

Variance Reduction for Multi-physics Analysis of Moving Systems

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Preliminary Exam

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Introduction

Shutdown Dose Rate (SDR) Analysis



- Fusion Energy Systems (FES)
 - Burning plasma, D-T fusion
 - ${}^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0\text{n}$
- Neutrons penetrate deeply into system components, causing activation
- Radioisotopes persist long after shutdown
- Important to quantify the dose caused by decay photons

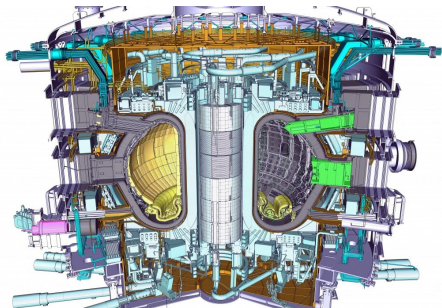


Figure : Cutaway view of ITER drawing.

- Example: maintenance procedure
 - Need to move component(s) around facility
 - Interested in SDR at a particular location
 - SDR will change as a function of the activated component's position over time



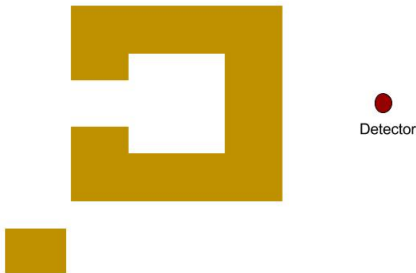
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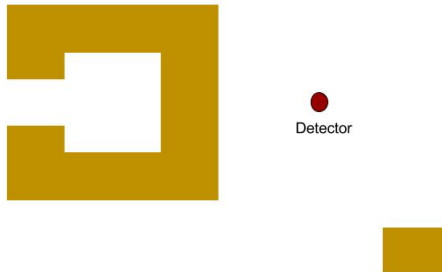
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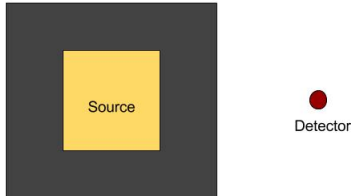
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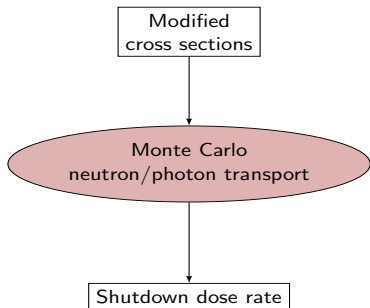


Optimize the **radiation transport** simulation used to calculate the **shutdown dose rate** at a particular location as activated components are **moving** around the facility.



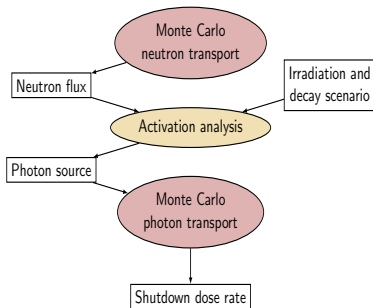
Deterministic vs. MC

- Direct 1-Step Method (D1S)



Add pros/cons of D1S, R2S

- Rigorous 2-Step Method (R2S)



- Monte Carlo (MC) analysis of fusion energy systems is:
 - Accurate for large, complex models
 - Challenging due to the highly attenuating structural materials
 - Results scored in regions that have low particle flux, have higher statistical uncertainty
- To decrease statistical uncertainty:
 - Increase number of histories
 - Use variance reduction (VR) techniques

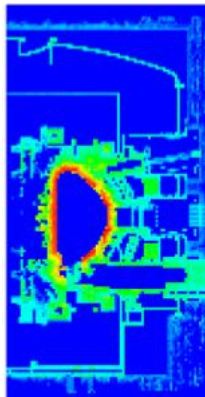


Figure : Photon flux in ITER tokamak building.





