

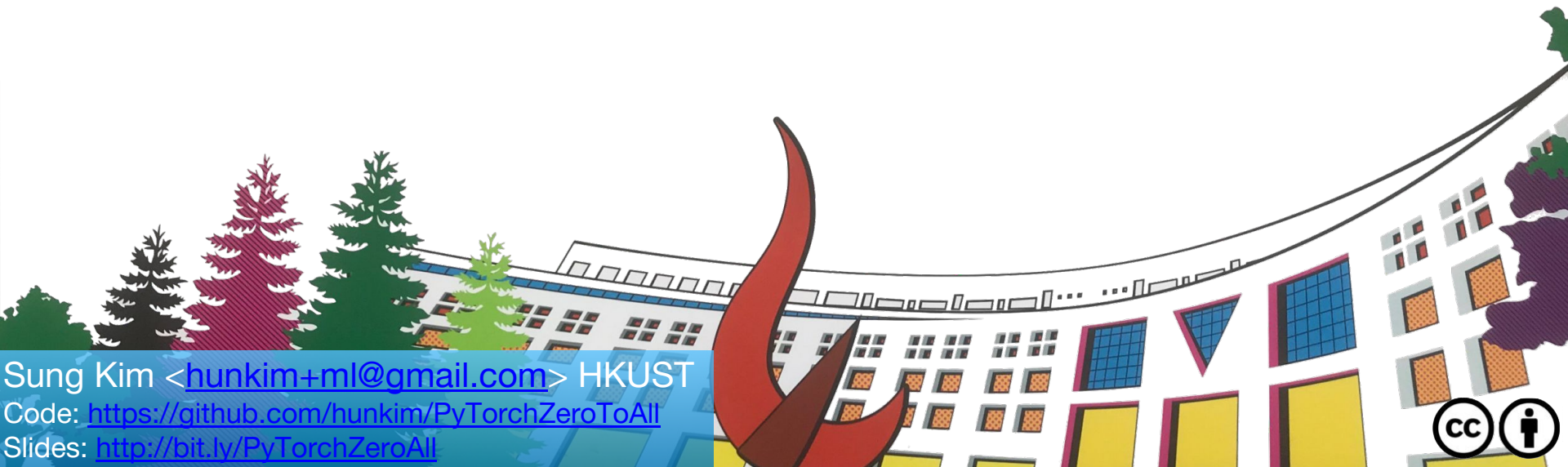
# ML/DL for Everyone with PYTORCH

## Lecture 11: RNN

Sung Kim <[hunkim+ml@gmail.com](mailto:hunkim+ml@gmail.com)> HKUST

Code: <https://github.com/hunkim/PyTorchZeroToAll>

Slides: <http://bit.ly/PyTorchZeroAll>



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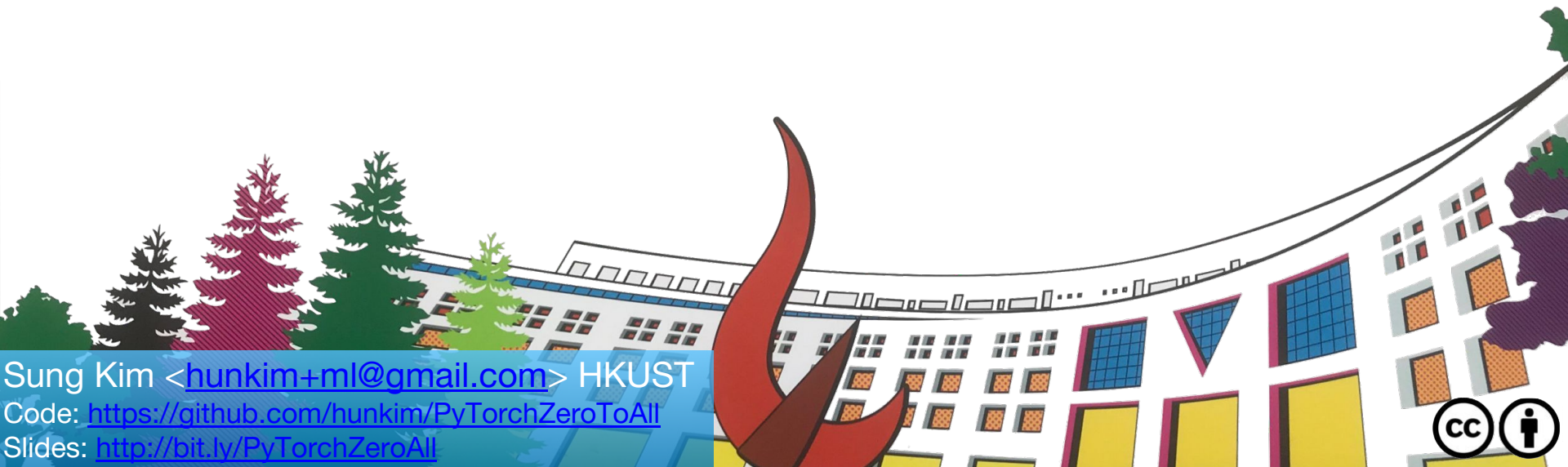
# ML/DL for Everyone with PYTORCH

## Lecture 11: RNN

Sung Kim <[hunkim+ml@gmail.com](mailto:hunkim+ml@gmail.com)> HKUST

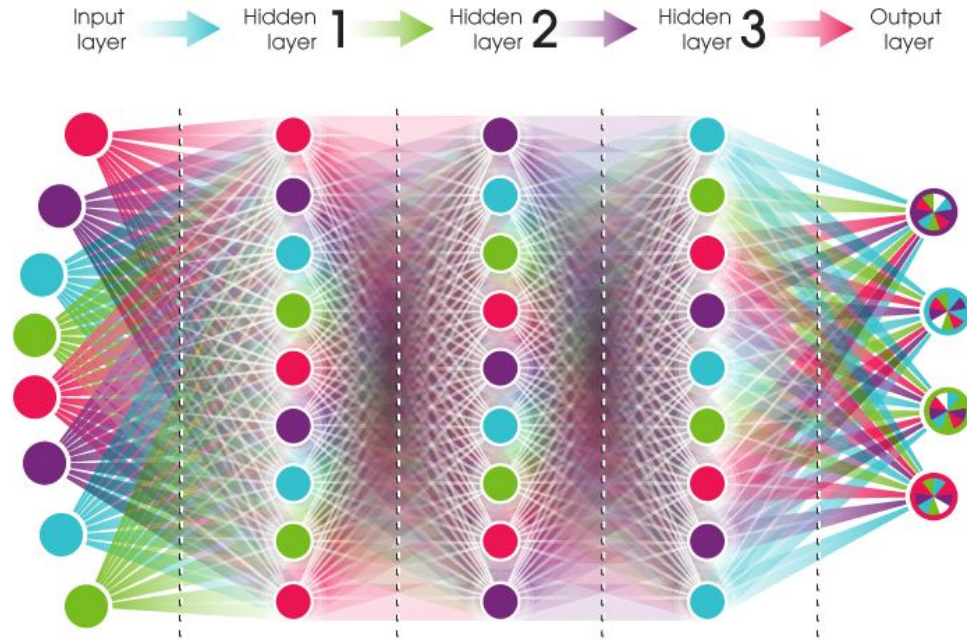
Code: <https://github.com/hunkim/PyTorchZeroToAll>

