



Training Neural Networks on Embedded Devices Targeting Embedded Environments

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Outline

Neural
Networks in
Embedded
Devices

Embedded
Linux

Neural
Networks

Benchmark
Applications

Discussion

1 Neural Networks in Embedded Devices

2 Embedded Linux

3 Neural Networks

4 Benchmark Applications

5 Discussion



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Neural Network Applications on Embedded Devices

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Embedded Devices





Goal : Neural Network Training on Scania ECU

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Predictive vehicle maintenance using data from a fleet of connected trucks

Why Training on the ECU?

- Training on devices reduces network usage, ensures data privacy, etc.
- Repurpose existing ECUs to perform neural network related tasks

Scope Repurpose Scania ECU, train neural network model, assess training performance



Goal : Neural Network Training on Scania ECU

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ARM Boards : Examples

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SoC	Application Domain	Architecture	Processor Core
nRF51822	Ultra low power, BLE	ARM v6-M	ARM Cortex M0
AM2732	Automotive	ARM v7-R	ARM Cortex R5
AM3358	Industrial / IoT	ARM v7-A	ARM Cortex A8
i.MX6S	Multimedia applications	ARM v7-A	ARM Cortex A9
BCM2711	Educational / IoT	ARM v8-A	ARM Cortex-A72
Snapdragon 460	Smartphones	ARM v8-A	ARM Cortex-A73, A53
Google Tensor	Pixel 6	ARM v8.2-A	ARM Cortex-X1, A76, A55
Apple A16 Bionic	iPhone 14 Pro	ARM v8.6-A	APL1W10
Apple M1	Macbooks / Mac Mini / iPads	ARM v8.5-A	APL1102



ARM Boards : Outline

ARM | Silicon Vendor | System Maker

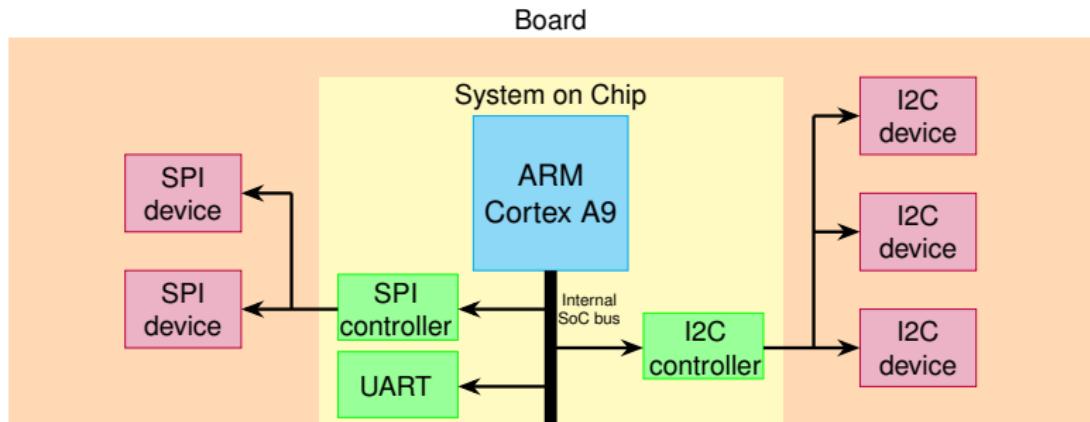
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Embedded Linux

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Operating System for Embedded Devices
- Customized for Specific Hardware