- Techniques to modify particle behavior
 - **Goal:** preferentially sample events that will contribute to results of interest
- Statistical weight of particles is adjusted to keep playing a fair game

Consistent Adjoint Driven Importance Sampling (CADIS)

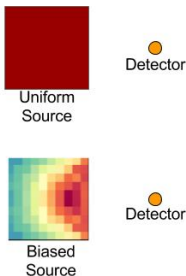
- Adjoint flux can define the importance of regions of phase space to the detector response
- Use **deterministic** estimate of the adjoint flux, Ψ^+ , to generate **Monte Carlo** VR parameters in a **consistent** manner
 - Define detector response function to be the adjoint source

$$H^+ \Psi^+ = q^+ \quad (1)$$

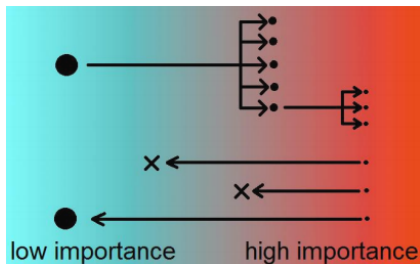
$$H^+ = -\hat{\Omega} \cdot \nabla + \sigma_t(\vec{r}, E) - \int_0^\infty dE' \int_{4\pi} d\Omega' \sigma_s(\vec{r}, E \rightarrow E', \hat{\Omega} \rightarrow \hat{\Omega}') \quad (2)$$

- Use the adjoint flux to generate MC source and transport biasing parameters

Source: sample from biased PDF



Transport: weight windows





VR for **photon** transport

- **Straightforward**
- Can use CADIS method to direct photons towards detector
 - Flux-to-dose-rate conversion factors define adjoint source

VR for **neutron** transport

- More **complicated**
- Biasing function needs to capture
 - ① Potential of regions to become activated
 - ② Potential to produce photons that will contribute to the SDR
- Can use CADIS if we can construct adjoint source that will fulfill these criteria



Multi-Step (MS)-CADIS

- VR method to optimize the initial radiation transport step of a coupled, multi-step process
 - Relies upon function that represents importance of particles to final response of interest
- When applied to SDR analysis, MS-CADIS will optimize the neutron transport
 - Use function that represents the importance of the neutrons to the final dose rate

- **Groupwise Transmutation (GT)-CADIS**
 - Implementation of MS-CADIS specifically for SDR analysis
 - Provides method to calculate optimal adjoint neutron source, q_n^+ , by first calculating, T , a term that relates the neutron flux to photon source
 - Calculate T : (move this to later slide)
 - ① Irradiate each material with neutrons from a single energy group, g
 - ② Record resulting photon emission in each energy group, h

$$T_{g,h} = \frac{q_{\gamma,h}(\phi_{n,g})}{\phi_{n,g}} \quad (3)$$



- MOVE: Use T to solve for adjoint neutron source:

$$q_n^+(E_n) = \int_{E_\gamma} T(E_n, E_\gamma) \phi_\gamma^+(E_\gamma) dE_\gamma \quad (4)$$



MCNP6 Moving Objects

- Update in future version of MCNP6
- Allows movement of objects, sources, delayed particles during single simulation
- Available for native MCNP geometry descriptions (not mesh)

Mesh Coupled implementation of R2S (MCR2S)

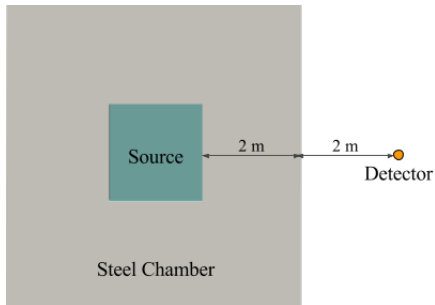
- Capability that allows components to move before photon transport step
- Transformations are applied to copies of moving components
- Original component still in original location, set to void material



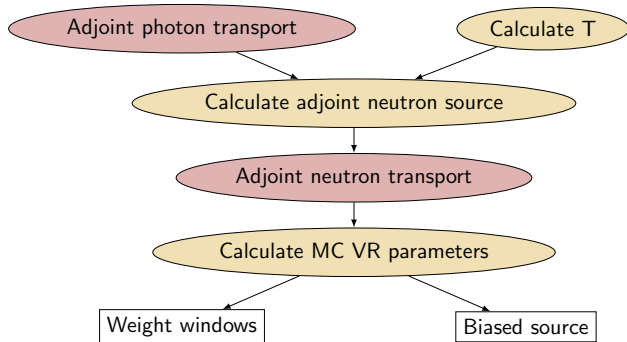
- MC method is most accurate way to obtain detailed particle flux distributions
 - Use MC codes for both neutron and photon transport steps of R2S
 - Need to use VR methods to optimize the transport calculations
- GT-CADIS, an implementation of MS-CADIS, has proven to optimize the neutron transport step of R2S
- MCNP6 and MCR2S have developed some capabilities for performing transport on moving geometries

