Neural-network-enabled passive localization of multiple sources in radioactive waste

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Overview

- The Swedish Legacy Waste (SLW)
- Neural network approach for source localisation
- Application to gamma spectroscopy
- Results
- Conclusions and outlook

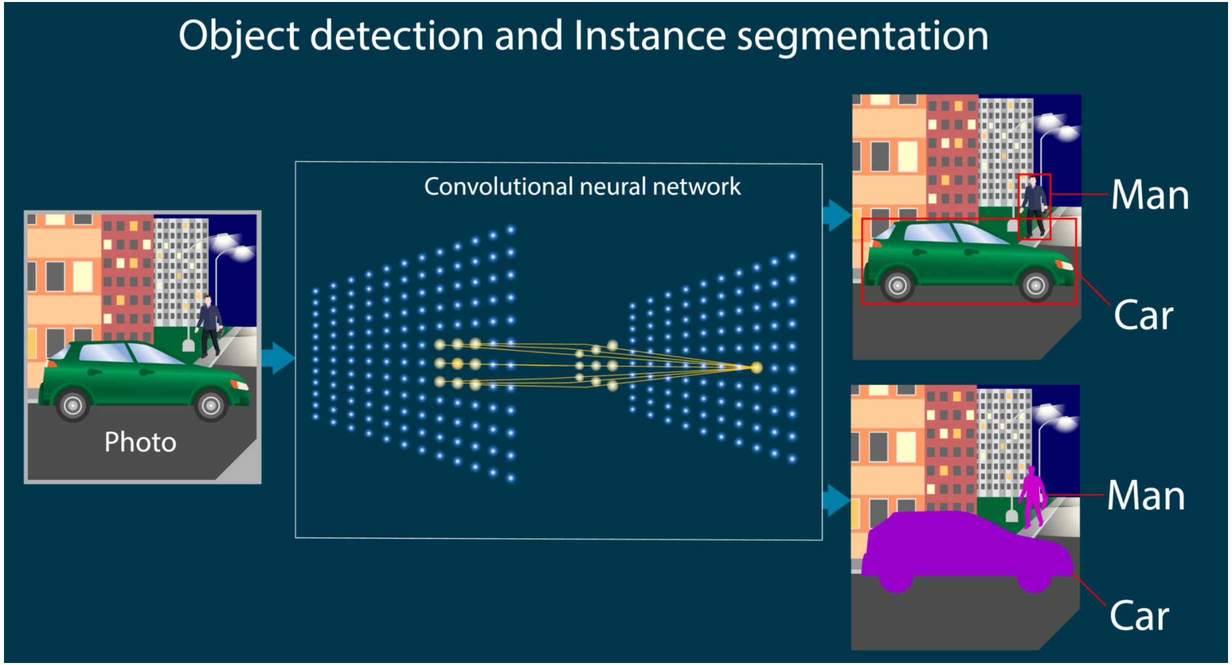
The Swedish Legacy Waste

The Swedish Legacy Waste (SLW)

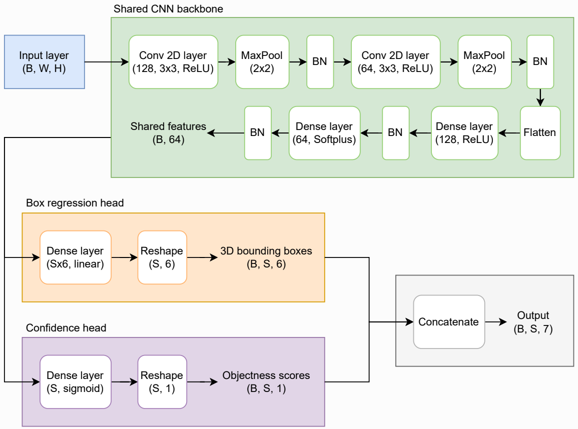
- ~ 8000 drums waste drums not compliant with modern standards.
- Concrete shielding: opening risks radioactive and/or toxic contamination.
- Must identify high-risk drums: actinides, concentrated sources, liquids, etc.
- Current standard approaches are insufficient.
- Passive source localization allows for extraction without opening the entire drum.