Slides: <http://bit.ly/PyTorchZeroAll>



# DNN, CNN, RNN

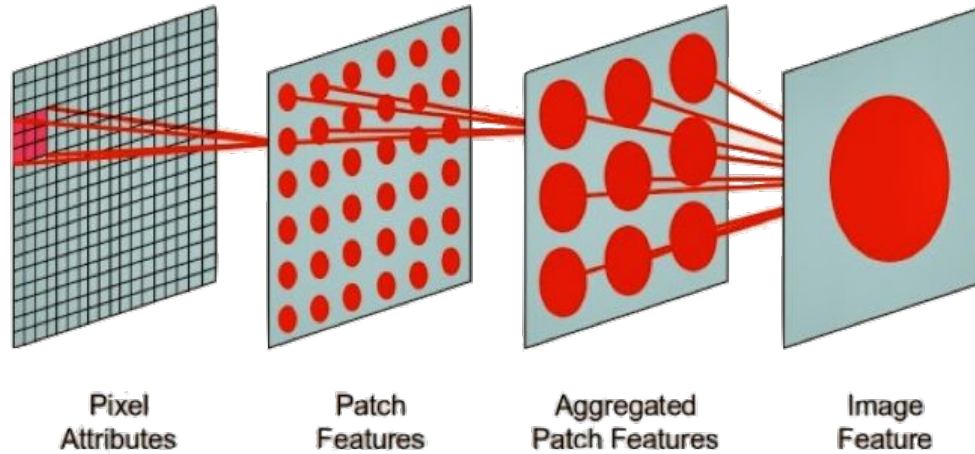
## DEEP NEURAL NETWORK



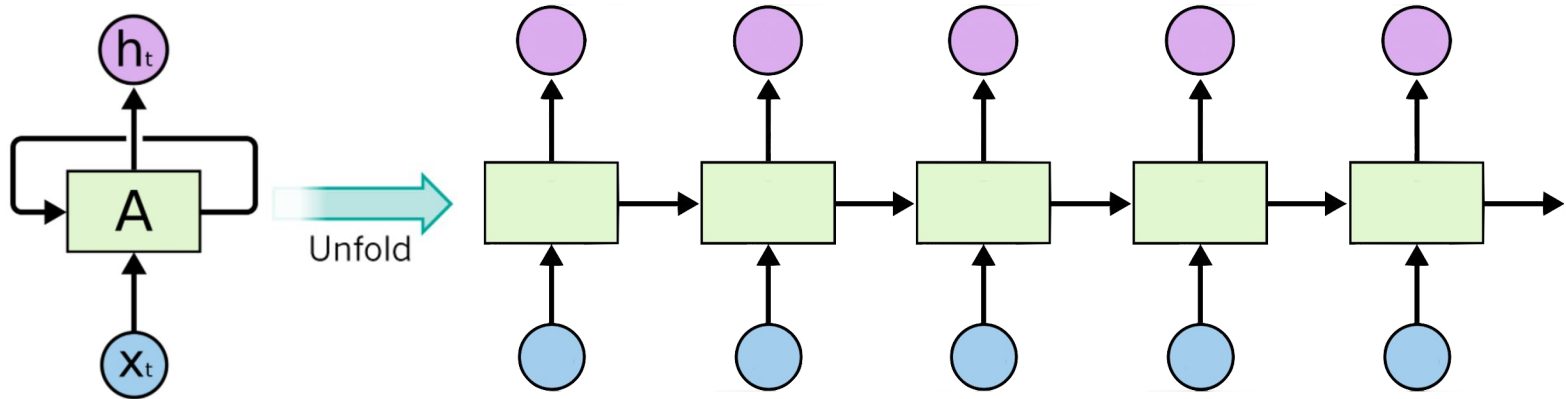
neuralnetworksanddeeplearning.com - Michael Nielsen, Yoshua Bengio, Ian Goodfellow, and Aaron Courville, 2016.

<https://blog.ttro.com/artificial-intelligence-will-shape-e-learning-for-good/>

# DNN, CNN, RNN

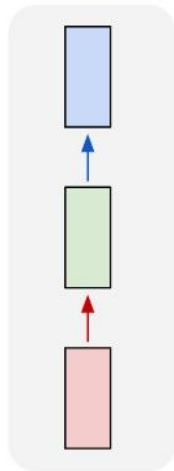


# DNN, CNN, RNN

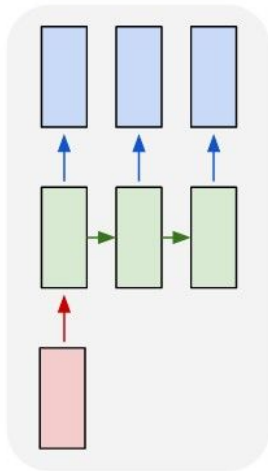


# RNN Applications

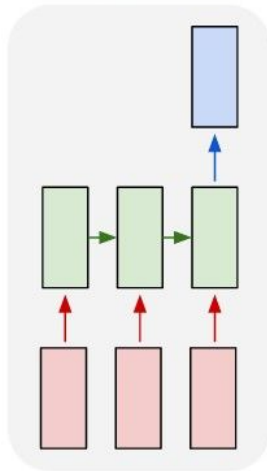
one to one



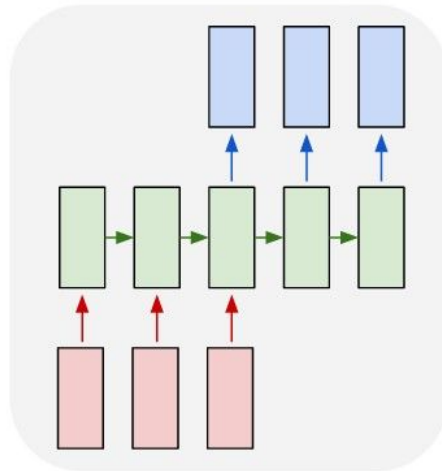
one to many



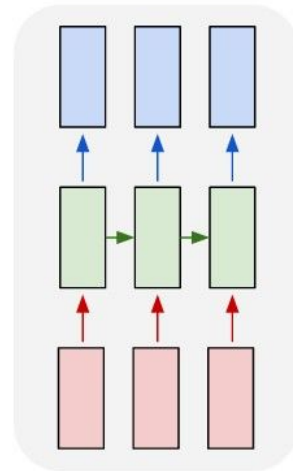
many to one



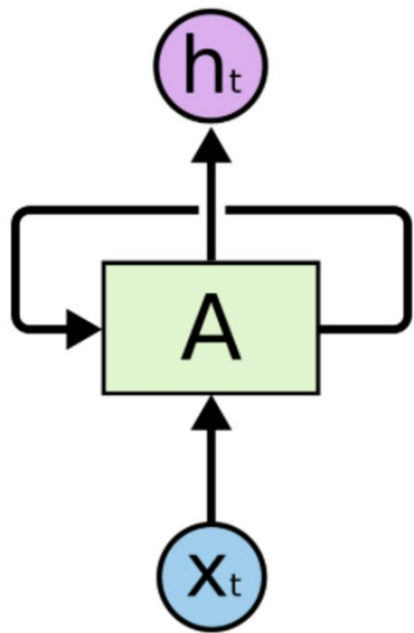
many to many



many to many



# RNN in PyTorch



```
cell = nn.LSTM(input_size=4, hidden_size=2, batch_first=True)
```

```
...
```

```
inputs = ... # (batch, seq_len, input_size) with batch_first=True
```

```
hidden = (... , ...) # (num_layers * num_directions, batch, hidden_size)
```

```
...
```

```
out, hidden = cell(inputs, hidden)
```



# One hot encoding for letters, h, e, l, l, o

```
# One hot encoding
```

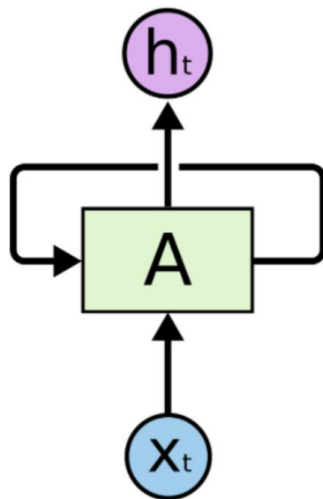
```
h = [1, 0, 0, 0]
```

```
e = [0, 1, 0, 0]
```

```
l = [0, 0, 1, 0]
```

```
o = [0, 0, 0, 1]
```

One node: 4 (*input-dim*) in 2 (*hidden\_size*)



