Towards detailed and interpretable bird migration forecasts

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Take home

A mechanistic movement model can be combined with deep neural networks to account for insufficiently understood dependencies to provide coherent descriptions of the processes under study.

We have used this approach to predict continental-scale bird migration at coarse (Voronoy) as well as fine-scale (hexagonal grid) tessellations. We predict not only aerial movements, but also explicitly capture take-off, flight, and landing dynamics in space and time.

Learn more

Links to the pdf of this poster, full papers and code: https://github.com/emielvanloon/BESmovement2025_extras

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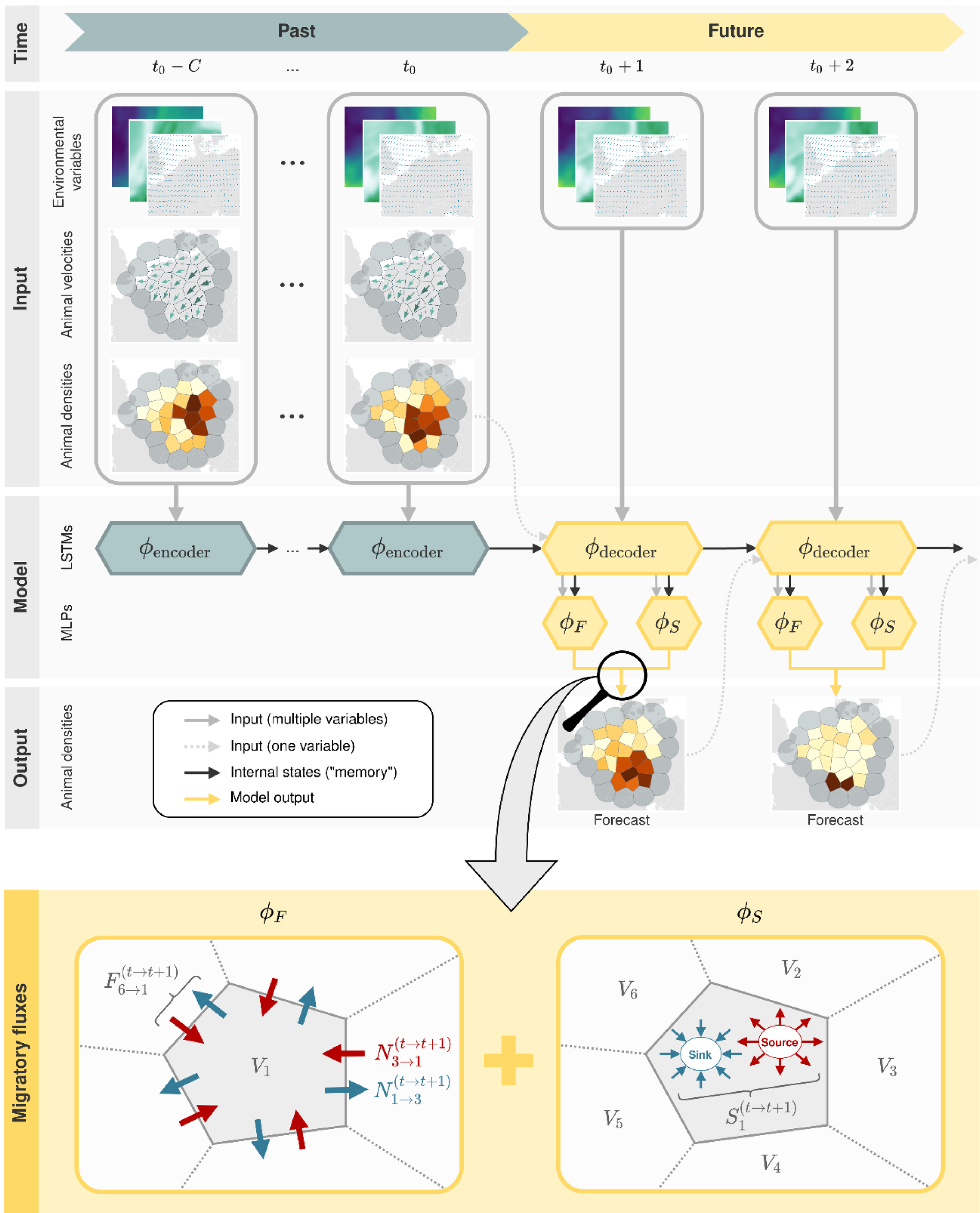
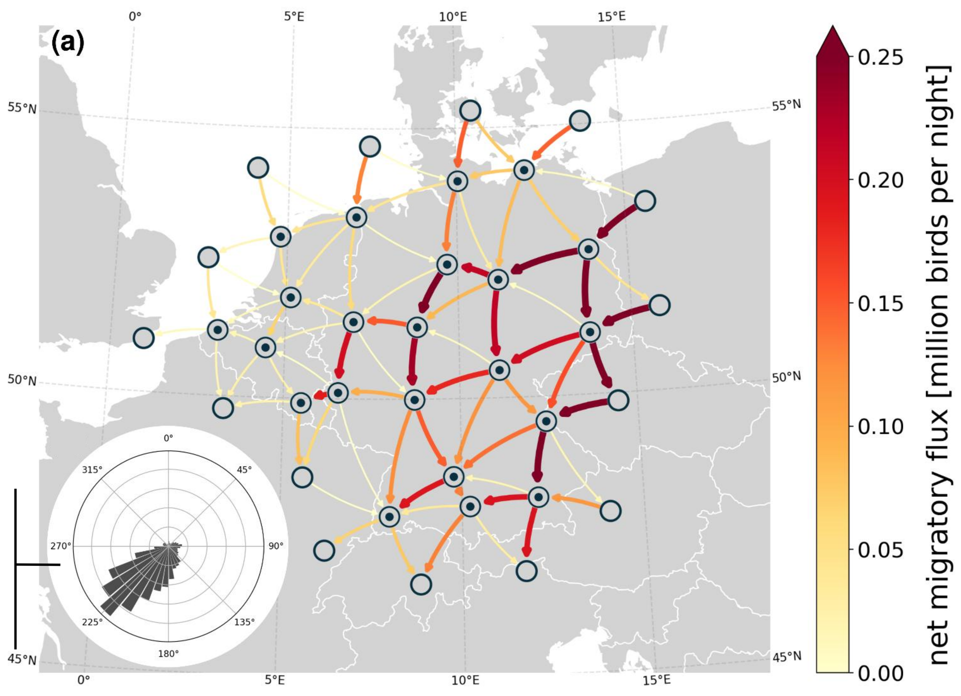
Results 1: Basic Model & First Application