Demonstration

- Geometry
 - Steel chamber
 - 2m x 2m x 2m central cavity
- Source
 - Volume source in central cavity
 - 13.8-14.2 MeV neutrons



- GT-CADIS workflow



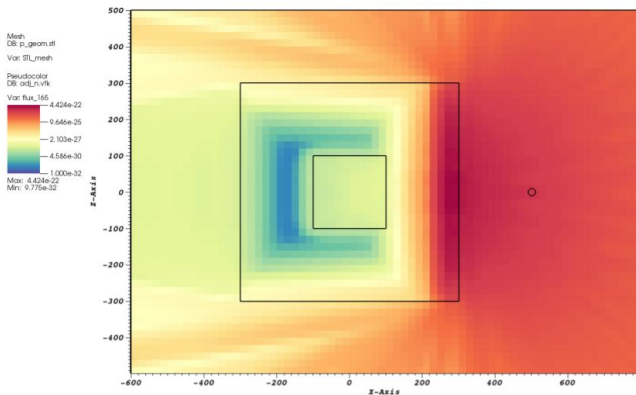


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.

GT-CADIS importance map is **insufficient** for moving systems.



Figure : Demo model. Steel chamber, walls are 2 m thick. 14 MeV neutron source in center. Chamber surrounded by air.

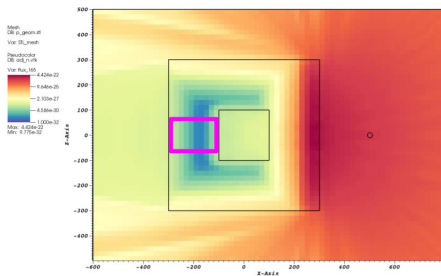


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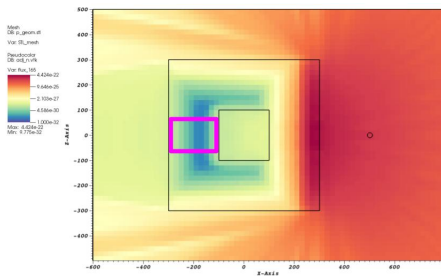


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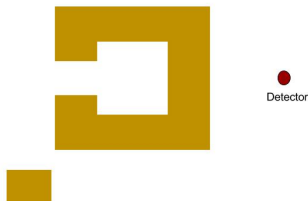


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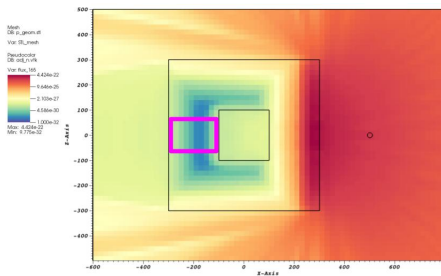


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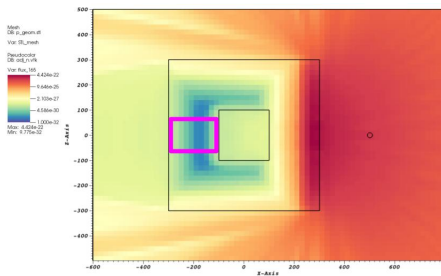


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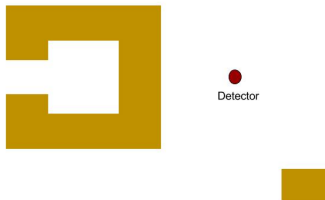


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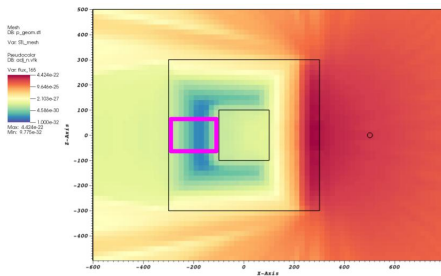