# One hot encoding

$h = [1, 0, 0, 0]$

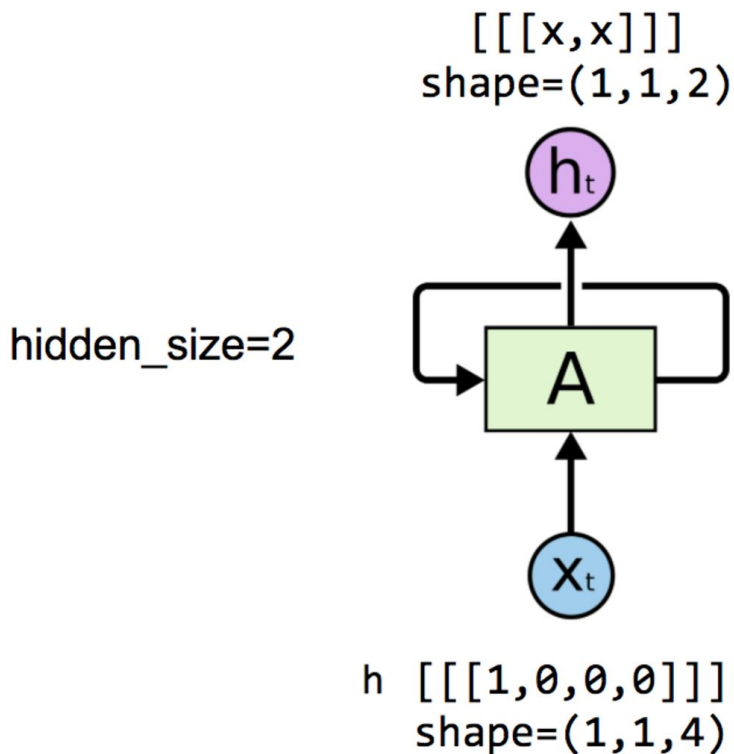
$e = [0, 1, 0, 0]$

$l = [0, 0, 1, 0]$

$o = [0, 0, 0, 1]$

$h$   $[[[1, 0, 0, 0]]]$   
 $\text{shape}=(1, 1, 4)$

One node: 4 (*input-dim*) in 2 (*hidden\_size*)



# One hot encoding  
 $h = [1, 0, 0, 0]$   
 $e = [0, 1, 0, 0]$   
 $l = [0, 0, 1, 0]$   
 $o = [0, 0, 0, 1]$

# One node: 4 (*input\_dim*) in 2 (*hidden\_size*)

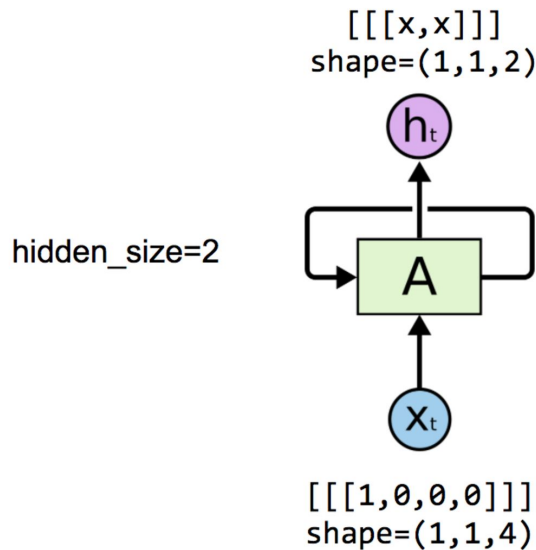
```
# One cell RNN input_dim (4) -> output_dim (2)
cell = nn.LSTM(input_size=4, hidden_size=2, batch_first=True)

# One Letter input
inputs = autograd.Variable(torch.Tensor([[h]])) # rank = (1, 1, 4)

# initialize the hidden state.
# (num_layers * num_directions, batch, hidden_size)
hidden = (autograd.Variable(torch.randn(1, 1, 2)),
          autograd.Variable(torch.randn((1, 1, 2))))

# Feed to one element at a time.
# after each step, hidden contains the hidden state.
out, hidden = cell(inputs, hidden)
print("out", out.data)
```

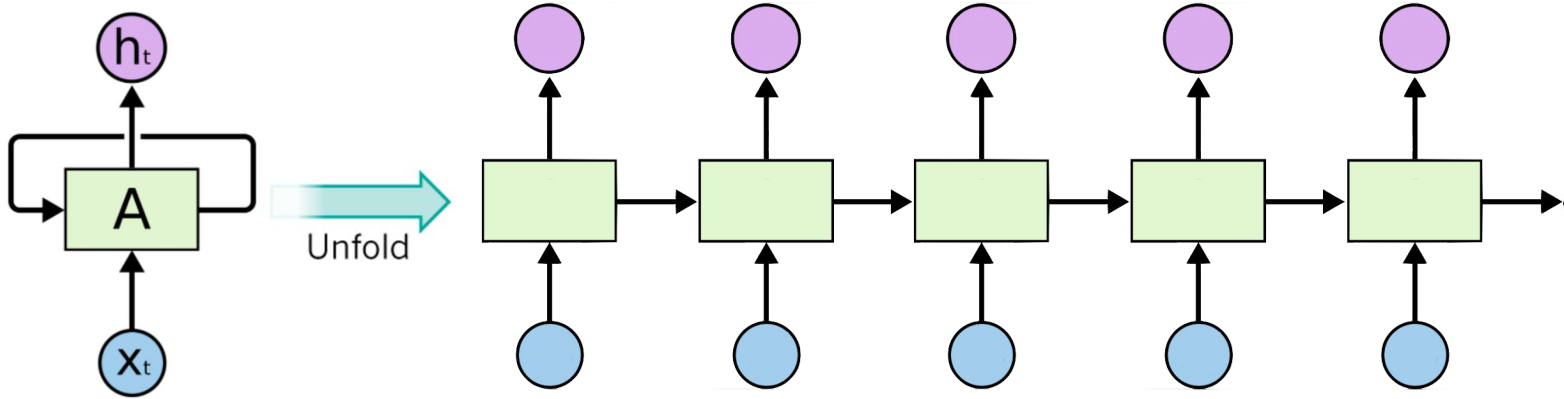
```
-0.1243  0.0738
[torch.FloatTensor of size 1x1x2]
```



# Unfolding to n sequences

hidden\_size=2  
seq\_len=5

shape=(1,5,2):  $[[[x,x], [x,x], [x,x], [x,x], [x,x]]]$



shape=(1,5,4):  $[[[1,0,0,0], [0,1,0,0], [0,0,1,0], [0,0,1,0], [0,0,0,1]]]$

h e l l o

# Unfolding to n sequences

```
# One cell RNN input_dim (4) -> output_dim (2). sequence: 5
cell = nn.LSTM(input_size=4, hidden_size=2, batch_first=True)
```

```
inputs = autograd.Variable(torch.Tensor([[h, e, l, l, o]]))
print("input size", inputs.size())
```

```
hidden = (autograd.Variable(torch.randn(1, 1, 2)), autograd.Variable(
    torch.randn((1, 1, 2)))) # clean out hidden state
```

```
out, hidden = cell(inputs, hidden)
print(out.data)
```

# One hot encoding

h = [1, 0, 0, 0]

e = [0, 1, 0, 0]

l = [0, 0, 1, 0]

o = [0, 0, 0, 1]

input size torch.Size([1, 5, 4])

(0 ,,,) =

-0.1825 0.0737

-0.1981 0.1164

-0.3367 0.2095

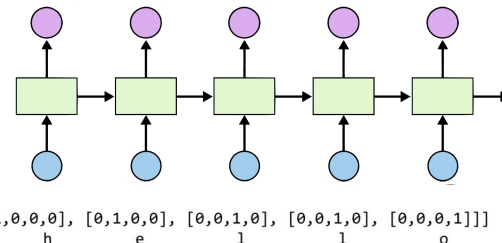
-0.3625 0.2503

-0.2038 0.3626

[torch.FloatTensor of size 1x5x2]

hidden\_size=2  
seq\_len=5

shape=(1,5,2): [[ [x,x], [x,x], [x,x], [x,x], [x,x] ]]

