Analysis of branching zero variance Monte Carlo games for radiation shielding problems

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Outline

Context of the work

- Solution of the Boltzmann transport equation using **Monte Carlo methods.**
- Monte Carlo is widely used in **radiation shielding problems,** but techniques to reduce the variance are needed $\rightarrow$ **importance sampling.**
- **"Zero variance games":**
  - the exact solution can be achieved;
  - need the solution of the importance equation.

What happens to the zero variance games for neutron transport problems where **neutron multiplication is allowed** (e.g., ex-core flux monitoring during reactor start-up)?

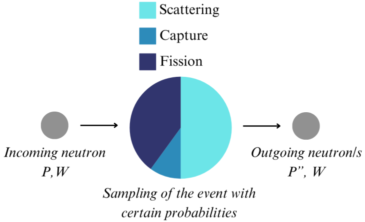
How would they perform?

Different kind of games

- Monte Carlo Game are defined by:
  - **stochastic rules** $\rightarrow$ Source Q, Flights T, Collisions C;
  - **suitable estimator.**
- Types of Games:
  - **natural (analog);**
  - **non-analog** $\rightarrow$ weight generation rules to preserve average tally for target response function (population control techniques often applied).
- Regarding the multiplicative phenomenon:
  - **branching games** $\rightarrow$ allow creation of branching histories;
  - **branchless games** $\rightarrow$ "1-in-1-out" approach.

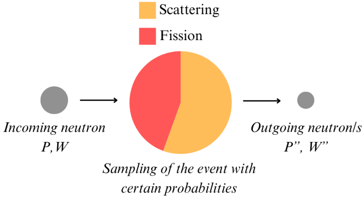
Comparison of games

Branching Analog



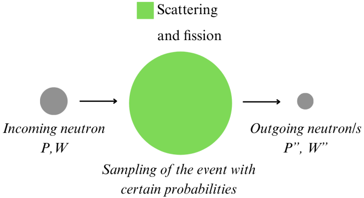
- All the reaction channels are available for the particle.
- Particle weight is not modified.

Branching Implicit Capture



- Capture reaction channel is suppressed.
- Remaining reaction channels probability and particle weight are rescaled.

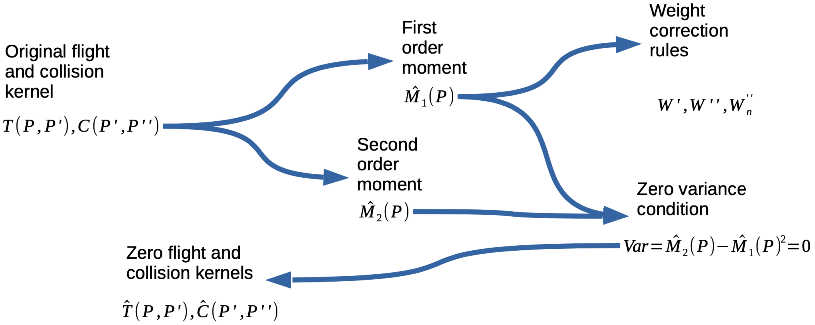
Branching Forced Fission



- A similar scheme is implemented in the TRIPOLI-4® code.
- The events of scattering and fission are not mutually exclusives.

Zero variance

- Sampling strategies such that **every particle carries the expected contribution to the detector $\rightarrow$ even with 1 particle the exact solution can be achieved.**
- Original "rules" modified by the zero variance condition.



Rules of the zero variance games

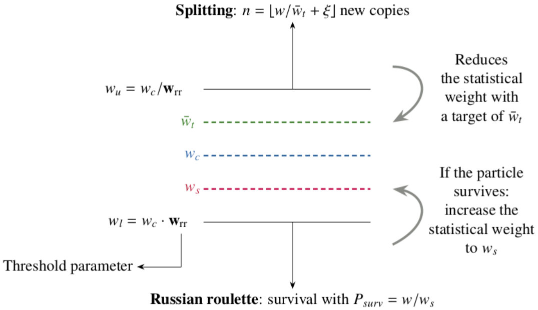
- Zero variance game's gules are derived by weighting:
  - flight kernel $\rightarrow T$
  - collision kernel $\rightarrow C$
  - source $\rightarrow Q$

  based on the expected contribution to score from sampled state.
- Given the new game rules the weight corrections are:

$$W' = \frac{T(P,P')}{\hat{T}(P,P')} \qquad W''_n = W' \frac{c_n(P')C_n(P',P'')}{\hat{c}_n(P')\hat{C}_n(P',P'')} \qquad W_Q = \frac{Q(P)}{\hat{Q}(P)}$$

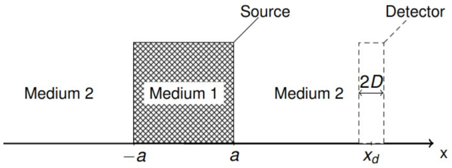
Population control

- Problem of **"immortal" particles** $\rightarrow$ population control methods used to stop the simulation.
  - **Russian Roulette** (R.R.): a particle history is terminated if the weight of the particle is too low to contribute significantly to the final score.
- Zero variance can be achieved only if population control is progressively suppressed: **weight cutoff (wct) = 0 $\rightarrow$ vanishing R.R. limit**

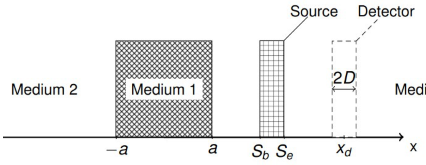


Verification of the proposed schemes

- Benchmark configuration → **1D infinite rod, 2- directions, mono-energetic problem with two media**.
- With the **Chenille Monte Carlo transport code (MGMC)**:
  - the detector response (R_{avg}) and the error (R_{err}) are estimated;
  - in the limit of **vanishing population control** the zero variance schemes are verified.