Neural network approach for source localisation

Object detection and localisation in images

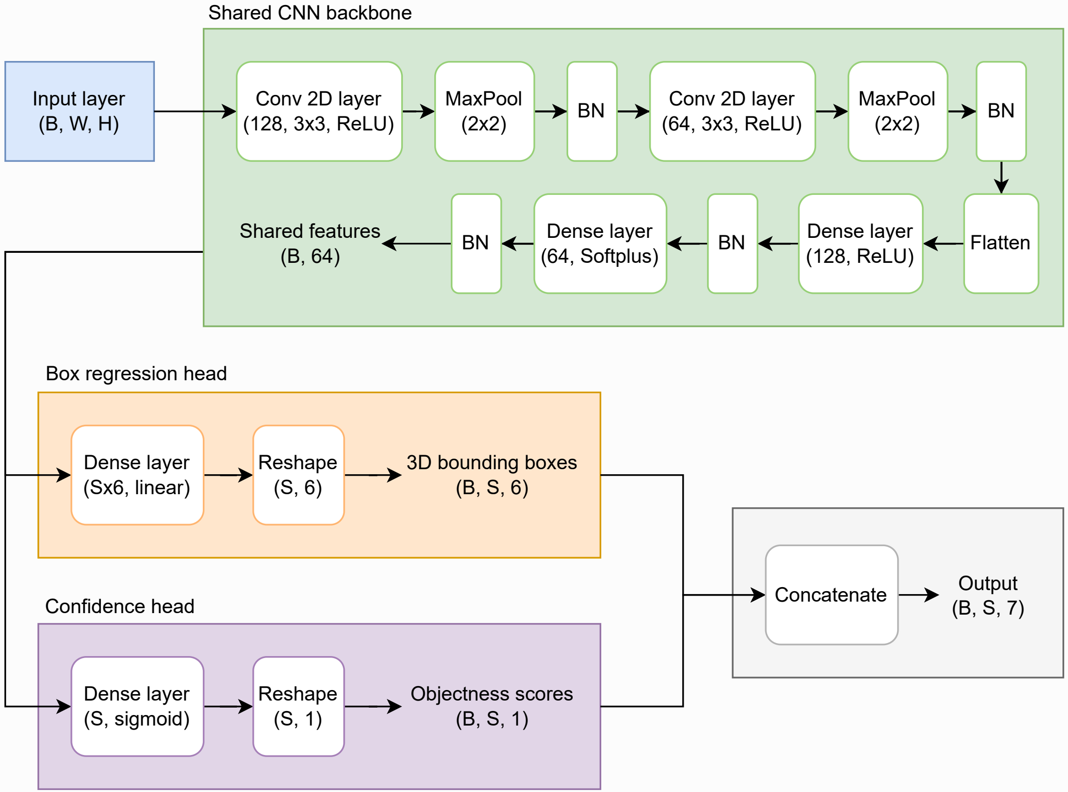


The neural network



- Currently, **localisation** is the only goal.
- Source order is permutation invariant. Labels contain multiple source slots.
  - Greedy assignment strategy matches the sources to their ground truth slots.
- Output: 3D bounding boxes. Cost function is a weighted sum of:
  - Huber (AKA smooth L1) loss: linear for large errors and quadratic for small errors.
  - Modified 3D complete intersection-over-union (CIoU) loss.
- NN must discern if a slot contains a source or not.
  - Confidence loss: weighted binary cross-entropy — 0 for invalid boxes and 1 for valid boxes.