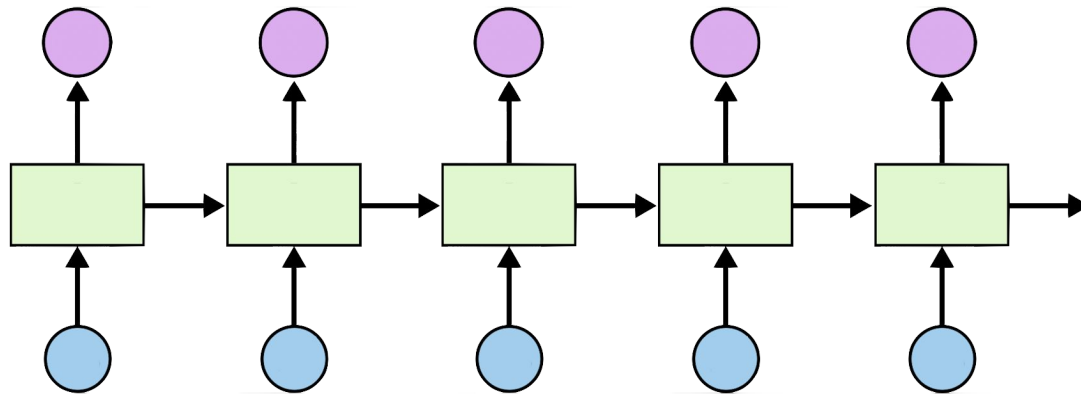


shape=(1,5,4): [[ [1,0,0,0], [0,1,0,0], [0,0,1,0], [0,0,1,0], [0,0,0,1] ]]

Hidden\_size=2  
sequence\_length=5  
batch\_size=3

# Batching input

shape=(3,5,2):  $\begin{bmatrix} [x,x] & [x,x] & [x,x] & [x,x] & [x,x] \\ [x,x] & [x,x] & [x,x] & [x,x] & [x,x] \\ [x,x] & [x,x] & [x,x] & [x,x] & [x,x] \end{bmatrix}$



shape=(3,5,4):  $\begin{bmatrix} [1,0,0,0] & [0,1,0,0] & [0,0,1,0] & [0,0,1,0] & [0,0,0,1] \\ [0,1,0,0] & [0,0,0,1] & [0,0,1,0] & [0,0,1,0] & [0,0,1,0] \\ [0,0,1,0] & [0,0,1,0] & [0,1,0,0] & [0,1,0,0] & [0,0,1,0] \end{bmatrix}$  # hello  
# eolll  
# lleeel

# Batching input

```
# One cell RNN input_dim (4) -> output_dim (2). sequence: 5, batch 3
# 3 batches 'hello', 'eolll', 'lleel'
```

```
# rank = (3, 5, 4)
```

```
inputs = autograd.Variable(torch.Tensor([[h, e, l, l, o],
                                          [e, o, l, l, l],
                                          [l, l, e, e, l]]))
```

```
print("input size", inputs.size()) # input size torch.Size([3, 5, 4])
```

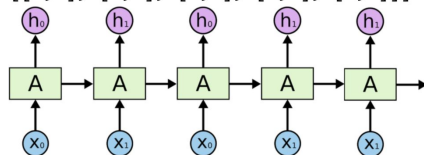
```
# (num_layers * num_directions, batch, hidden_size)
```

```
hidden = (autograd.Variable(torch.randn(1, 3, 2)), autograd.Variable(
    torch.randn((1, 3, 2))))
```

```
out, hidden = cell(inputs, hidden)
```

```
print("out size", out.size()) # out size torch.Size([3, 5, 2])
```

```
shape=(3,5,2): [[ [x,x], [x,x], [x,x], [x,x], [x,x]],
                 [[x,x], [x,x], [x,x], [x,x], [x,x]],
                 [[x,x], [x,x], [x,x], [x,x], [x,x]]]
```



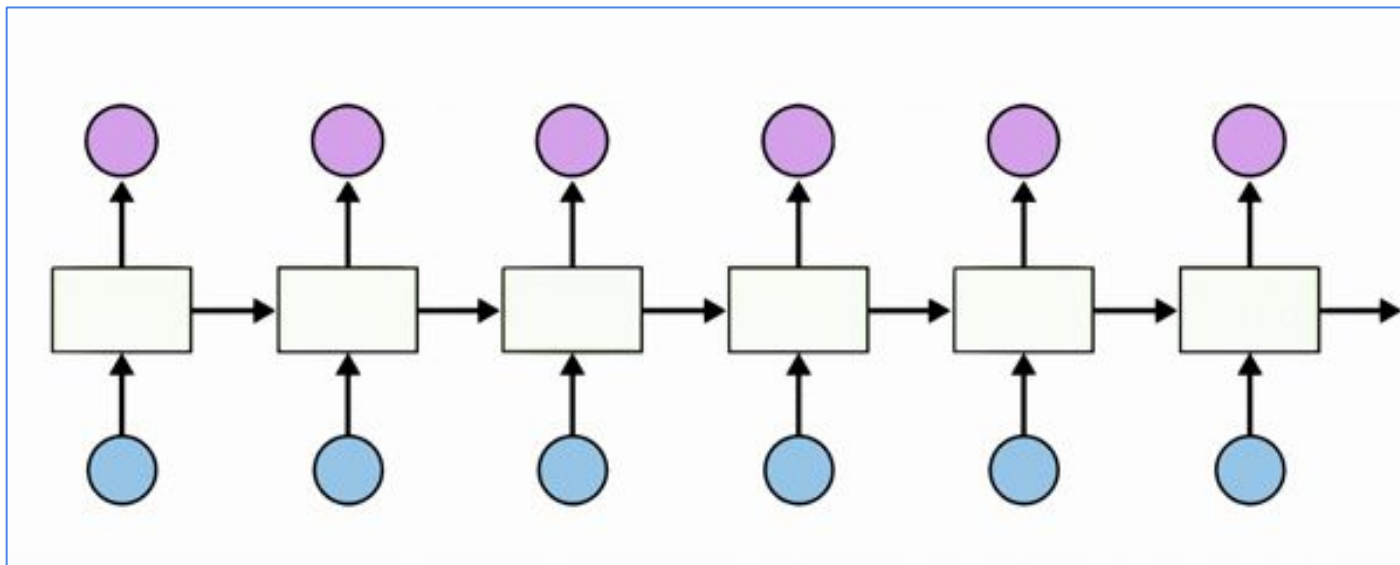
Hidden\_size=2  
sequence\_length=5  
batch\_size=3

```
shape=(3,5,4): [[[1,0,0,0], [0,1,0,0], [0,0,1,0], [0,0,1,0], [0,0,0,1]] # hello
                 [[0,1,0,0], [0,0,0,1], [0,0,1,0], [0,0,1,0], [0,0,1,0]] # eolll
                 [[0,0,1,0], [0,0,1,0], [0,1,0,0], [0,1,0,0], [0,0,1,0]] # lleel]
```



# Teach RNN 'hihell' to 'ihello'

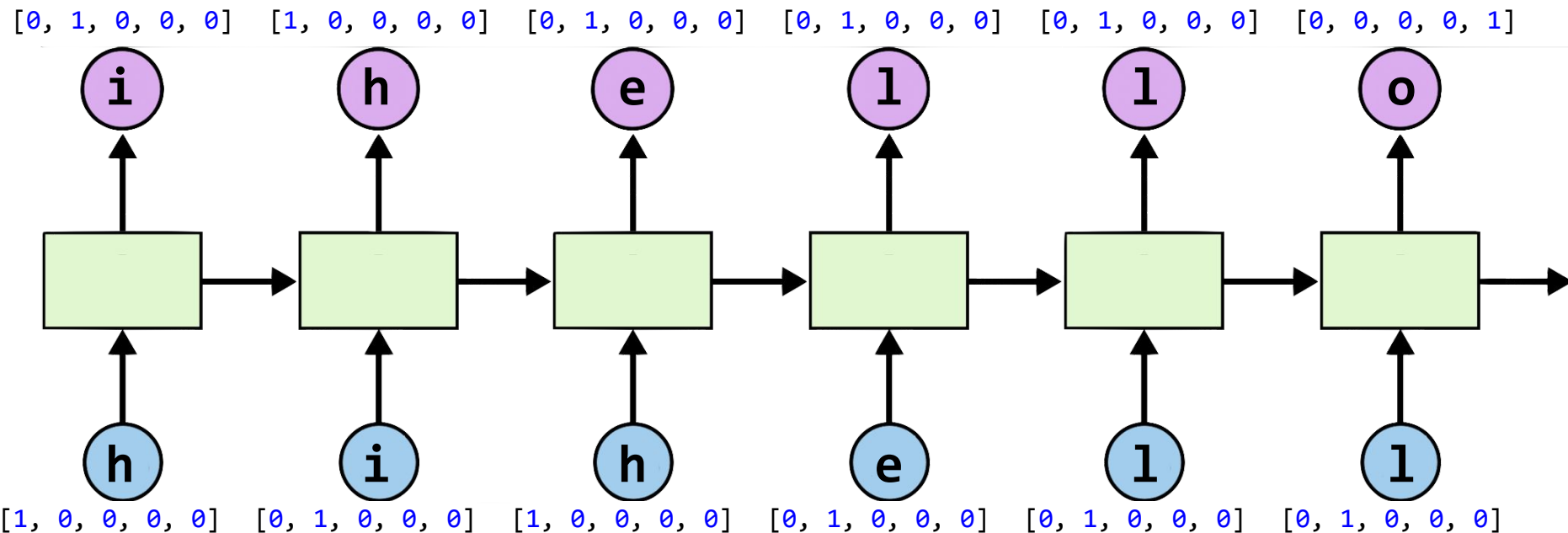
$[1, 0, 0, 0, 0]$ ,	# h 0
$[0, 1, 0, 0, 0]$ ,	# i 1
$[0, 0, 1, 0, 0]$ ,	# e 2
$[0, 0, 0, 1, 0]$ ,	# l 3
$[0, 0, 0, 0, 1]$ ,	# o 4