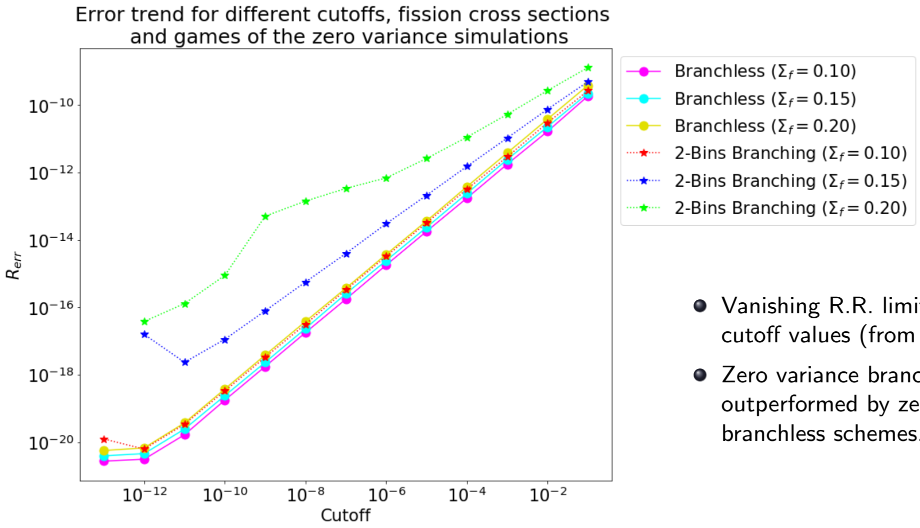


Case A geometry



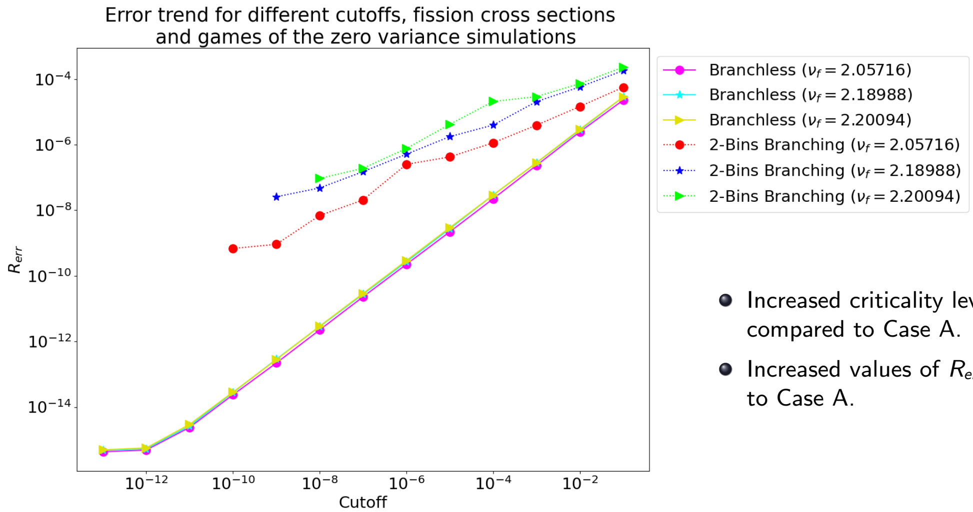
Case B geometry

Case A: R_{err} evolution



- Vanishing R.R. limit $\rightarrow$ decreasing cutoff values (from right to left).
- Zero variance branching schemes outperformed by zero variance branchless schemes.

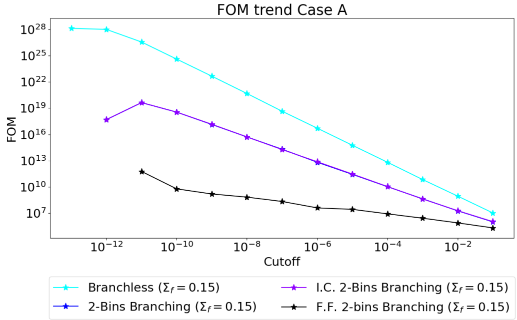
Case B: R_{err} evolution

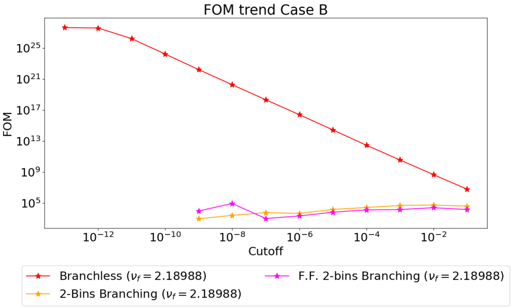


- Increased criticality levels compared to Case A.
- Increased values of R_{err} compared to Case A.

General FOM comparison

- Chosen Figure Of Merit $\rightarrow FOM = \dfrac{1}{(R_{analytical}/R_{err})^2 \Delta t}$





- In terms of FOM: Branchless $>$ Branching analog $\approx$ Branching implicit capture $>$ Branching forced fission

Conclusions

- Objectives achieved:
  - new zero-variance games derived **from implicit capture/forced fission games;**
  - implemented in Chenille (MGMC) and **compared with analog and branchless zero-variance games;**
  - tested on problems with:
    - different criticality levels,
    - various importance functions,
    - different fission child probability densities.
- Results:
  - branching zero-variance: suitable for multiplicative media, unbiased, but **feasibility decreases with branching histories;**
  - branchless zero-variance: better overall **FOM performance;**
  - still relevant for production Monte Carlo codes.

Thank you!

Questions?