FluxRGNN: Migratory movements are modelled on the Voronoi tessellation of radar locations. Past environmental conditions, vertically integrated bird densities and velocities at each radar are fed to a long short-term memory network (LSTM) to extract relevant information.

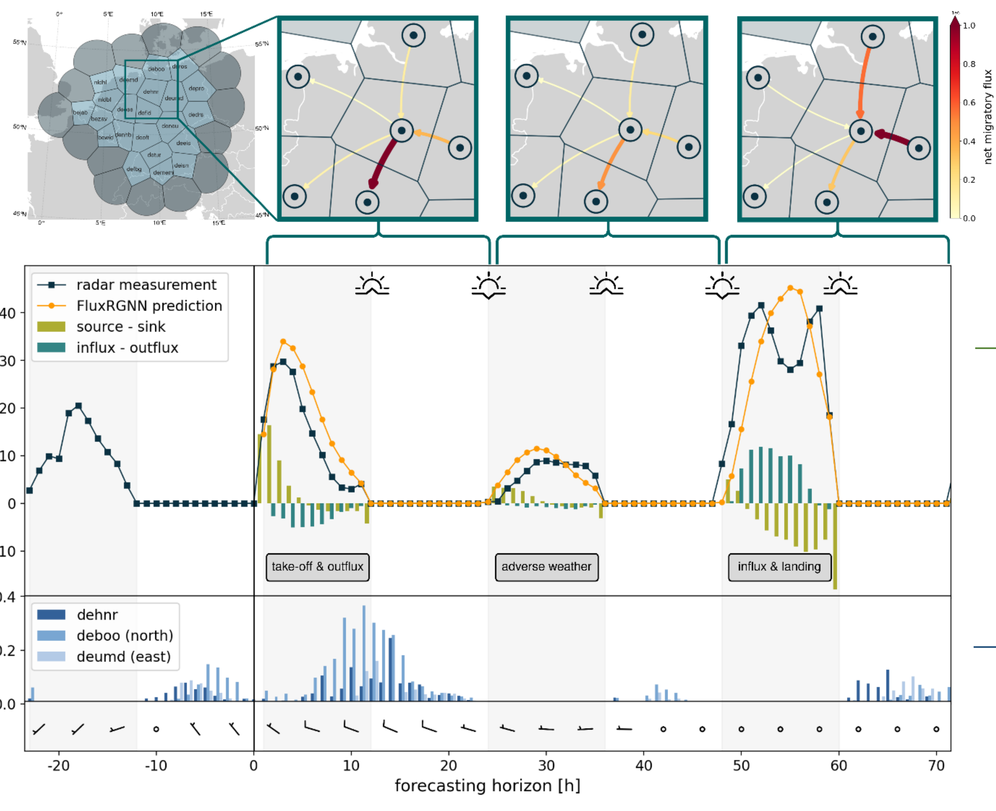
A second LSTM combines this information with environmental forecasts and previous model outputs. Finally, two multi-layer perceptrons predict bird movement fluxes between adjacent Voronoi cells and local source/sink terms.

The predicted terms are combined into bird density forecasts according to a mechanistic description of population-level movements.



The distribution of flight directions measured at all radars and time points.

Average nightly migratory fluxes predicted by FluxRGNN using radar measurements of nocturnal bird migration in autumn 2017.



Predicted fluxes (integrated over 24 hrs) between the Voronoi cell of **dehnr** and its neighbouring cells.

Hourly measured and predicted bird densities together with source/sink terms, net fluxes across the Voronoi cell boundary. The first 24 hours were fed to FluxRGNN as contextual information. Nighttime hours are shaded in grey.

Selection of relevant environmental variables: hourly precipitation and wind conditions at 850hPa.

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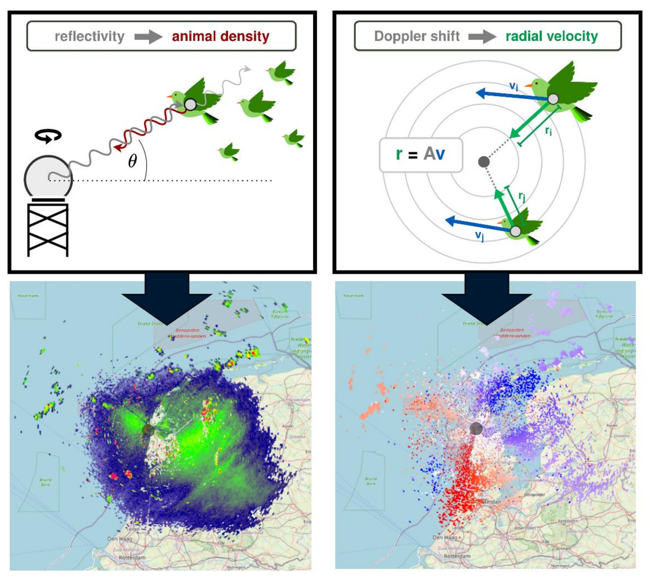
Motivation

Accurate and detailed spatio-temporal bird migration predictions are required for effective bird conservation and human-bird conflict mitigation.