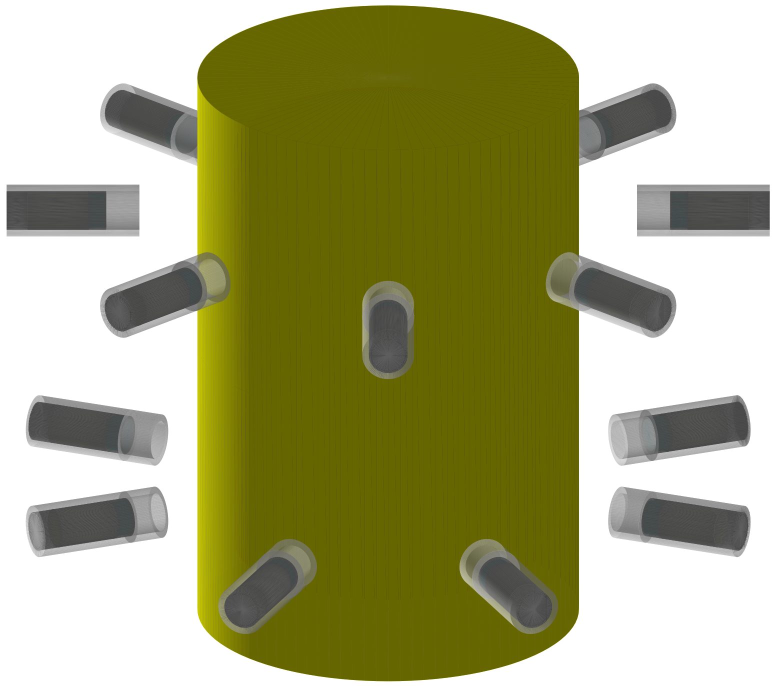
The neural network



Application to gamma spectroscopy

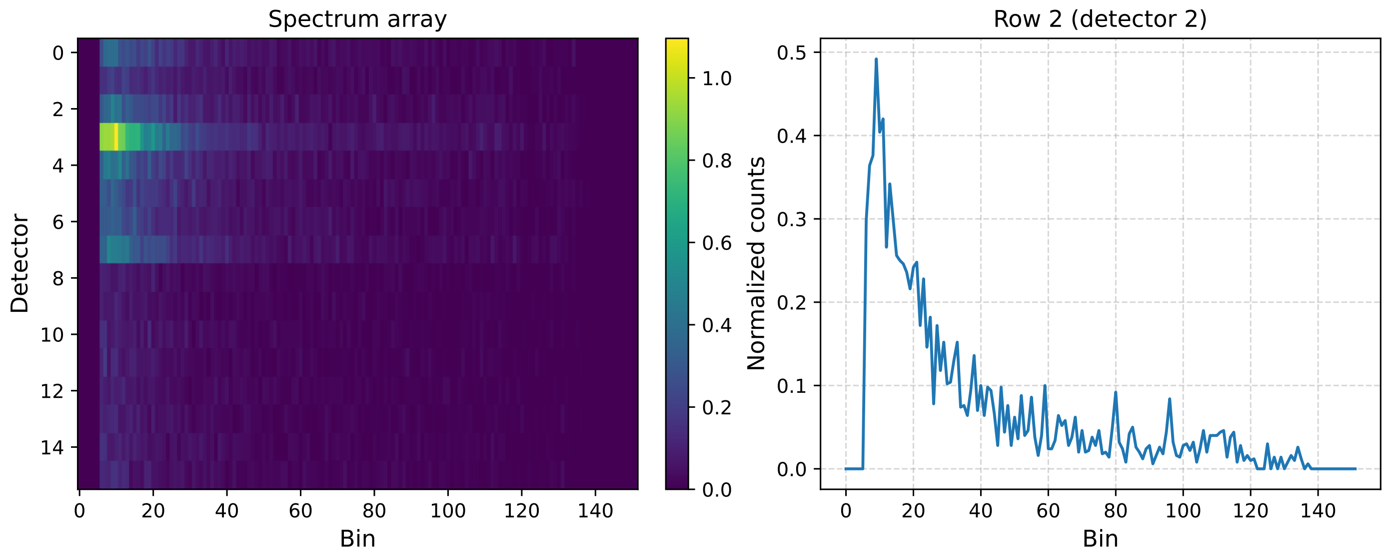
Data generation

- Simulations of simplified measurement setup in Geant4.
- 16 NaI(Tl) detectors: cost-effective, field-deployable.
- Source positions and sizes were randomized to make the training (and validation) datasets.
    - Up to three simultaneous sources.
    - Co-60 and Cs-137, 10^6 simulated events per source.
- Data augmentation and five-fold cross validation.