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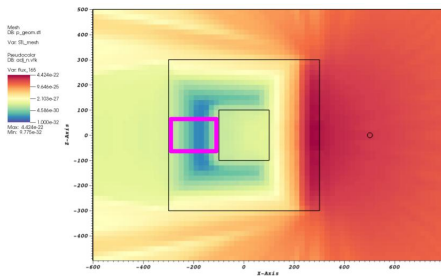


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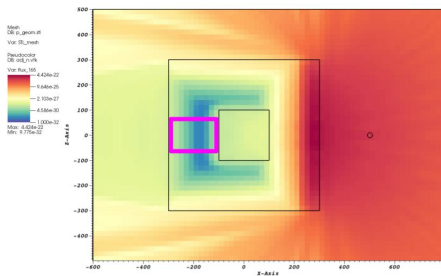


Figure : GT-CADIS adjoint neutron flux. Functions as importance map.

Proposal



- MS-CADIS optimizes initial radiation transport step in a coupled, multi-step process
- Need to derive new adj neutron source

- System of coupled, multi-physics:

$$\textit{Primary} : H\phi(u) = q(u) \quad (5)$$

$$\textit{Secondary} : L\Psi(v) = b(v) \quad (6)$$

- Adjoint identities:

$$\langle \phi^+, q \rangle = \langle \phi, q^+ \rangle \quad (7)$$

$$\langle \Psi^+, b \rangle = \langle \Psi, b^+ \rangle \quad (8)$$

- MS-CADIS requires a representation of the relationship between primary and secondary physics:

$$b(v) = \langle \sigma_b(u, v), \phi(u) \rangle \quad (9)$$

- Response to secondary physics:

$$R_{final} = \langle \omega_R(v), \psi(v) \rangle \quad (10)$$

- Set ω_R as adjoint source and invoke adjoint identity:

$$R_{final} = \langle \omega_R, \psi \rangle = \langle b, \psi_R^+ \rangle \quad (11)$$

- Substitute Eq. 9 :

$$R_{final} = \langle \langle \sigma_b(u, v), \phi(u) \rangle, \psi_R^+(v) \rangle \quad (12)$$

- Switch the order of integration

$$R_{final} = \langle \langle \sigma_b(u, v), \psi_R^+(v) \rangle, \phi(u) \rangle \quad (13)$$

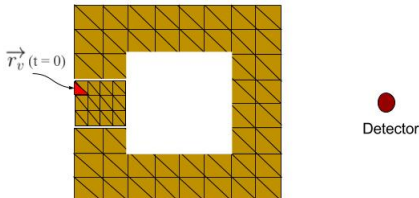
- Set response of primary physics equal to final response of the system and invoke the adjoint identity to solve for q^+ :

$$R_{final} = \langle \langle \sigma_b(u, v), \psi_R^+(v) \rangle, \phi(u) \rangle = \langle q(u), \phi_R^+(u) \rangle \quad (14)$$

$$q^+(u) \equiv \langle \sigma_b(u, v), \psi_R^+(v) \rangle \quad (15)$$

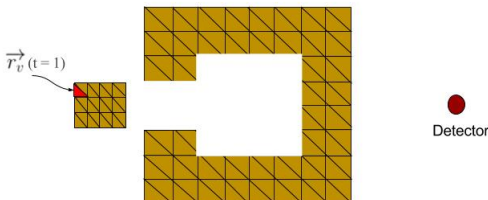
- Geometry movement during secondary physics effects the construction of the adjoint neutron source
 - Adjoint flux in volume element v at time t : $\Psi^+(\vec{r}_v(t), t)$
 - Position of volume element v at time t : $\vec{r}_v(t)$

