(Some of the) ML-based Reconstruction in MicroBooNE

Wire-Cell Summit 2024
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This talk is only on a subset of ML-based reconstruction efforts on MicroBooNE

Describe a new workflow that combines several Convolutional Network Outputs with 3D point cloud reconstruction

Preview of first application of these reco products for a inclusive CC Nue selection
Reco. Overview

**Wireplane Images**

- +optical info

**SSNet CNN**

- particle-type
- pixel labels

**Wirecell in-time Cosmic tagging**

**LArMatch CNN**

- 3D Spacepoint and Keypoint Creation

**3D Spacepoint Reco.**

- Clustering, track, Shower, vertex reco.

**LArPID CNN**

- Cluster particle ID w/ context

**Neutrino Interaction Candidates**
LArMatch: Wireplane Images to 3D Charge and Keypoints

Goal: augmenting between-plane charge consistency with local features and priors on particle trajectory paths

Identifying true 3D locations of ionization by matching patterns across planes
Network can be divided into two parts:
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(1) CNN on (2D) images encodes relevant information for each pixel as 16-d vector.

Spacepoints are formed from simple spatially consistency and inherit pixel features.
Network can be divided into two parts:

(2) Each spacepoint is evaluated by multiple multilayer perceptrons which output various labels.
LArMatch: Neutrino Keypoint Scores

Neutrino Keypoint Score (ghost points removed)
Color scale: Score inverse to distance to keypoint
Yellow: 1.0 (0 cm) → purple 0.0 (>10 cm)
Keypoint labels are provided by learning a score between 0 and 1 that is proportional to distance to nearest keypoint. Final keypoint found by fitting spatial pattern.

Keypoint types:
- Track start/end
- Shower start
- Michel decay point
- Delta ray start

Types evaluated separately (non-exclusive)
LArMatch: Neutrino Vertex Position Resolution

- In MC, 68% of reconstructed neutrino vertices are within 9.2mm of simulated interaction position
  - Wire spacing is 3mm, so this is within 3 wires, which is quite good
Spacepoint Reconstruction

Spacepoint reconstruction into particle candidates greatly simplified by semantic labels from CNNs and other algorithms. Starts by separating passing points as:

- Non-cosmic track-like
- Non-cosmic shower-like
- Cosmic track-like
- Cosmic shower-like

Cosmic designation from Wirecell in-time/out-of-time tagger.

Track/shower designation from SSNet (evaluated on 2D images with labels pushed to spacepoints)

Keypoints initially remove spacepoints in order to prevent overclustering (points from more than one particle)
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Particle Clustering/Reco: Completeness and Purity

**Purity**: fraction of points within reco cluster from single particle

**Completeness**: fraction of true points from particle captured within cluster
LArPID Network

- A CNN to classify reconstructed 3D tracks and showers
  - Similar to work by NOvA: *PhysRevD.100.073005*
- Does particle identification (PID)
  - Outputs five score indicating how likely that the input is a muon, pion, proton, photon, or electron
- Outputs reconstruction quality metrics
  - Completeness prediction: fraction of true particle reconstructed in input track/shower
  - Purity prediction: fraction of reconstructed track/shower that was created from true particle
LArPID Inputs/Preprocessing

- In 2D images, select all pixels included in 3D prong hits
- Crop to 512 x 512 window. Center prong in image if it fits, otherwise crop around prong end point (if it’s a track) or start point (if it’s a shower)
- Normalize pixel values (subtract mean, divide by standard deviation)
- Provide full event images (with cosmics removed) along with prong images
LArPID Network Architecture

- Use tried and tested ResNet architecture (arXiv:1512.03385)
- Limit CNN depth to 34 layers due to computational constraints
LArPID: Used learned weighting for Multi-task loss

• Use learned weights to combine losses from three tasks (arXiv:1705.07115)
  - Loss = \( \exp(-s_{cr}) L_{cr} + \exp(-s_{pr}) L_{pr} + 2\exp(-s_{pc}) L_{pc} + s_{cr} + s_{pr} + s_{pc} \)
    - \( L_{cr} \) = mean square error completeness regression loss
    - \( L_{pr} \) = mean square error purity regression loss
    - \( L_{pc} \) = cross entropy particle classification loss

• Training sample: on the order of 100k prongs (tracks/showers) of each particle type (electrons, photons, muons, pions, and protons)
  - Weight \( L_{pc} \) contributions to account for class imbalance

• Validation sample:
  - 10k prongs, 2k per particle type

• Training
  - Data augmentation: randomly flip input images
  - Trained for 20 epochs with a variable learning rate scheduler:

![Curve showing learning rate change over epochs](image)
LArPID: Classification Performance

- Results shown with true prong purity > 0.6 cut for accurate labels
- Overall validation accuracy: 91.1%