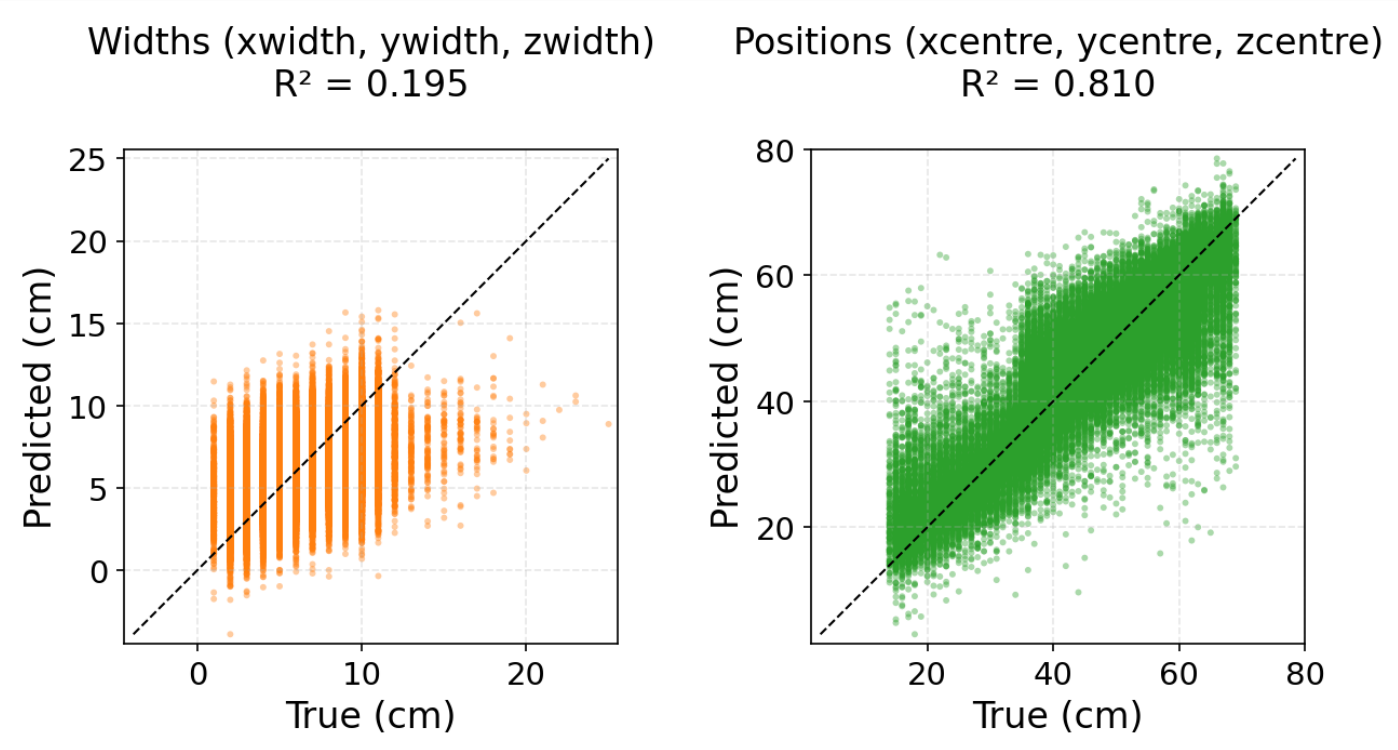
Input data: ”spectrum array” as image

Rather than extracting certain spectral qualities the convolutional neural network sees the whole spectra. Note: spectra are binned to 10-keV bins.

