The study of animal movement has broad applications across various disciplines, including the planning of anthropogenic projects such as dams (Weber, 2006) and roads (Colchero, 2011), the design of marine protected areas (Fulton, 2015), the study of environmental ecology (Johnson, 2008), population dynamics (Morales, 2010), and the modeling of disease spread (Wilber, 2022). This wide range of applications is matched by an equally diverse set of movement models. Generally, these models fall into one of three categories: Eulerian, which treats movement at the population level similarly to fluid dynamics; Lagrangian, which models individual movement as a parametric function of time; and agent-based models, which simulate individual movement as interactions between agents and their environment (Weber, 2006). Agent-based models are particularly useful as they explicitly capture the ways individuals respond to their surroundings and to one another.

A variety of approaches exist for developing agent-based models, including stochastic difference equations (Preisler, 2004), state-space models (Newman, 1998), and weighted distribution models (Johnson, 2008). Each of these methods requires explicit assumptions about underlying processes, as they impose a predefined functional form on movement dynamics. For example, stochastic difference equations rely on potential functions, state-space models assume a specific distribution for step length and turning angles, and weighted distribution models frame movement as a resource selection problem. More recently, deep learning models have gained attention for their ability to relax these assumptions (Wijeyakulasuriya, 2020). As universal approximators (Hornik, 1991), deep learning models can learn movement dynamics directly from data without requiring a predefined functional form. This allows deep learning methods, in the presence of enough data, to more accurately capture the real relationship between movement and covariates. However, most deep learning models, including those developed by (Wijeyakulasuriya, 2020), frame movement prediction as a problem of forecasting specific displacements at each time step. While useful in a variety of applications, this approach makes them unsuitable for multi-step simulations, as prediction errors compound over time. Effective long-term simulations require models that either achieve extreme accuracy—an impractical demand—or generate distributions over possible future movements. The continuous nature of the predictor makes integrating over all possible movement paths computationally prohibitive.

A promising alternative is to discretize the space into a grid of possible “choices” and then frame movement modeling as a probabilistic deep learning classification problem where each class represents an option available to the animal. In this formulation, at each time step, the animal's movement can be represented as a decision, , among a set of possible choices, where each choice corresponds to a grid cell the animal might reasonably move to, given its current location. Then, with information about these choices, , the model predicts the conditional probability of the animal moving to a specific grid cell in the next time step. The advantage of this alternative is that by limiting movement to a finite set of choices at each time step, this approach allows for the efficient computation of full probability distributions over multiple time steps, making it far more suitable for multi-step simulations.

In this paper we illustrate the application of probabilistic deep learning to movement modeling by (1) providing a guide on overcoming the practical challenges that arise in application and then (2) illustrating the technique with Chinook salmon movement data.

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