$$q_v^+ = \int_t \Psi^+(\vec{r}_v(t), t) \sigma_{b,v}(t) dt \quad (16)$$



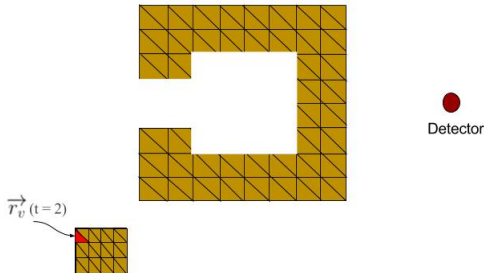
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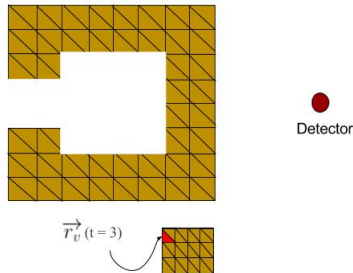
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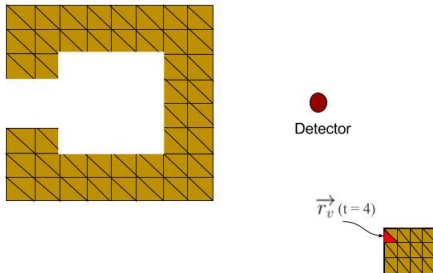


Time-integrated Adjoint Primary Source



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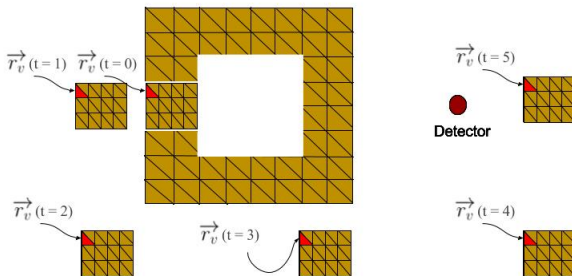
- To apply time-integration to GT-CADIS:
 - ① Perform adjoint photon transport at each time step of geometry movement
 - ② Integrate over time

$$q_{n,v}^+(E_n) = \int_t \int_{E_\gamma} T_v(E_n, E_\gamma, t) \phi_\gamma^+(\vec{r}_v(t), E_\gamma, t) dE_\gamma dt \quad (17)$$

- $\phi_\gamma^+(\vec{r}_v(t), E_\gamma, t)$ is the adjoint flux of photons of energy E_γ , in volume element v , at time t
- $T_v(E_n, E_\gamma, t)$ is the T value of the material in volume element v , at decay time t

- Average the adjoint photon flux calculated at each time step

$$\phi_{\gamma,v,h}^+ = \frac{\sum t_{mov} \phi_{\gamma,v,h,t_{mov}}^+ \Delta t_{mov}}{t_{tot}} \quad (18)$$



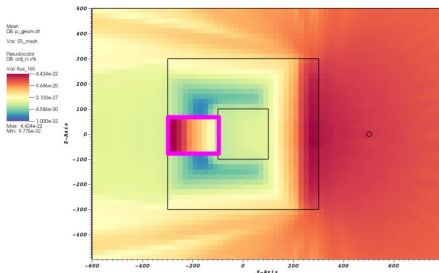
- Calculate T for each voxel

$$T_{v,g,h} = \frac{q_{\gamma,v,h}(\phi_{n,v,g})}{\phi_{n,v,g}} \quad (19)$$

- Combine with adjoint photon flux in each voxel

$$q_{n,v,g}^+ = \frac{\sum_{t_{mov}} (\sum_h T_{v,g,h} \phi_{\gamma,v,h,t_{mov}}^+) \Delta t_{mov}}{t_{tot}} \quad (20)$$

- Perform deterministic adjoint neutron transport using the time-integrated source
- Resultant adjoint neutron flux should look something like this:

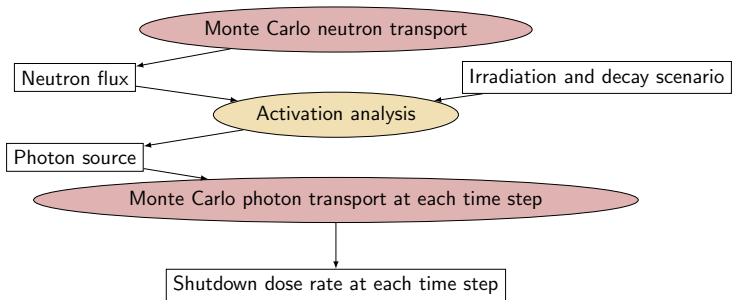


- Use this adjoint neutron flux to generate biasing parameters that will optimize the MC neutron transport step of R2S.