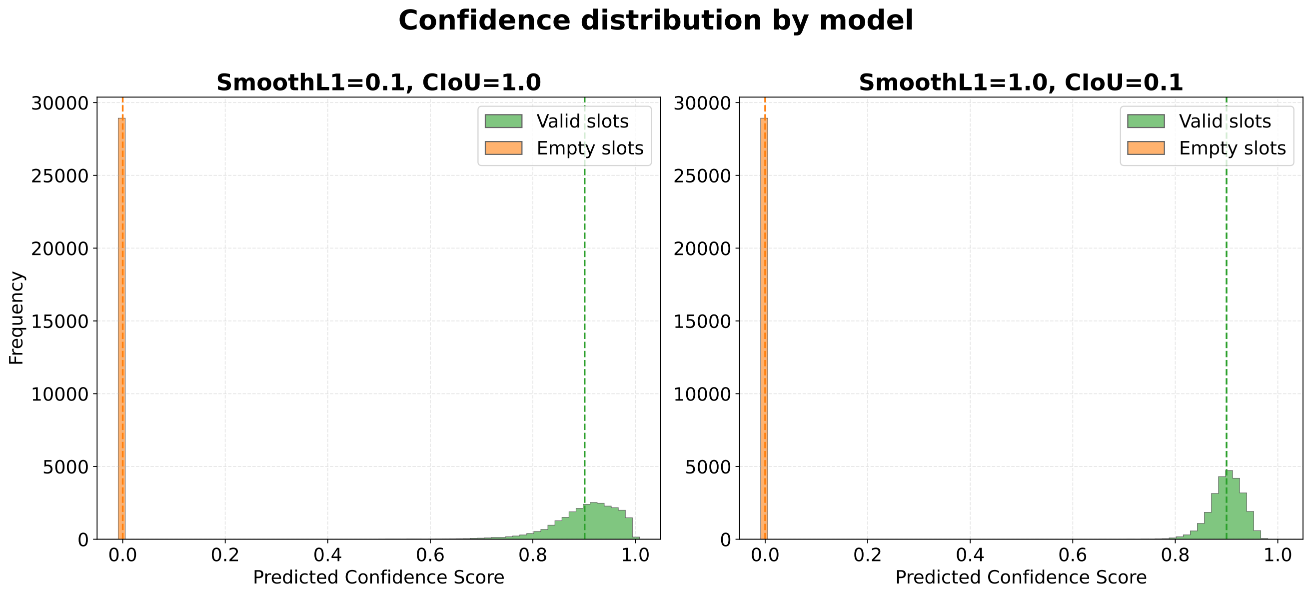


Results

R^2-scores for weights $\lambda_{\text{CIoU}} = 1.0$, $\lambda_{\text{Huber}} = 1.0$



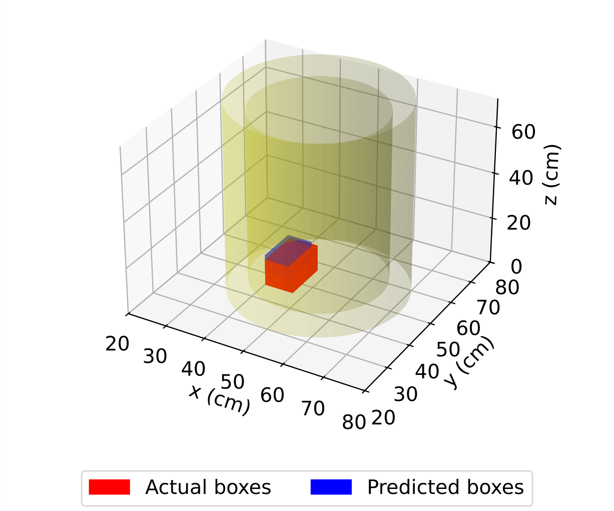
Confidence predictions

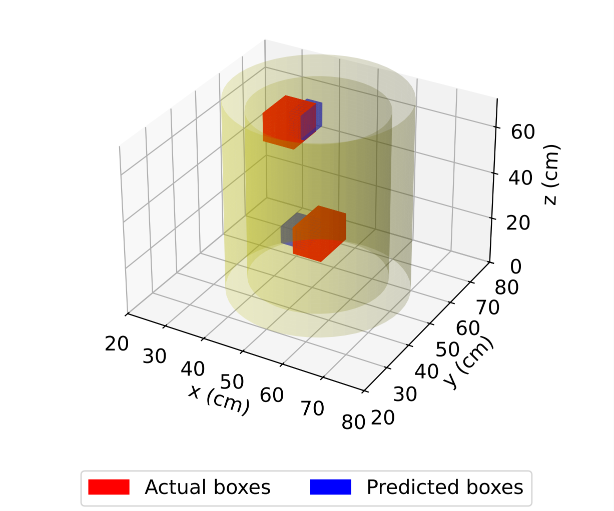


Gradient interference from one task may impair other tasks. CIoU likely has more turbulent gradients when box overlap is poor.