Weather radars generate promising data, yet turning these into accurate predictions remains a challenge, a.o. due to the complexity of individual behaviors and the sparsity of the **radar network**.

Migratory movement by birds can be measured through weather radar



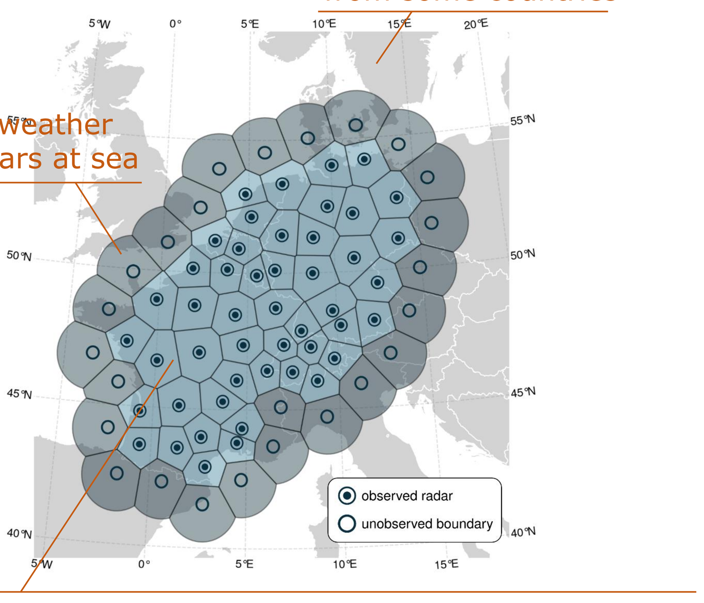
radar reflectivity bird densities appear in green,; pink pixels indicate extremely high reflectivity from wind turbines and boats.

Doppler shift estimates the ground speed in the direction of the radar beam - movements towards in blue and movements away in red.

Radars form a continental-scale network, which is unfortunately not perfect; some issues:

data not available from some countries

no weather radars at sea



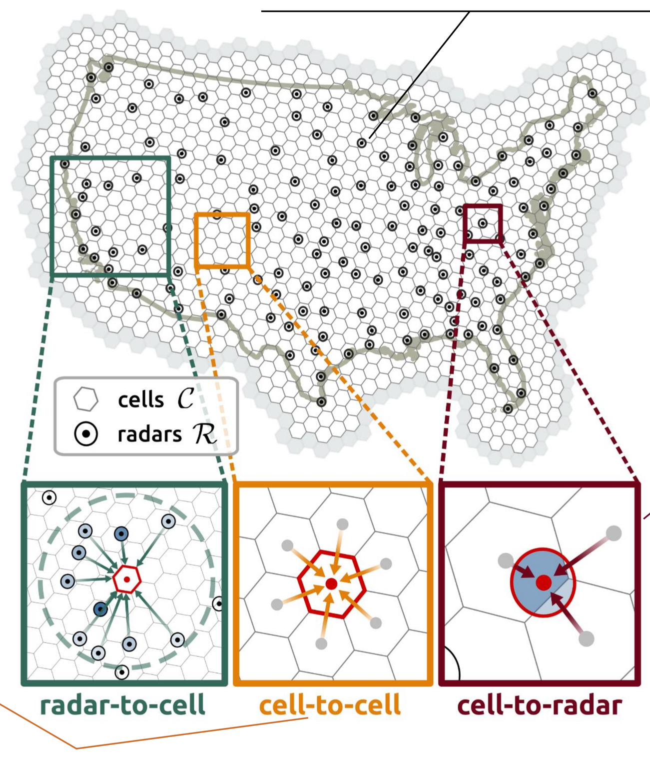
radar observations are not space-covering (only a small circle within each Voronoy polygon)

Results 2: Refinements & New Application

FluxRGNN+ allows for higher resolution forecasts on any desired tessellation (involving a regularization parameter λ) and includes an alternative flux parameterization to integrate available velocity measurements. It thereby ensures meaningful estimates of implicitly learned take-off and landing processes.