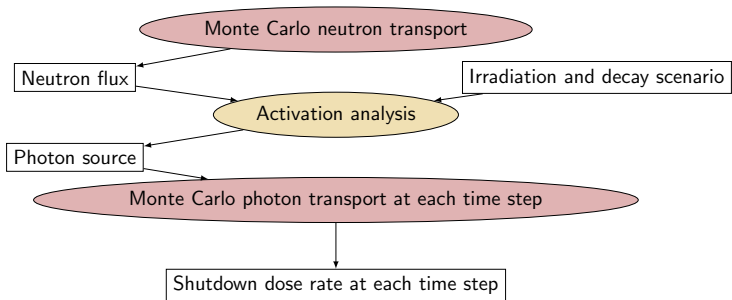


- Tools to update position of geometry based on user-defined motion data
 - ① Tool to produce step-wise geometry files
 - ② DAGMC update to facilitate on-the-fly geometry transformations
- Common functionality:
 -

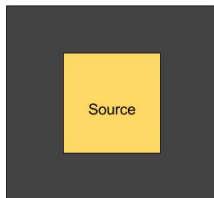
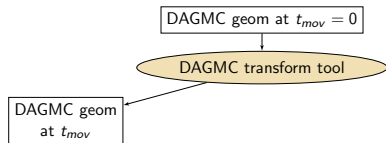
- R2S workflow for geometry movement after shutdown



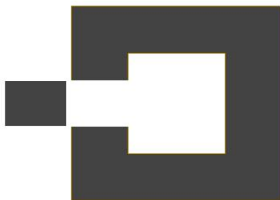
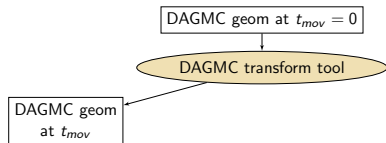
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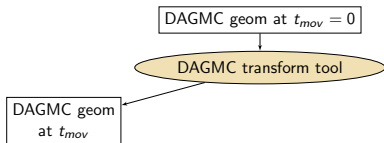
- Generate geometry files at each time step of movement after shutdown



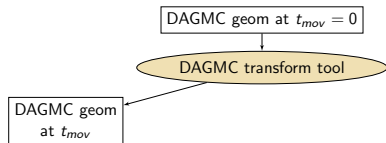
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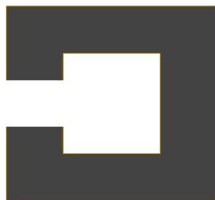
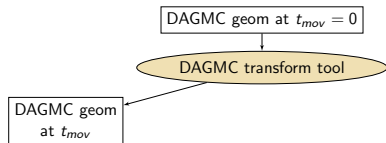
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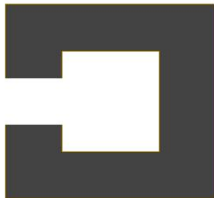
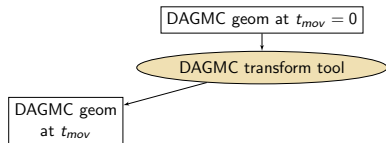
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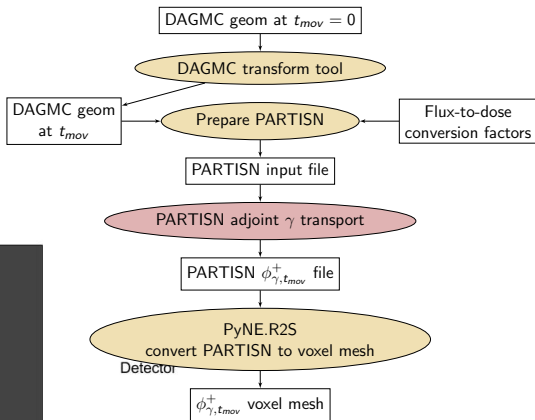
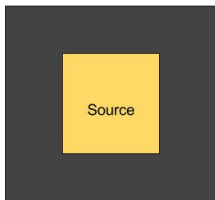