# Teach RNN 'hihell' to 'ihello'

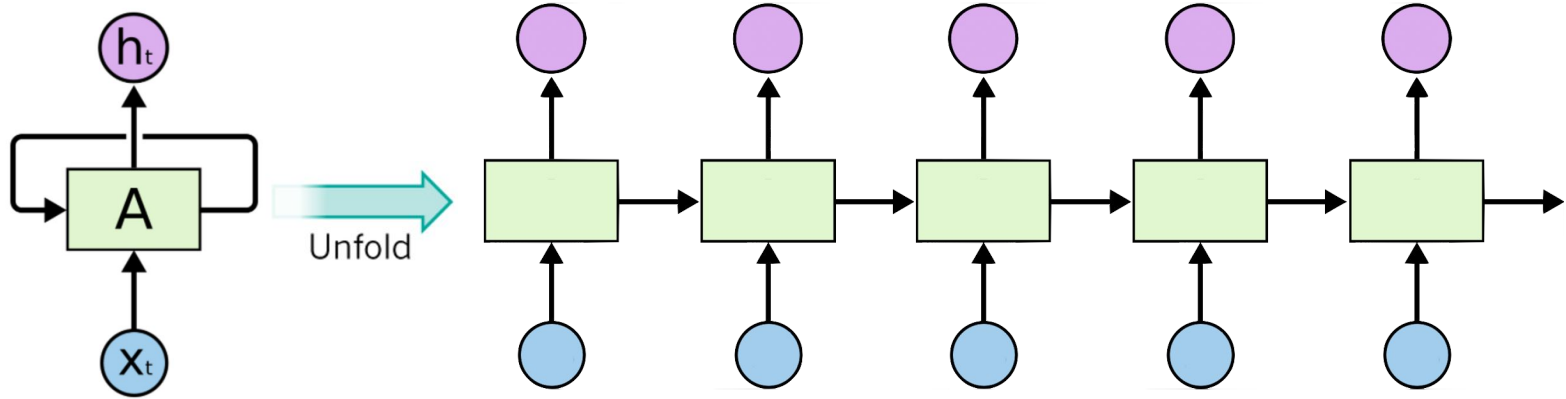
output\_dim = 5

[1, 0, 0, 0, 0],	# h 0
[0, 1, 0, 0, 0],	# i 1
[0, 0, 1, 0, 0],	# e 2
[0, 0, 0, 1, 0],	# l 3
[0, 0, 0, 0, 1],	# o 4



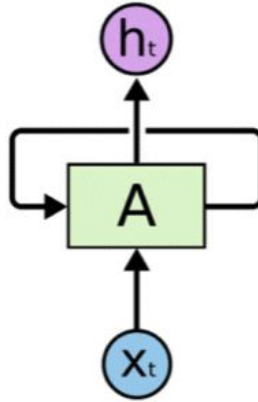
Input\_dim = 5

# Unfolding one to n sequences



# Teach RNN 'hihell' to 'ihello'

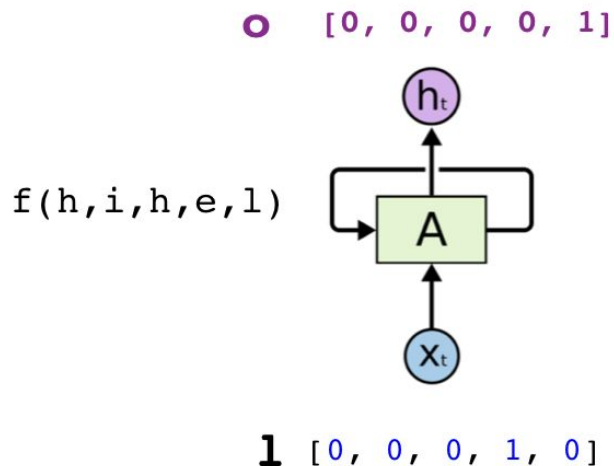
[1, 0, 0, 0, 0],	# h 0
[0, 1, 0, 0, 0],	# i 1
[0, 0, 1, 0, 0],	# e 2
[0, 0, 0, 1, 0],	# l 3
[0, 0, 0, 0, 1],	# o 4



# RNN input and output

[1, 0, 0, 0, 0],	# h 0
[0, 1, 0, 0, 0],	# i 1
[0, 0, 1, 0, 0],	# e 2
[0, 0, 0, 1, 0],	# l 3
[0, 0, 0, 0, 1],	# o 4

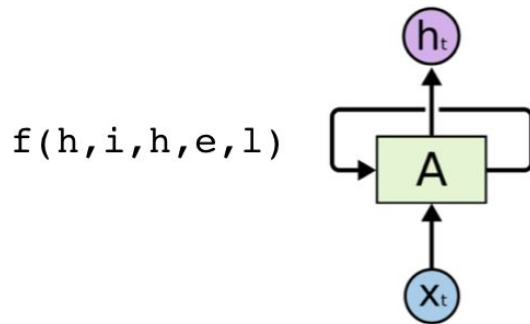
```
self.rnn = nn.RNN(input_size=5, hidden_size=5, batch_first=True)
```



# Designing Loss

Predict Y, one of five {h, i, e, l, o}

○ [0, 0, 0, 0, 1]



Some input: X **1** [0, 0, 0, 1, 0]

# Designing Loss

Predict Y, one of five {h, i, e, l, o}  $Y \in R^{N \times ?}$

○ [0, 0, 0, 0, 1]

$f(h, i, h, e, l)$

logSoftmax

Linear

NLLLoss

Some input: X **1** [0, 0, 0, 1, 0]

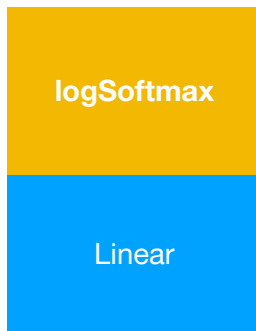
# Designing Loss

```
out = rnn_out.view(-1, 5)
```

Predict Y, one of five {h, i, e, l, o}  $Y \in \mathbb{R}^{N \times 5}$

○ [0, 0, 0, 0, 1]

$f(h, i, h, e, l)$



With  
NLLLoss

Some input: X **1** [0, 0, 0, 1, 0]



# (I) Data preparation



```
idx2char = ['h', 'i', 'e', 'l', 'o']
```

```
# Teach hihell -> ihello
```

```
x_data = [[0, 1, 0, 2, 3, 3]] # hihell
```

```
x_one_hot = [[[1, 0, 0, 0, 0], # h 0  
              [0, 1, 0, 0, 0], # i 1  
              [1, 0, 0, 0, 0], # h 0  
              [0, 0, 1, 0, 0], # e 2  
              [0, 0, 0, 1, 0], # l 3  
              [0, 0, 0, 1, 0]]] # l 3
```

```
y_data = [1, 0, 2, 3, 3, 4] # ihello
```

```
# As we have one batch of samples, we will change them to variables only once
```

```
inputs = Variable(torch.Tensor(x_one_hot))
```

```
labels = Variable(torch.LongTensor(y_data))
```