Example predictions

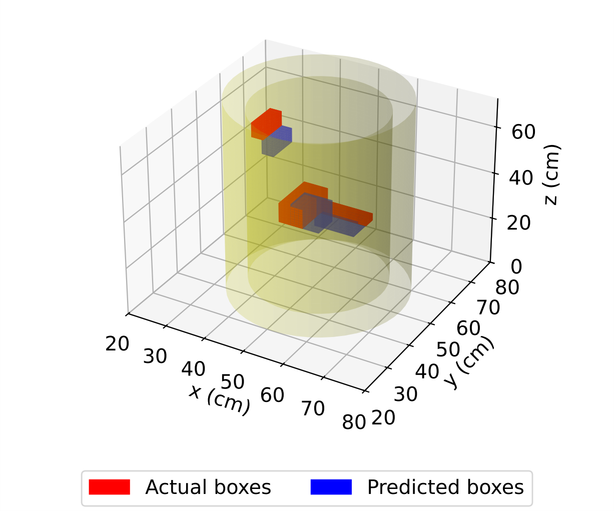
For 1-2 sources, box distances are at centimetre-level. Improved data quality (i.e. more detectors and better spectra) likely would improve volume estimation.

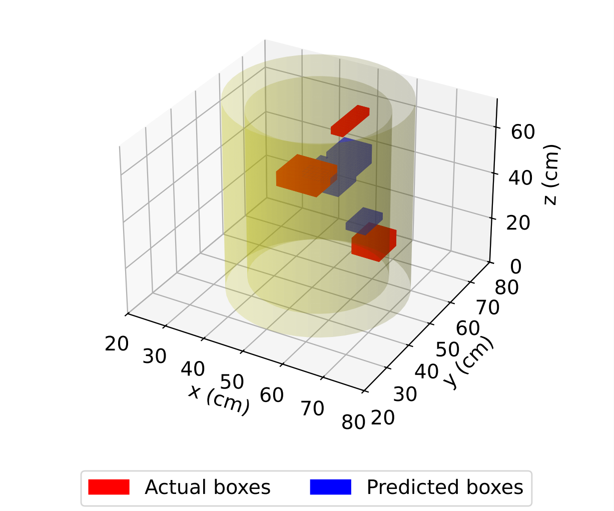




Example predictions

IoU worsens with increasing number of sources! Greedy assignment strategy less likely to give optimal solution.





Conclusions and outlook

Applicability in waste characterization

- The NN can recognize spectral patterns tied to the source position.
- It gives a bounding box representing the source position.
- It can determine the number of sources for the up to three tested.
- It struggles with volumetric estimation and ground-truth – prediction box overlap.
- It is dependent on training data, which is dependent on the measurement setup.

✓ Localising sources helps workers avoid unnecessary exposure to radiation and other hazardous materials.

✓ A simple setup allows for efficient measurements with little downtime.

✓ Improving the assignment algorithm, the data quality, the number of simulations and their quality will likely improve the method.

Paper preview

Passive localisation of multiple gamma emitters in shielded radioactive waste with deep convolutional neural networks

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ABSTRACT

The safe characterisation of legacy radioactive waste remains a major challenge in nuclear decommissioning. Conventional passive methods often struggle to accurately localise sources in shielded waste containers due to signal attenuation and scattering. To address this challenge, we present a scalable convolutional neural network model for passive three-dimensional localisation of multiple gamma-emitting sources within concrete-lined waste containers. Given the logistical difficulties of obtaining large-scale labelled datasets for radioactive waste, the model is trained on synthetic data generated via Monte Carlo simulations of a concrete-lined waste drum passively measured with an array of robust, cost-effective sodium iodide detectors. Using full energy spectra as input, the model predicts three-dimensional bounding boxes representing source positions and spatial extents, along with objectness scores to determine source count. The training strategy incorporates permutation-invariant assignment loss to enable robust multi-source detection without predefined ordering. Validation on a simulated sample dataset that contains up to three simultaneous radioactive sources demonstrates that the model can successfully determine the number of sources and their locations. These findings suggest that data-driven, passive approaches can provide a cost-effective and mechanically simple alternative to conventional tomographic and imaging systems for complex radioactive waste scenarios.

Outlook

- Presumably applicable to other types of spectra.
  - Current studies: neutron TOF in fission using plastic scintillators.
- Inhomogeneous waste matrices greatly affect spectra.
  - Simulations have been improved with randomized inhomogeneities.
- Assignment strategy affects predictions for higher numbers of sources.
  - Updated model uses the Jonker-Volgenant algorithm.

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VETENSKAP OCH KONST

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