Detector



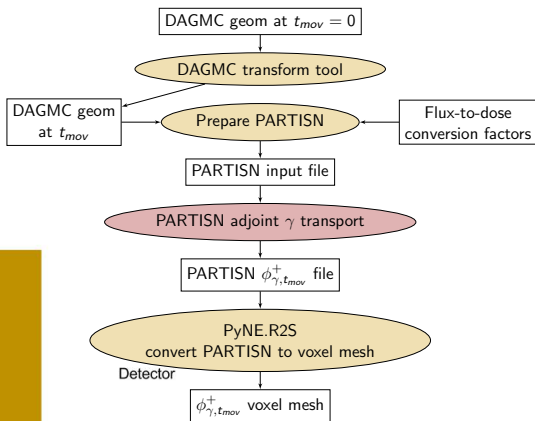
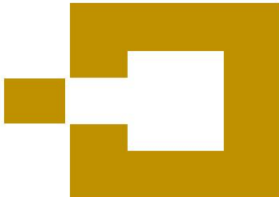
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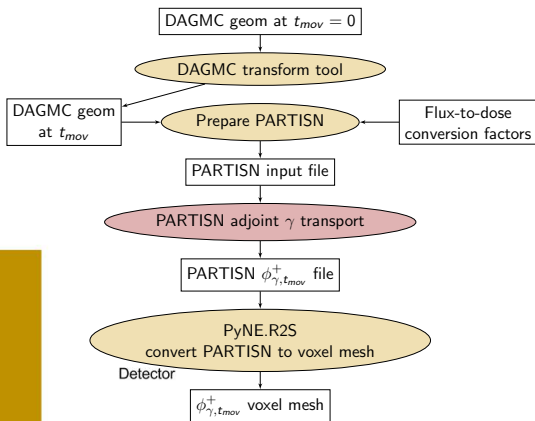
- Perform adjoint photon transport at each time step



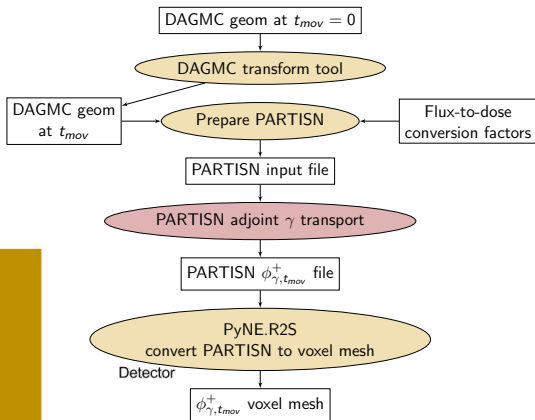
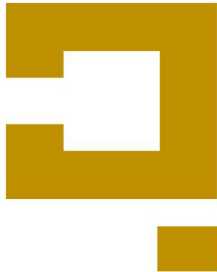
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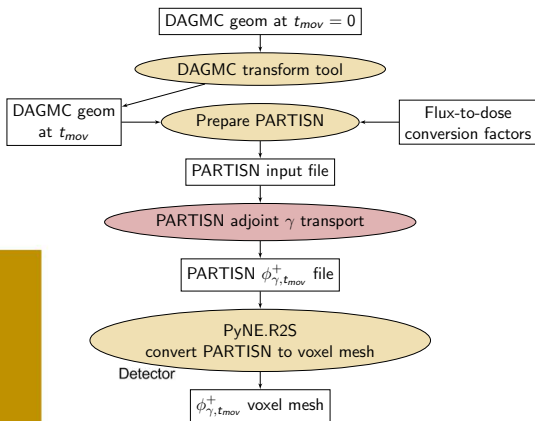
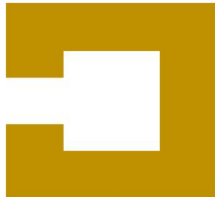
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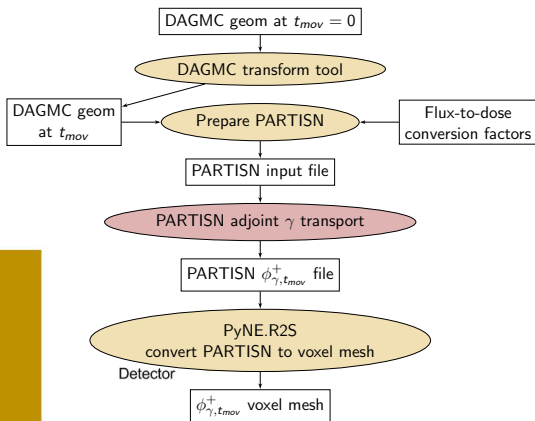
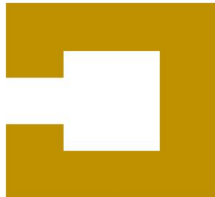
- Perform adjoint photon transport at each time step