## (2) Parameters



```
num_classes = 5
input_size = 5 # one-hot size
hidden_size = 5 # output from the LSTM. 5 to directly predict one-hot
batch_size = 1 # one sentence
sequence_length = 6 # |ihello| == 6
num_layers = 1 # one-layer rnn
```

## (3) Our model

```
def __init__(self, num_classes, input_size, hidden_size, num_layers):
    super(RNN, self).__init__()

    self.num_classes = num_classes
    self.num_layers = num_layers
    self.input_size = input_size
    self.hidden_size = hidden_size
    self.sequence_length = sequence_length

    self.rnn = nn.RNN(input_size=5, hidden_size=5, batch_first=True)

def forward(self, x):
    # Initialize hidden and cell states
    h_0 = Variable(torch.zeros(
        x.size(0), self.num_layers, self.hidden_size))

    # Reshape input
    x.view(x.size(0), self.sequence_length, self.input_size)

    # Propagate input through RNN
    # Input: (batch, seq_len, input_size)
    # h_0: (batch, num_layers * num_directions, hidden_size)

    out, _ = self.rnn(x, h_0)
    print(out.size())
    return out.view(-1, num_classes)
```

$$Y \in R^{N \times 5}$$

```
num_classes = 5
input_size = 5 # one-hot size
hidden_size = 5 # output from the LSTM.
batch_size = 1 # one sentence
sequence_length = 6 # |ihello| == 6
num_layers = 1 # one-layer rnn
```

## (4) Loss & Training

```
# Instantiate RNN model
rnn = RNN(num_classes, input_size, hidden_size, num_layers)
print(rnn)

# Set loss and optimizer function
# CrossEntropyLoss = LogSoftmax + NLLLoss
criterion = torch.nn.CrossEntropyLoss()
optimizer = torch.optim.Adam(rnn.parameters(), lr=0.1)

# Train the model
for epoch in range(100):
    outputs = rnn(inputs)
    optimizer.zero_grad()
    loss = criterion(outputs, labels)
    loss.backward()
    optimizer.step()
    _, idx = outputs.max(1)
    idx = idx.data.numpy()
    result_str = [idx2char[c] for c in idx.squeeze()]
    print("epoch: %d, loss: %1.3f" % (epoch + 1, loss.data[0]))
    print("Predicted string: ", ''.join(result_str))

print("Learning finished!")
```

```
num_classes = 5
input_size = 5 # one-hot size
hidden_size = 5 # output from the LSTM.
batch_size = 1 # one sentence
sequence_length = 6 # |ihello| == 6
num_layers = 1 # one-layer rnn
```

```

# Instantiate RNN model
rnn = RNN(num_classes, input_size, hidden_size, num_layers)
print(rnn)

# Set loss and optimizer function
# CrossEntropyLoss = LogSoftmax + NLLLoss
criterion = torch.nn.CrossEntropyLoss()
optimizer = torch.optim.Adam(rnn.parameters(), lr=0.1)

# Train the model
for epoch in range(100):
    outputs = rnn(inputs)
    optimizer.zero_grad()
    loss = criterion(outputs, labels)
    loss.backward()
    optimizer.step()
    _, idx = outputs.max(1)
    idx = idx.data.numpy()
    result_str = [idx2char[c] for c in idx.squeeze()]
    print("epoch: %d, loss: %1.3f" % (epoch + 1, loss.data[0]))
    print("Predicted string: ", ''.join(result_str))

print("Learning finished!")

```

(5)



the results

```

epoch: 1, loss: 1.673
Predicted string: ehehee
epoch: 2, loss: 1.403
Predicted string: ehehel
epoch: 3, loss: 1.240
Predicted string: ehelll
...
epoch: 95, loss: 0.458
Predicted string: ihello
epoch: 96, loss: 0.458
Predicted string: ihello
epoch: 97, loss: 0.458
Predicted string: ihello
epoch: 98, loss: 0.458
Predicted string: ihello
epoch: 99, loss: 0.458
Predicted string: ihello
epoch: 100, loss: 0.458
Predicted string: ihello

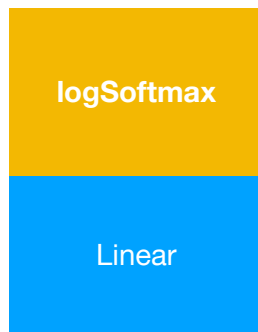
```

# Exercise 11-1:

## Implement softmax classifier for 'hihell' to 'ihello'

Predict Y, one of five {h, i, e, l, o}  $Y \in R^{N \times 5}$

○ [0, 0, 0, 0, 1]

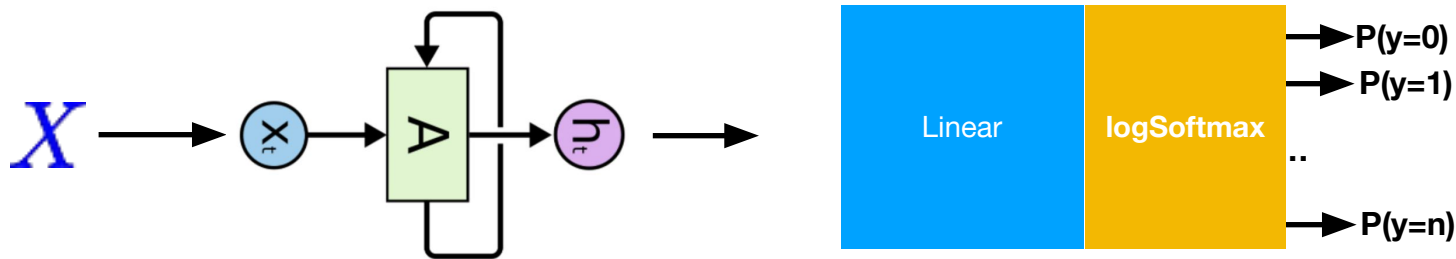


With  
NLLLoss

Some input: X **1** [0, 0, 0, 1, 0]

*Why does it not work?*

## Exercise 11-2: Combine RNN+Linear

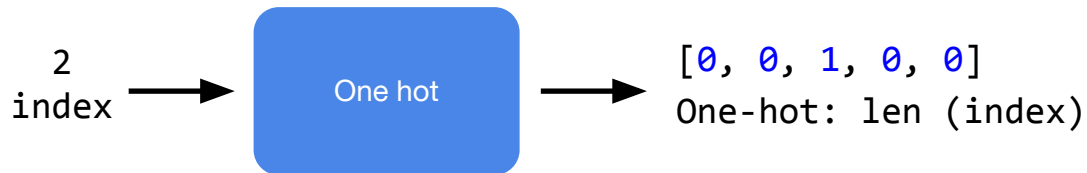


NLLLoss

With NLLLoss

*Why does it train faster (more stable)?*

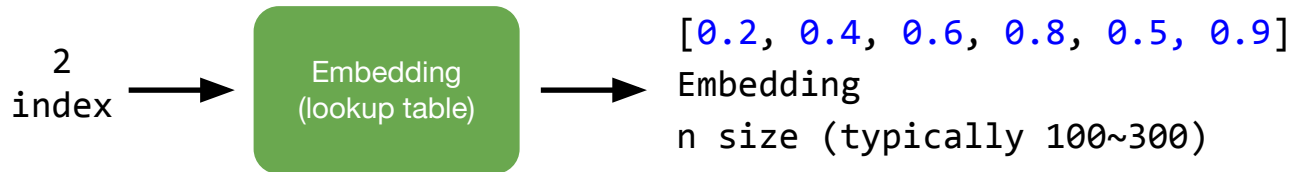
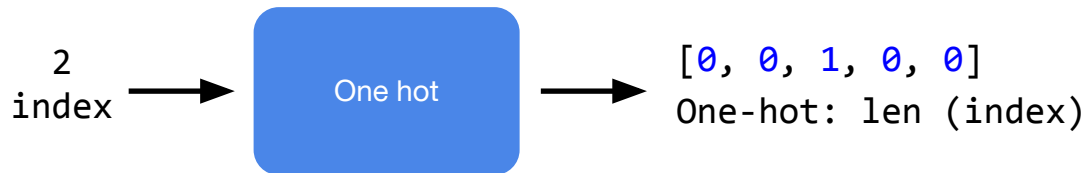
# One hot VS embedding



```
x_one_hot = [[[1, 0, 0, 0, 0], # h 0  
              [0, 1, 0, 0, 0], # i 1  
              [1, 0, 0, 0, 0], # h 0  
              [0, 0, 1, 0, 0], # e 2  
              [0, 0, 0, 1, 0], # l 3  
              [0, 0, 0, 1, 0]]] # l 3
```