To evaluate the model, we used the NEXRAD radar network for the USA (Crum & Alberty, 1993; Ansari et al., 2018). Atmospheric variables were extracted from the ERA5 reanalysis dataset (Hersbach et al., 2020), habitat types and other landscape characteristics were extracted from the NLCD landcover data (Yang et al., 2018). The autumn migration season (1 Aug. to 15 Nov.) was considered. Years 2013 to 2018 for model training, 2019 for hyperparameter tuning and model selection, and 2020-2021 for final model evaluation.

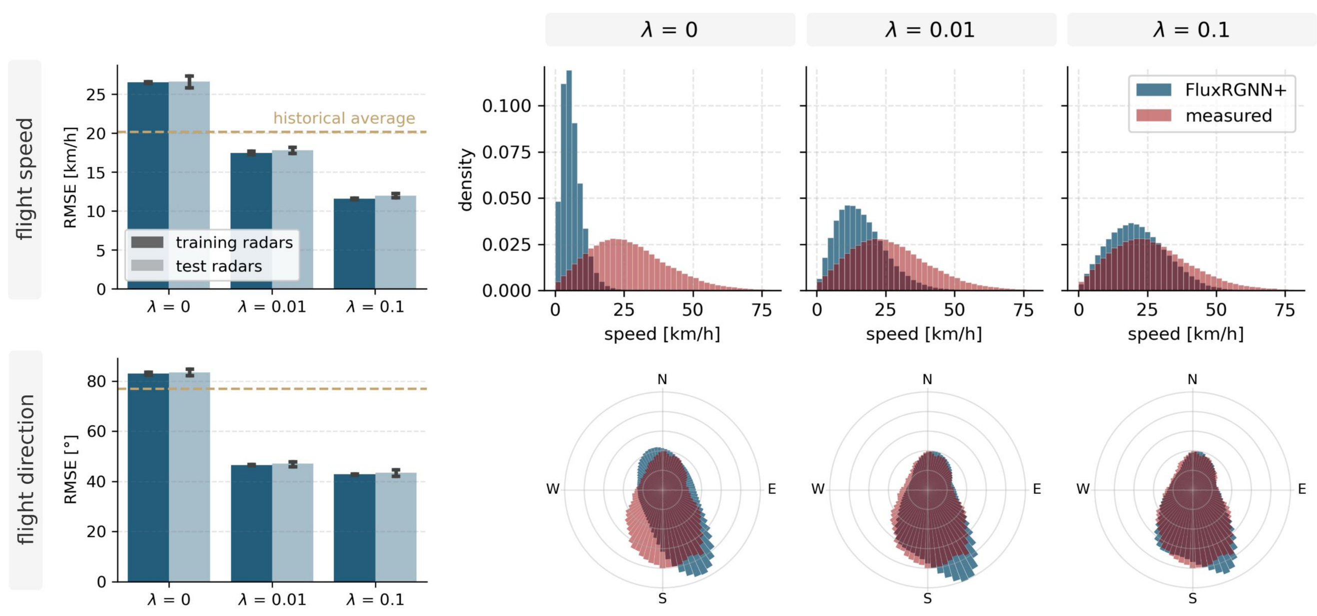
Black circles indicate measurement areas around radars, the movements are modeled on a hexagonal tessellation.



Encoding: $f_{R \to C}$ maps sparse radar measurements to model entities (hexagonal cells).

Forecast is generated based on within-cell source/sink terms S_i and cell-to-cell fluxes $F_{j \to i}$.

