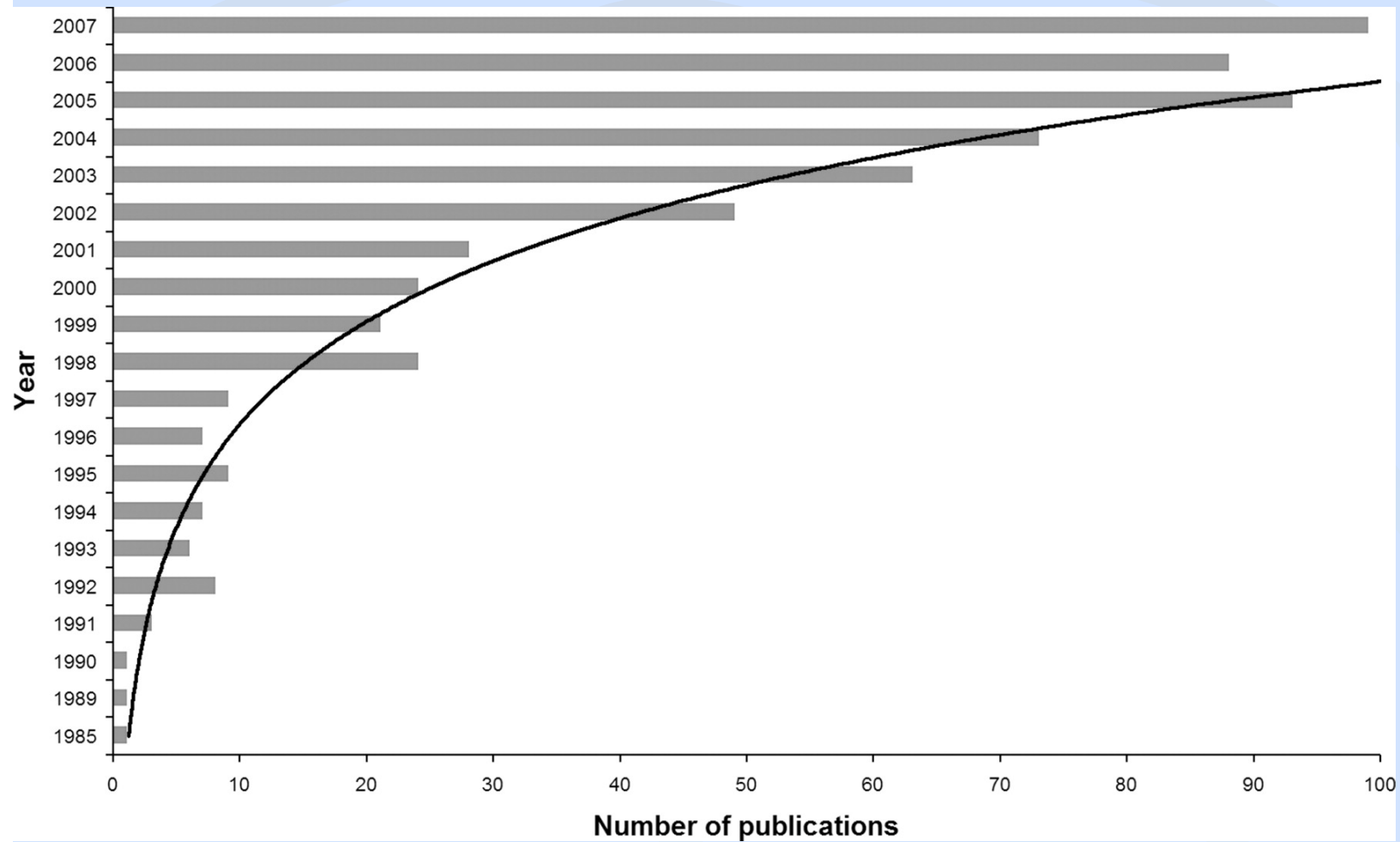
What does the future hold?



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Number of publications on MCTP between 1985 and 2007 (source: ISI Web of knowledge)



Radiation Protection Dosimetry

Spezi, E. et al. Radiat Prot Dosimetry 2008 131:123-129; doi:10.1093/rpd/ncn277



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What does the future hold?

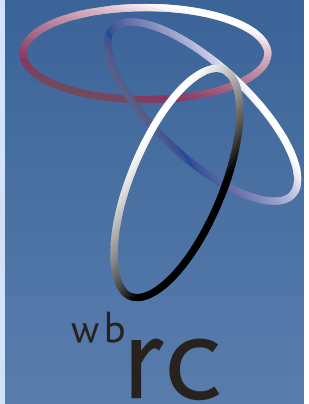
- ▶ It is only a matter of time before all radiotherapy treatment planning calculations are Monte Carlo based: Yes, Monte Carlo calculations have always been a matter of time! If a planner began an Eclipse eMC treatment plan when this talk began they will finish it after this talk is completed.
- ▶ All radiotherapy treatment planning systems will in the future be marketed as Monte Carlo based. Radiation Oncology Medical Physicists will have to understand the strengths and weaknesses of these systems. There is a real opportunity for the widespread use of analogue Monte Carlo interfaced to commercial treatment planning systems via Dicom in this area.
- ▶ There will be renewed interest in the conversion from Hounsfield Number to relative electron density.



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The End



- ▶ Thankyou for your attention.
- ▶ General References
 - ▶ Spezi, E. et al. Radiat Prot Dosimetry 2008 131:123-129
 - ▶ Ma. Effect of statistical uncertainties on Monte Carlo treatment planning Phys Med Biol 50 (2005) 891-907
 - ▶ Rogers, D.W.O., Fifty years of Monte Carlo simulations for medical physics Phys. Med. Biol. 51 (2006) R287-R301



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