Kernel, Bootloaders, Device Trees
Cross Compiling Toolchains, Root Filesystems



Embedded Linux

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Build Systems

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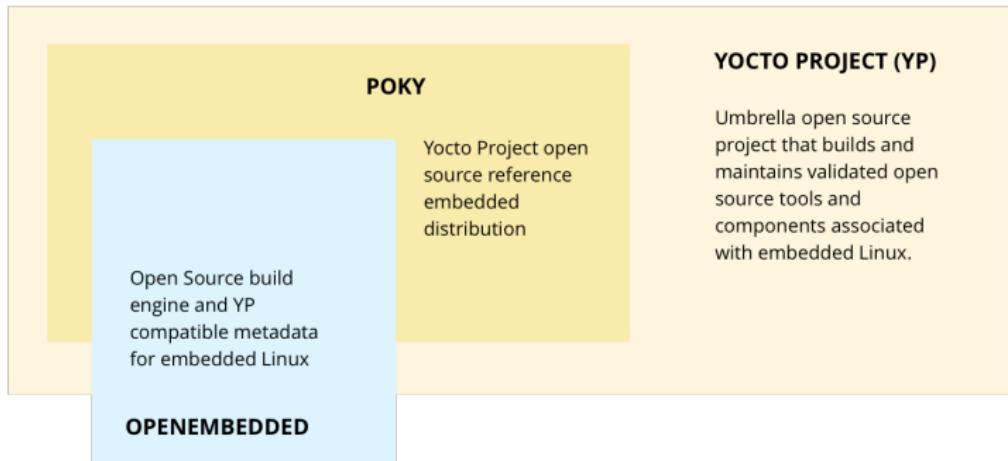
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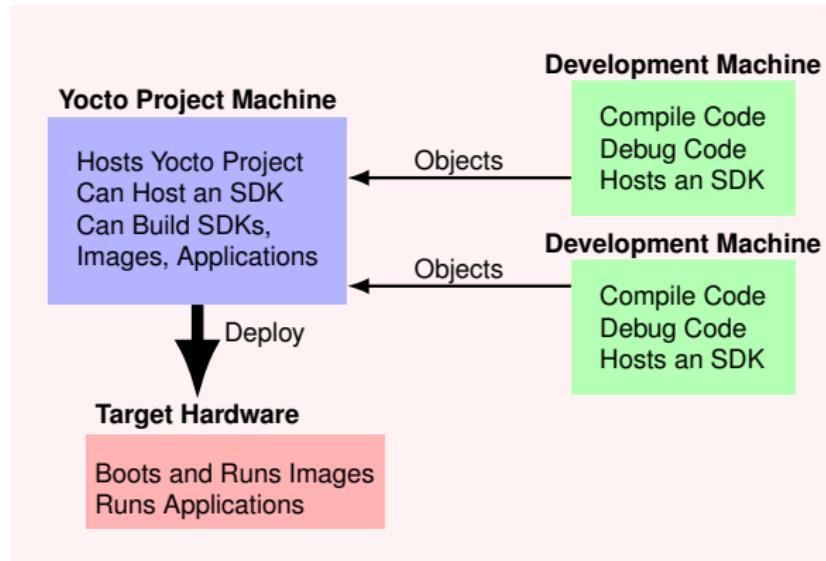
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Yocto Project





Yocto Project : Development





Software Versions

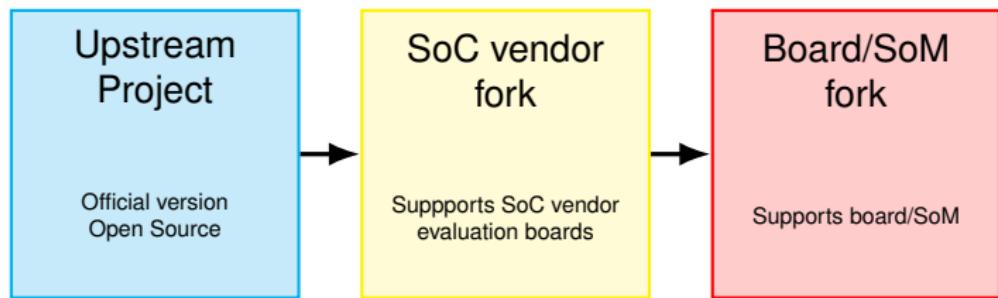
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Scania ECU to MCIMX6Q-SDB