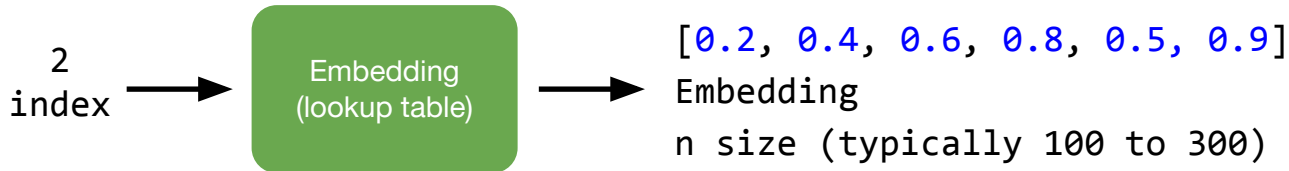


# One hot VS embedding

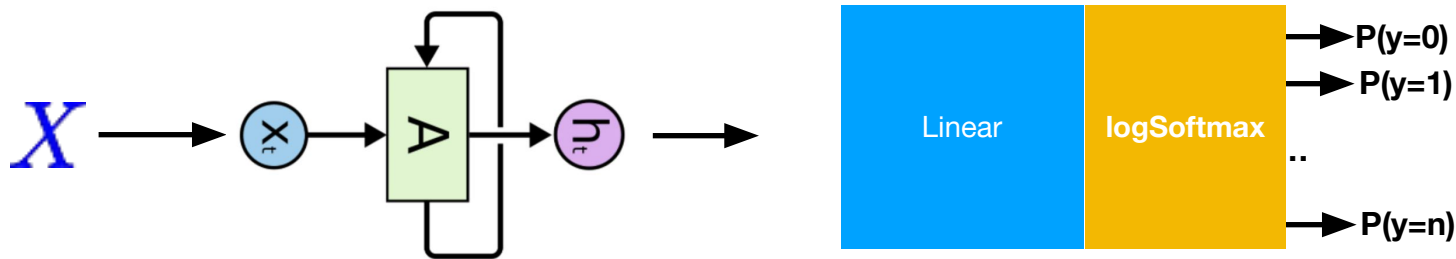


# One hot VS embedding

```
self.embeddings = nn.Embedding(vocab_size, output_size)
...
emb = self.embeddings(x)
```



## Exercise 11-3: Combine RNN+Linear using embedding



NLLLoss

**With NLLLoss**

*Why does it train faster (more stable)?*

## Exercise 11-4: Teach RNN a long sequence

```
sentence = ("if you want to build a ship, don't drum up people together to "  
            "collect wood and don't assign them tasks and work, but rather "  
            "teach them to long for the endless immensity of the sea.")
```

# Under the hood: RNN

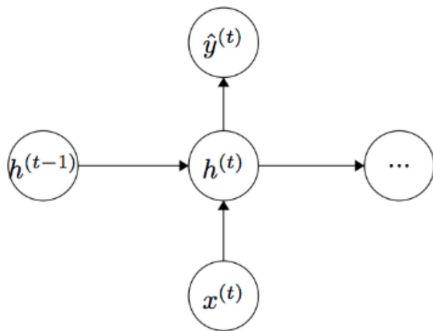


Figure 3: The inputs and outputs to a neuron of a RNN

# Under the hood: RNN

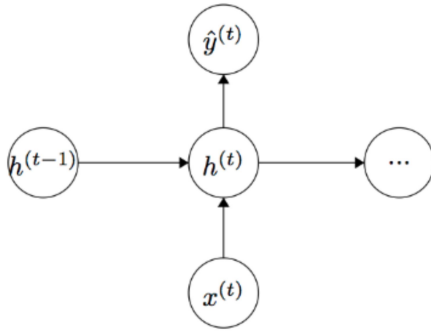


Figure 3: The inputs and outputs to a neuron of a RNN

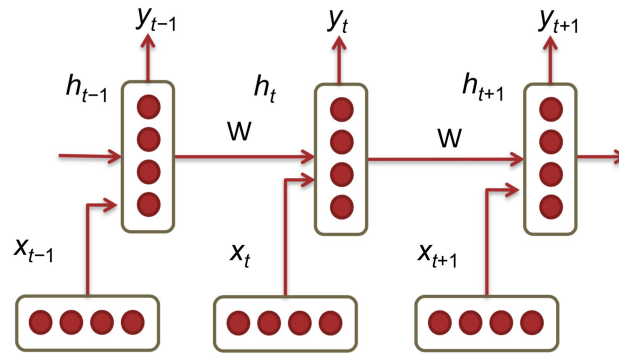


Figure 2: A Recurrent Neural Network (RNN). Three time-steps are shown.

# Under the hood: RNN

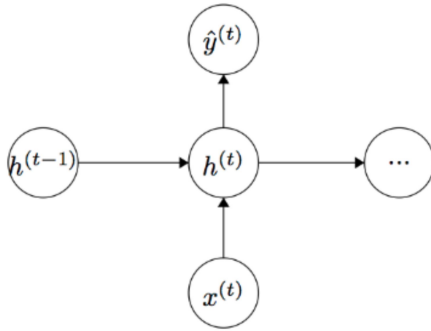


Figure 3: The inputs and outputs to a neuron of a RNN

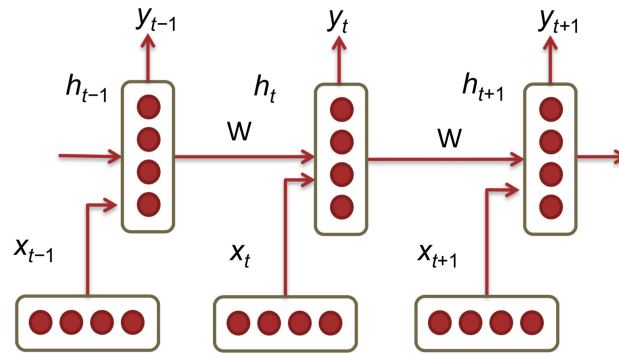
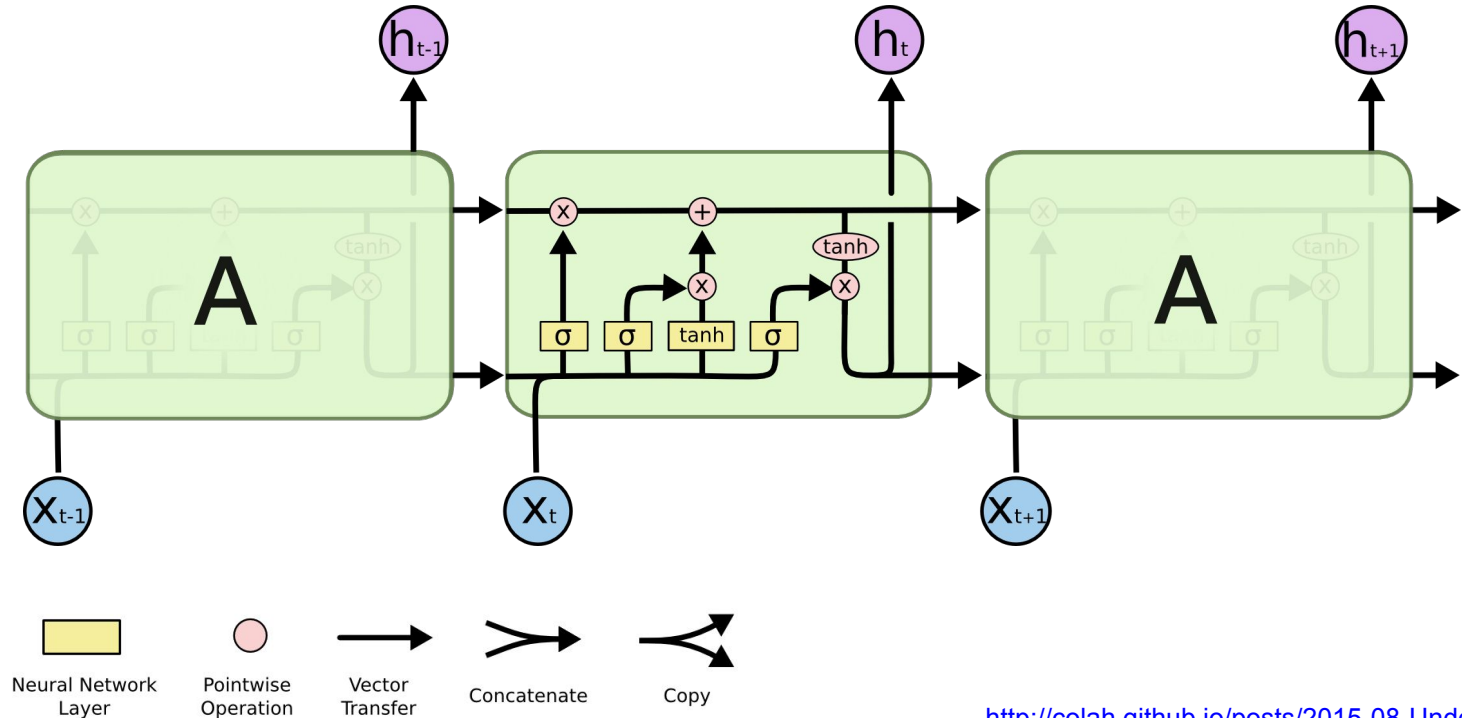