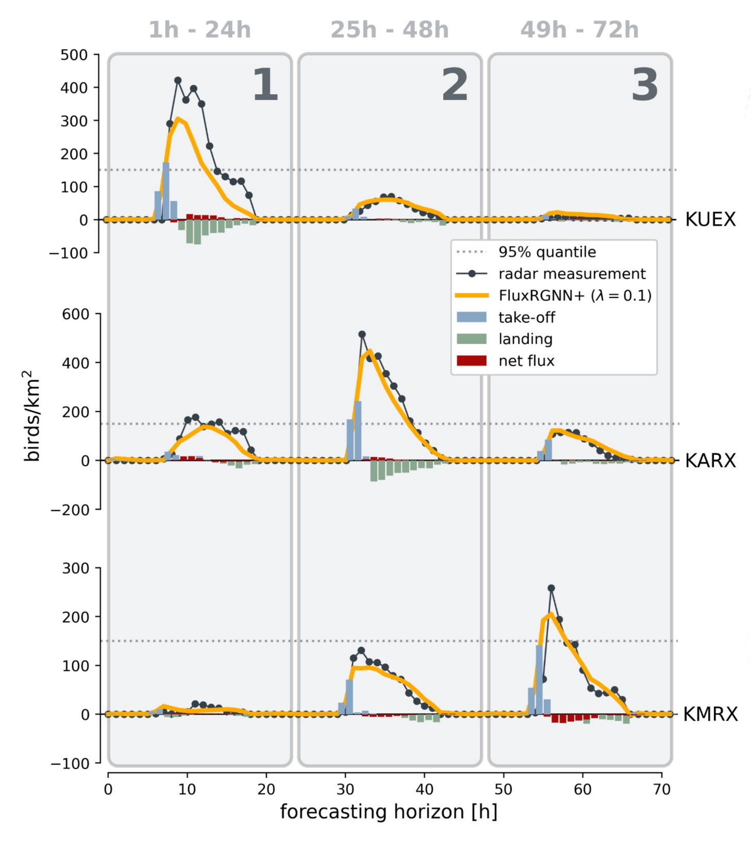
Decoding: $f_{C \to R}$ maps cell-level predictions back to measurement space.

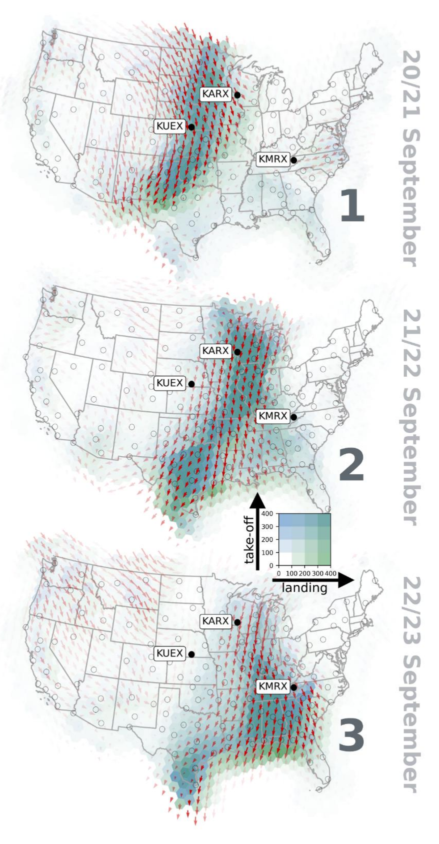


Averaged errors for training and test radars are comparable; lowest errors with λ of 0.1.

Histograms of predicted and measured quantities for test radars; best agreement with λ of 0.1.

Evaluation of predicted flight speeds and directions, trained with varying λ, using 10 fold cross-validation.





Example forecast of three consecutive high intensity migration nights (nrs 1-3) in September 2021 trained with λ = 0.1 on years 2013-2020.

The three time series include the radars marked in the maps on the right. To distinguish between take-off and landing, we separate hours with positive and negative source/sink term and aggregate them respectively.

Red arrows on the maps indicate average velocities in areas with substantial migration.

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Acknowledgements

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