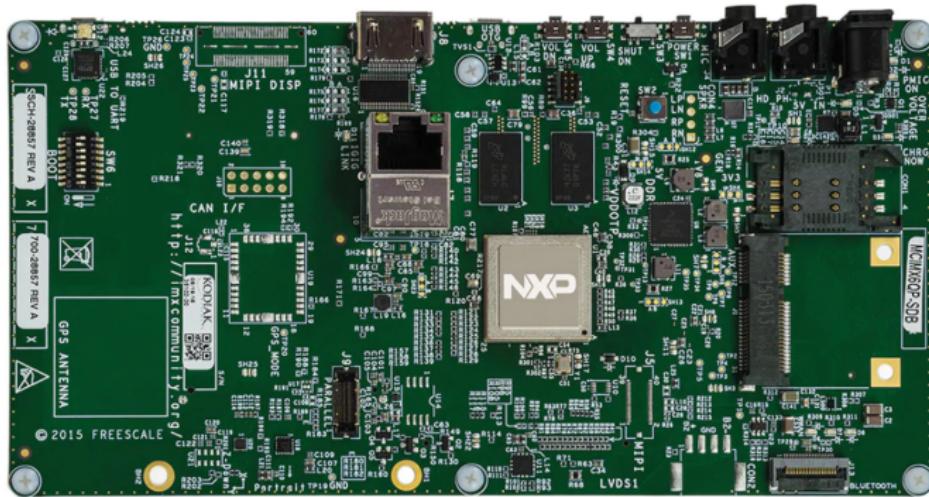
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Handwritten Digit Recognition

Neural Network



MNIST



Neural Network

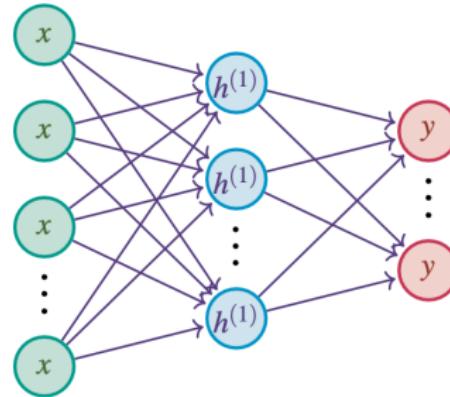
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$$y_k = \sigma \left(\sum_{j=0}^m w_{kj} x_j \right)$$



Neural Network Training

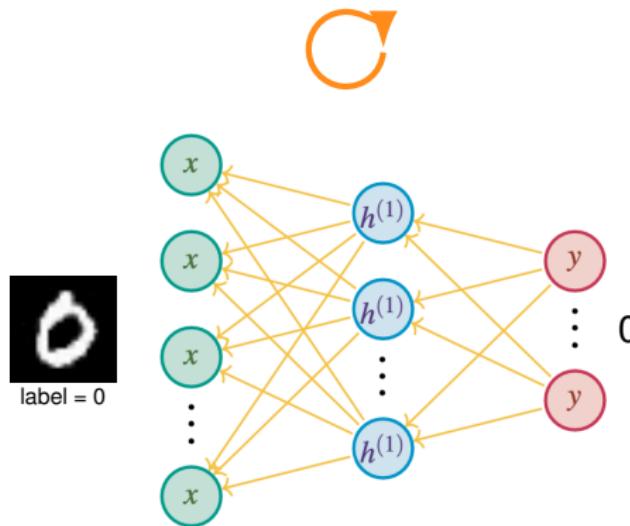
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Learning Algorithm

Algorithm 1 Mini Batch Gradient Descent with learning rate η and the Mean Squared Error (MSE) cost function

Require: initial weights $w^{(0)}$, number of epochs E , batch size B , training data with T entries

Ensure: final weights $w^{(E*T)}$

```
for  $e = 0 \rightarrow E - 1$  do
    for  $b = 0 \rightarrow T/B$  do
        for  $t = b * B \rightarrow (b + 1) * B$  do
            estimate  $\nabla \mathcal{L}(w^{(t)})$ 
            compute  $\Delta w^{(b)} += -\nabla \mathcal{L}(w^{(t)})$ 
        end for
         $w^{(e+1)} := w^{(e)} + \eta \Delta w^{(e)}$ 
    end for
end for
return  $w^{(T)}$ 
```