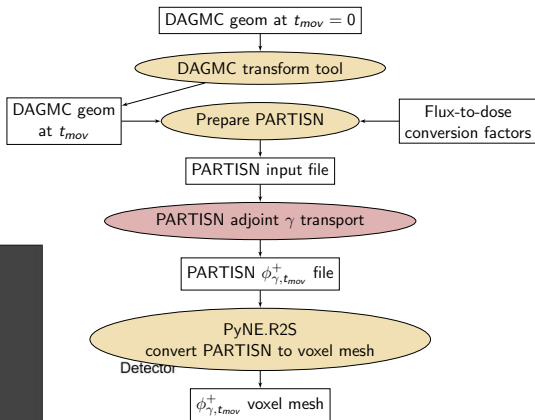
- Perform adjoint photon transport at each time step

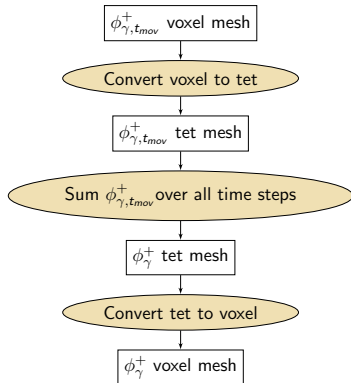


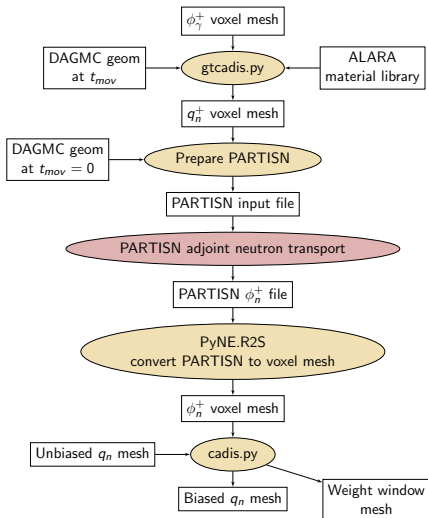
- Perform adjoint photon transport at each time step

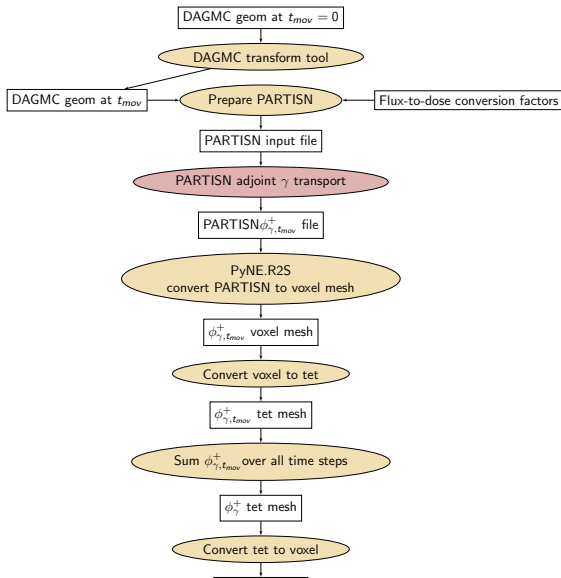


- Perform adjoint photon transport at each time step











- Assumptions
 - Photon transport occurs much faster than geometry movement \therefore reasonable to do quasi-static simulation
 - Period of geometry movement is short enough that the photon source will not change appreciably \therefore can use same photon source for all MC calculations
- Challenges
 - Depending on complexity of model and fidelity of time resolution, can amass large number of CAD geometry files, volume mesh tally files
 - Need to optimize this workflow in order to keep file storage at minimum

Questions?