Figure 2: A Recurrent Neural Network (RNN). Three time-steps are shown.

$$h_t = Wf(h_{t-1}) + W^{(hx)}x_t$$

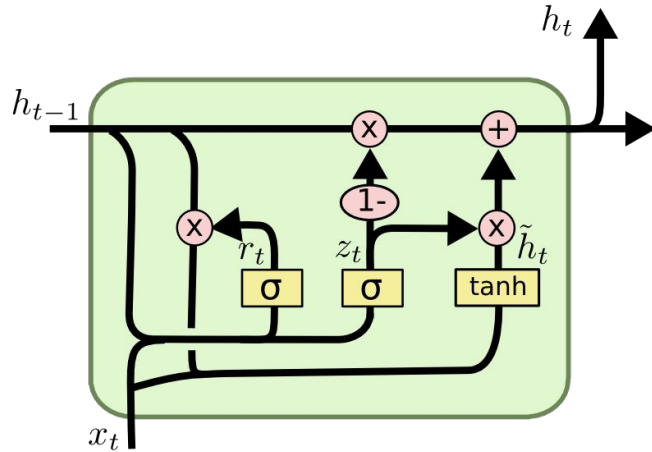
$$\hat{y} = W^{(S)}f(h_t)$$

# Under the hood: LSTM





# Under the hood: LSTM

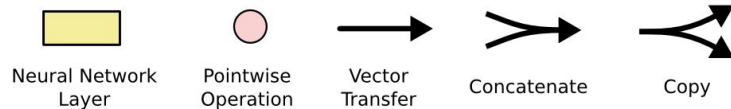


$$z_t = \sigma(W_z \cdot [h_{t-1}, x_t])$$

$$r_t = \sigma(W_r \cdot [h_{t-1}, x_t])$$

$$\tilde{h}_t = \tanh(W \cdot [r_t * h_{t-1}, x_t])$$

$$h_t = (1 - z_t) * h_{t-1} + z_t * \tilde{h}_t$$



# Exercise 11-5: Implement RNN

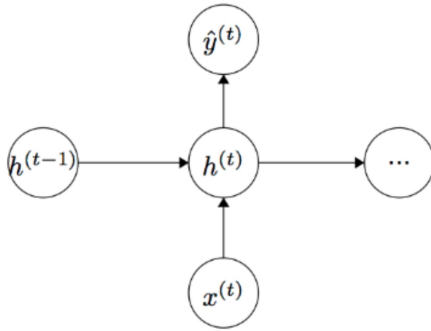


Figure 3: The inputs and outputs to a neuron of a RNN

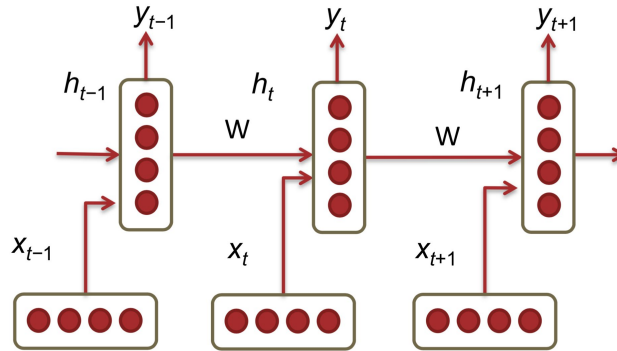


Figure 2: A Recurrent Neural Network (RNN). Three time-steps are shown.

$$h_t = Wf(h_{t-1}) + W^{(hx)}x_t$$

$$\hat{y} = W^{(S)}f(h_t)$$

**Hint:** [http://blog.varunajayasiri.com/numpy\\_lstm.html](http://blog.varunajayasiri.com/numpy_lstm.html)

# Exercise 11-5: Implement RNN

```
class RNN(nn.Module):
    def __init__(self, input_size, hidden_size):
        super(RNN, self).__init__()

        self.input_size = input_size
        self.hidden_size = hidden_size

        ...

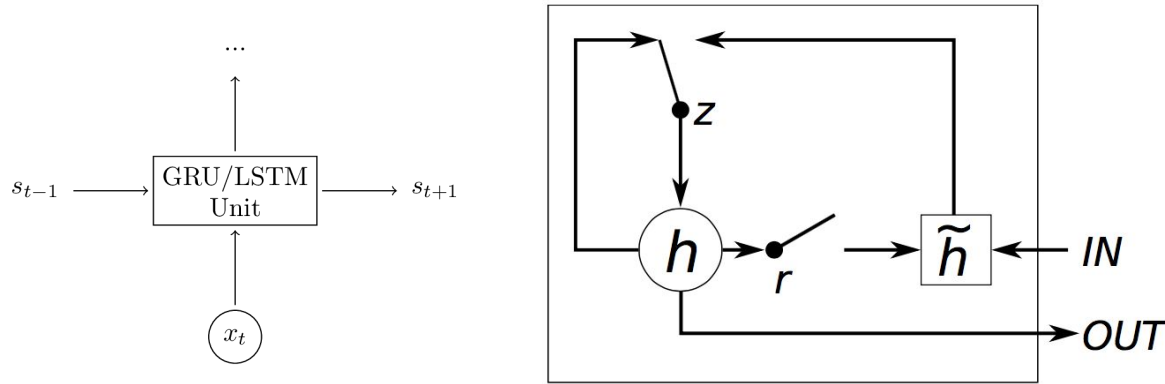
    def forward(self, input, hidden):
        hidden = ...
        output = ...
        return output, hidden
```

```
rnn = RNN(...)
```

$$h_t = Wf(h_{t-1}) + W^{(hx)}x_t$$

$$\hat{y} = W^{(S)}f(h_t)$$

# Exercise 11-6: Implement GRU



$$\begin{aligned}z &= \sigma(x_t U^z + s_{t-1} W^z) \\r &= \sigma(x_t U^r + s_{t-1} W^r) \\h &= \tanh(x_t U^h + (s_{t-1} \circ r) W^h) \\s_t &= (1 - z) \circ h + z \circ s_{t-1}\end{aligned}$$

- [http://blog.varunajayasiri.com/numpy\\_lstm.html](http://blog.varunajayasiri.com/numpy_lstm.html)
- <http://www.wildml.com/2015/10/recurrent-neural-network-tutorial-part-4-implementing-a-grulstm-rnn-with-python-and-theano/>

**WHAT  
NEXT?**



## Lecture 12: Seq2Seq