▷ \mathcal{L} here is MSE



Neural Network Inference

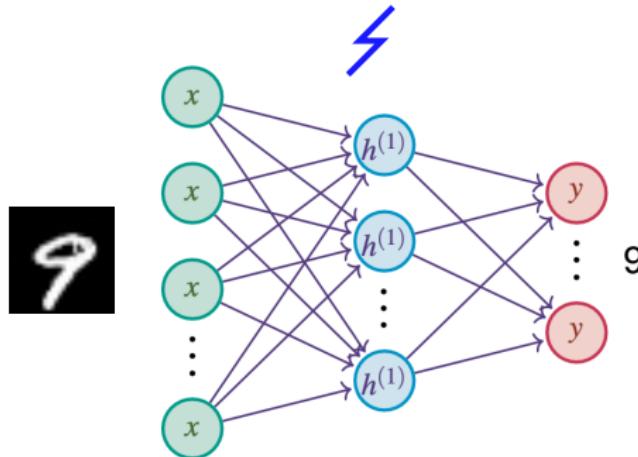
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Traditional Paradigm

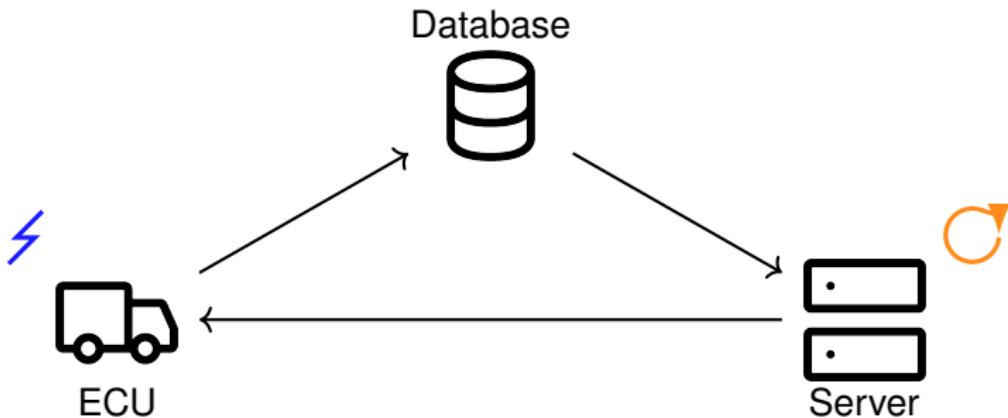
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Federated Learning

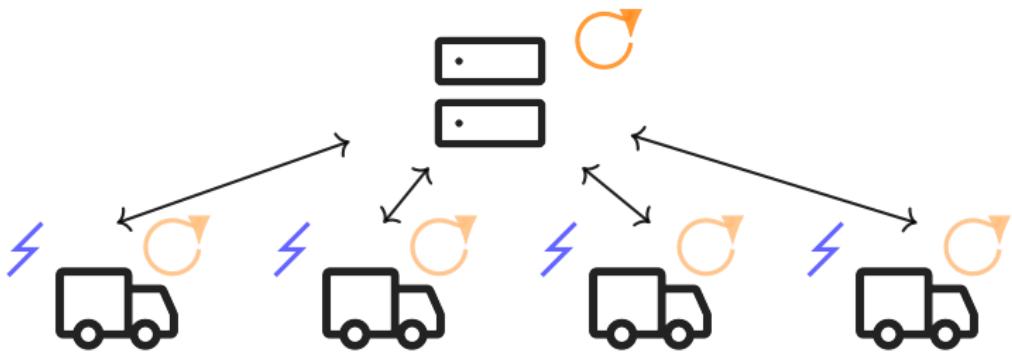
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HDR-NN Implementations

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github.com/paperbound/hdrnn-arm