Validation Sample Accuracy Statistics

<table>
<thead>
<tr>
<th></th>
<th>True electrons</th>
<th>True photons</th>
<th>True muons</th>
<th>True pions</th>
<th>True protons</th>
</tr>
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<tbody>
<tr>
<td>Fraction classified as</td>
<td>83.5%</td>
<td>4.8%</td>
<td>0.1%</td>
<td>0.4%</td>
<td>0.1%</td>
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<td>electrons</td>
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<td>Fraction classified as</td>
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<tr>
<td>Fraction classified as</td>
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<td>0%</td>
<td>93.6%</td>
<td>12.1%</td>
<td>0.2%</td>
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<td>6.1%</td>
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<td>1.4%</td>
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<tr>
<td>Fraction classified as</td>
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<td>0.2%</td>
<td>0.2%</td>
<td>1.5%</td>
<td>98.2%</td>
</tr>
<tr>
<td>protons</td>
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</tbody>
</table>
LArPID: Completeness and Purity Regression

Predicted vs. True Completeness, Validation Sample

Predicted vs. True Purity, Validation Sample

MicroBooNE In Progress

T. Wongjirad

Wire-Cell Sumit [04/12/2024]
LArPID: Probing the use of context

Original Scores
Electron score = -3.6
Photon score = -0.03

Scores are
\log(\mathcal{L}(\text{class}|x))

Using secondary shower to classify as photon despite obscured information near vertex?
LArPID: Probing the use of context

Prong image

Manipulated Context Image
[second shower pixels removed]

Original Scores
Electron score=-1.53
Photon score=-0.25

Scores are
\[ \log(\mathcal{L}(\text{class}|x)) \]

Manipulation leads to less confidence in photon classification
(but still favors photon-ness)
LArPID: Probing the use of context

Prong image

Context Image

Original Scores
Electron score = 0
Photon score = -7.02
Pion score = -6.02

Scores are $\log(L(\text{class}|x))$

Majority of pixels are of an electron: but it is an electron from the decay of a charged pion.
LArPID: Probing the use of context

Manipulated Prong image

Manipulated Context Image

Original Scores
Electron score= -0.01
Photon score= -5.02
Pion score= -8.63

Scores are $\log(L(\text{class}|x))$

Pion score drops significantly

Change the pion+electron stub into electron shower (from another event)
LArPID: Probing the use of context

**Manipulated Prong image**

**Manipulated Context Image**

**Original Scores**
- Electron score = -7.9
- Photon score = 0.0
- Pion score = -12.8

Scores are \( \log(L(\text{class}|x)) \)

Gap moves classification to photon (despite shower trunk \( dE/dx \) being that from electron)

Move electron shower and detach from vertex
LArPID: Probing the use of context

Manipulated Prong image

Manipulated Context Image

Original Scores
Electron score= -7.9
Photon score= 0.0
Pion score= -12.8

Scores are log(\(\mathcal{L}(\text{class}|x)\))

Work on-going to more quantitatively interrogate the use of valuable context image: e.g. how about examples near/far outside the training sample kinematic domain?

Move electron shower and detach from vertex
Ultimately, sufficient quality of these tools is in the ability to do physics. Testing with inclusive CC electron-neutrino and muon-neutrino

• Selection simply utilizes:
  - Basic reconstruction quality cuts
    • Neutrino vertex found by LArMatch, doesn’t overlap with tagged cosmic activity
  - Cuts on LArPID particle scores
    • No muon tracks
    • One forward-going electron shower identified with high confidence (high electron score, low photon and pion scores)
Inclusive CC Nue Selection Efficiency/Purity

- Backgrounds included: cosmic, CC numu, NC numu, and NC nue
- Selection purity above 80%, efficiency rises above 60% around 1 GeV
- **Caveat:** MC samples used to calculate purity and efficiency numbers were also used in prong CNN training (additional MC simulation not available in time)
  - Large training sample, not much over-fitting
- Selection is preliminary, performance will increase as selection criteria are refined
Testing on data

- We ran our new selection on a small MicroBooNE open data set
- New probable CC $\nu_e$ events were found!
  - Event displays for four low-energy probable CC $\nu_e$ events not identified in other reconstruction frameworks are shown on the following slides

Results still in the works, but have not yet seen signs of large problems due to domain shift
Example Data Event Selected

Reconstructed neutrino energy: 305.6 MeV
Cosmic Removed 3D points and Clusters

Run 5339 Subrun 115 Event 5764

Reconstructed Nu Candidate
1 Track (green hits, cyan path)
1 Shower (copper hits, red line)
Example Data Event Selected

Run 5339 Subrun 115 Event 5764

Shower trunk obscured in both U and V plane → leads to missing shower trunk in 3d hits, but seen by 2D CNN in Y plane
Conclusions

- **New** MicroBooNE reconstruction workflow completed
  - Represents only a subset of all the ML work done on MicroBooNE
- Makes use of CNNs that greatly ease the task of 3D spacepoint reconstruction
- We have applied the outputs for a CC inclusive selection and early tests show promise
  - No large data/MC disagreement yet seen
  - Competitive with past analyses
- Public note on this selection coming soon
  (check out Matt Rosenberg’s poster at Neutrino 2024)