- C based HDR-NN
- C++ / Eigen
- C++ / libtorch (PyTorch)
- Python / Numpy



C based HDR-NN

```
/*-HDR-Neural-Network*/
typedef struct
{
    float *bias;
    float *weights;
    float *nabla_w;
} Neuron;

typedef struct LayerT
{
    int size;
    int incidents;
    Neuron *neurons;
    float *activations;
    float *z_values;
    float *nabla_b;
    struct LayerT *next;
    struct LayerT *previous;
} Layer; // Network.layers except for input

typedef struct
{
    Layer *layers;
    int depth;
} Network; // HDRNN
```

```
static void feed_forward(Network *network, float *image)
{
    // First layer is the image
    float *activations = image;

    Layer *layer = network->layers;
    while (layer != NULL)
    {
        for (int i = 0; i < layer->size; i++)
        {
            Neuron *neuron = &layer->neurons[i];
            float zvalue = 0;
            for (int j = 0; j < layer->incidents; j++)
            {
                zvalue += neuron->weights[j] * activations[j];
            }
            layer->z_values[i] = zvalue + neuron->bias;
            layer->activations[i] = sigmoid(layer->z_values[i]);
        }
        activations = layer->activations;
        layer = layer->next;
    }
}
```



C++ / Eigen based HDR-NN

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- Eigen is a C++ template library for linear algebra
- Analogous to Python / Numpy



C++ / libtorch based HDR-NN

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- PyTorch doesn't support MCIMX6Q
- Porting libtorch using QEMU



HDR-NN configurability

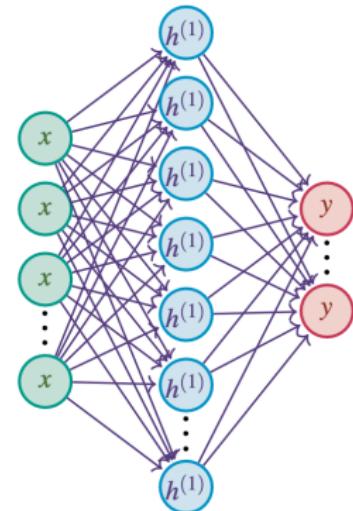
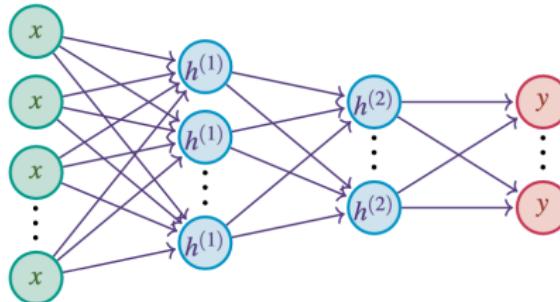
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HDR-NN configurability

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```
→ ./bin/hdrnn
nothing to do
Usage: ./bin/hdrnn

      <command> [<args>]

Commands:
  infer [-i, --image IMAGE_PATH] [-n, --net c-math.nn]
  train [-s, --shape 32] [-e, --epochs 30]
        [-q, --quiet] [-bs, --batch_size=10]
        [-lr, --learning_rate 3] [-n, --net c-math.nn]
```



Experiment Considerations

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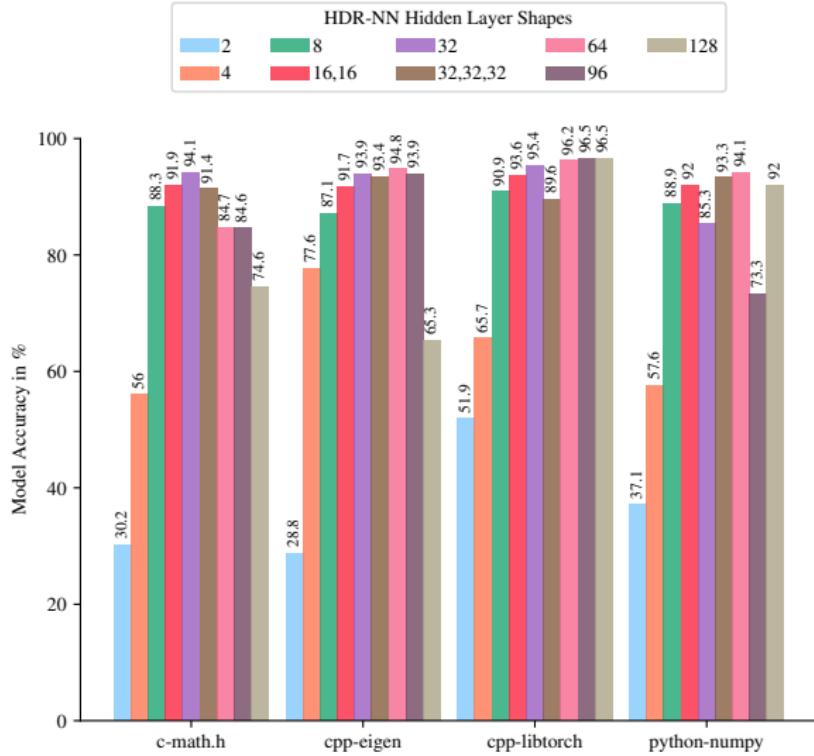
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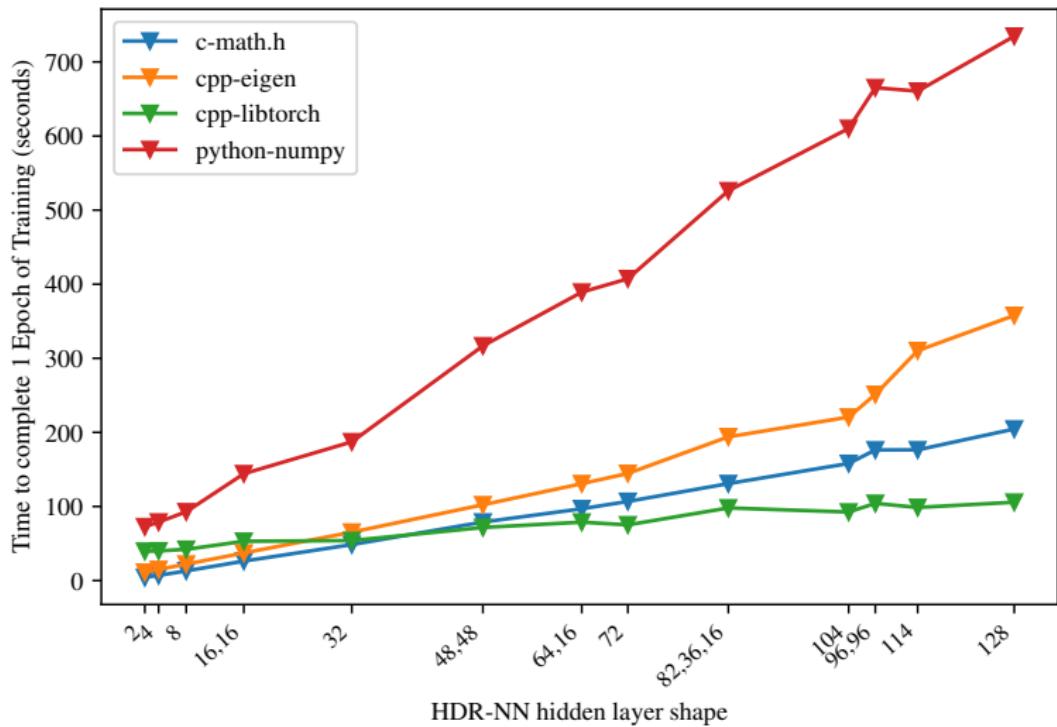
- Try multiple shapes
- Vary learning algorithm parameters
- Compare Accuracies
- Compare Execution Time



Accuracy



Training Time





Reverse Engineering Scania ECU

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Discussion

- Goal : Get a vanilla U-Boot running on ECU
- Extract device tree information
- Silent bootloader, No visibility into Board/SoM fork



Neural Network Software Development on Embedded Devices

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Discussion

- Embedded Platforms are fragmented in both *hardware* and *software*
- C is easier to target harder to Implement
- Python commonly found in Neural Network Research, harder to port



Future Work

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Discussion

- Reverse Engineering Efforts on the ECU
- Performance engineering the C based implementation
- Adding more target devices
- Adding more implementations (TTE)



End

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Thank you