Lecture 12:

Long Short-Term Memory Networks (LSTMs) – Part II

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University California, Berkeley

Machine Learning Algorithms

MSSE 277B, 3 Units

Course Map

Lecture 1: Course Overview and Introduction to Machine Learning

Lecture 2: Bayesian Methods in Machine Learning

classic ML tools & algorithms

Lecture 3: Dimensionality Reduction: Principal Component Analysis

Lecture 4: Linear and Non-linear Regression and Classification

Lecture 5: Unsupervised Learning: K-Means, GMM, Trees

Lecture 6: Adaptive Learning and Gradient Descent Optimization Algorithms

Lecture 7: Introduction to Artificial Neural Networks - The Perceptron

ANNs/AI/Deep Learning

Lecture 8: Introduction to Artificial Neural Networks - Building Multiple Dense Layers

Lecture 9: Convolutional Neural Networks (CNNs) - Part I

Lecture 10: CNNs - Part II

Lecture 11: Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTMs)

Lecture 12: Combining LSTMs and CNNs

Lecture 13: Running Models on GPUs and Parallel Processing

Lecture 14: Project Presentations

Lecture 15: Transformer

Lecture 16: GNN

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Outline

- LSTM for Classification
- Bidirectional LSTMs
- Stacked LSTMs
- LSTM + CNN

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Outline

- **LSTM for Classification**
- Bidirectional LSTMs
- Stacked LSTMs
- LSTM + CNN

LSTM II: LSTM for Classification

minimal model:

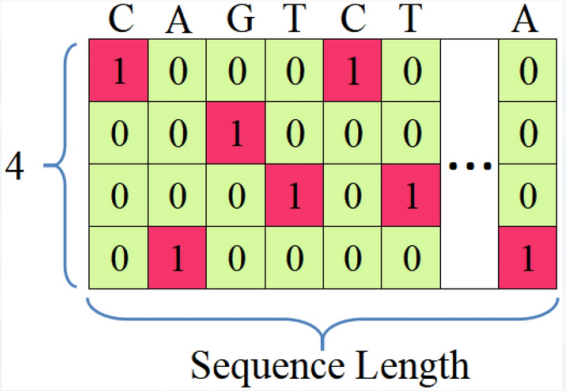
```
[N_samples, LengthSeq, N_features] = X.shape
[N_samples,            N_classes ] = Y.shape


model = Sequential()

model.add(LSTM(n_neurons, activation = 'tanh',\
                          input_shape = (LengthSeq , N_features)))

model.add(Dense(N_classes, activation = 'softmax'))

opt = optimizers.Adam()
model.compile(loss = 'categorical_crossentropy', optimizer = opt,\
                         metrics = ['accuracy'])

model.summary()
```

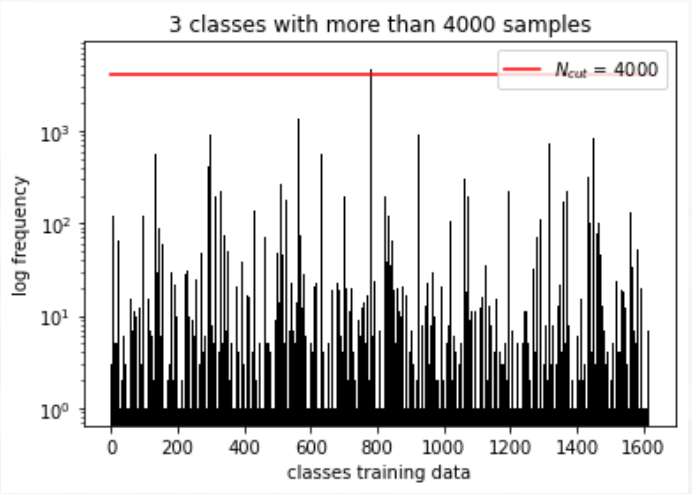
Y is one-hot encoded

LSTM II:

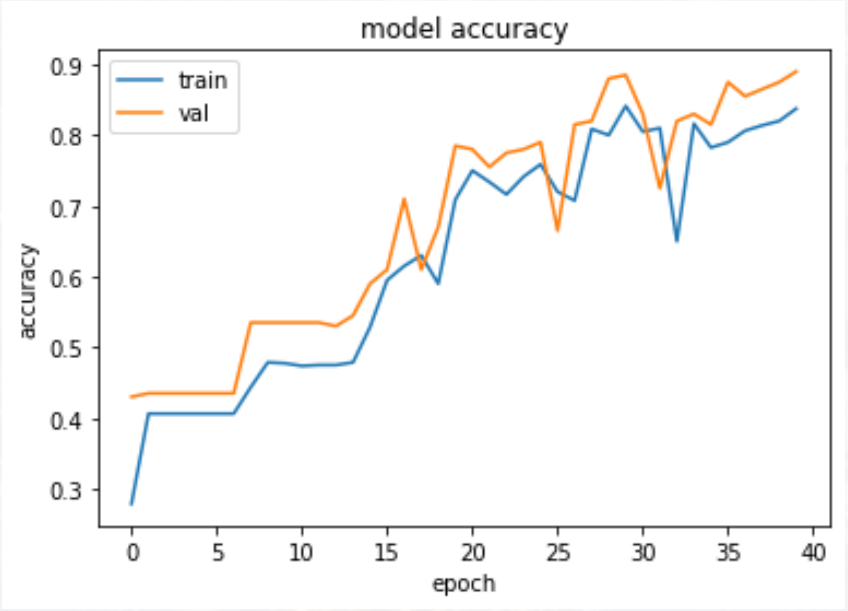
LSTM for Classification

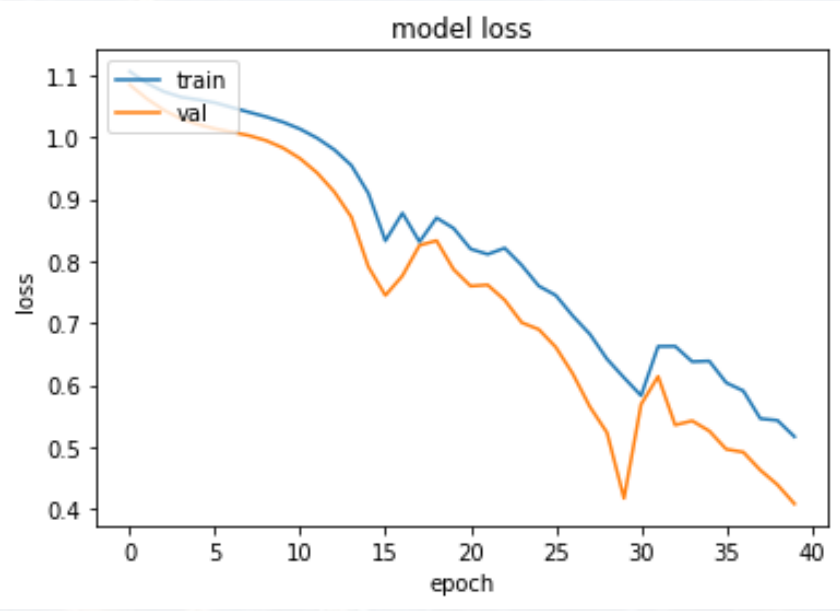
barcode example





for computational reasons:
- **three** classes
- **1k** samples total
- sequences cut to length **500**

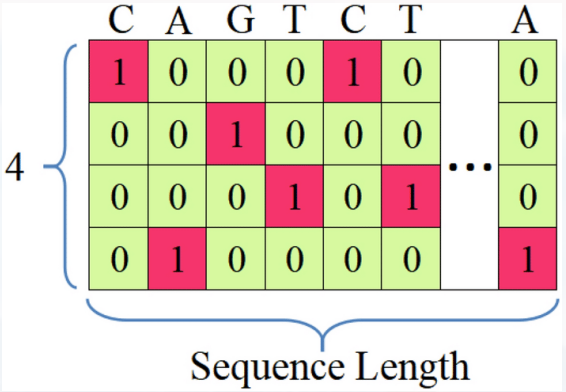


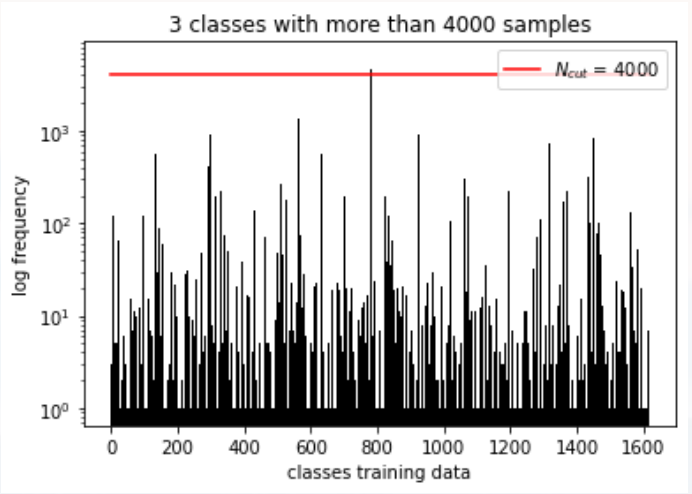


LSTM II:

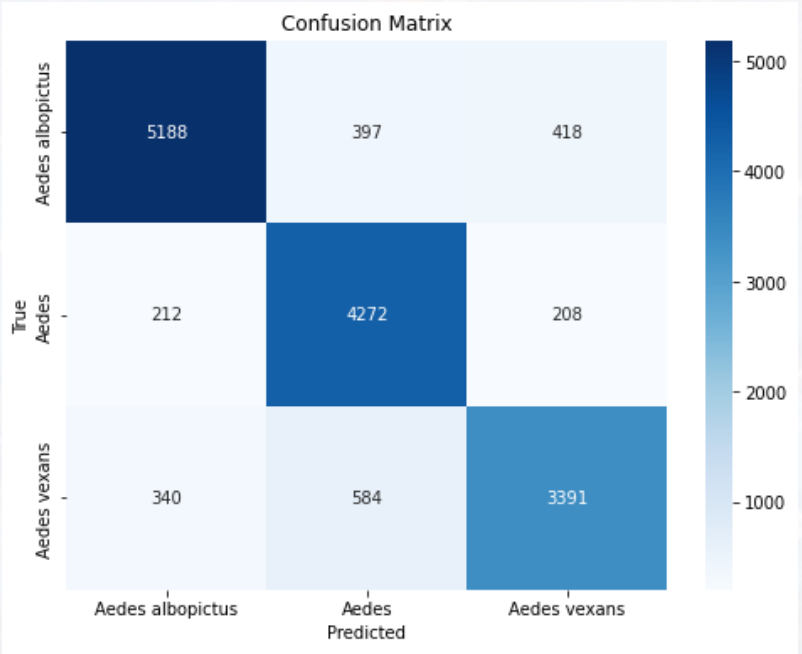
LSTM for Classification

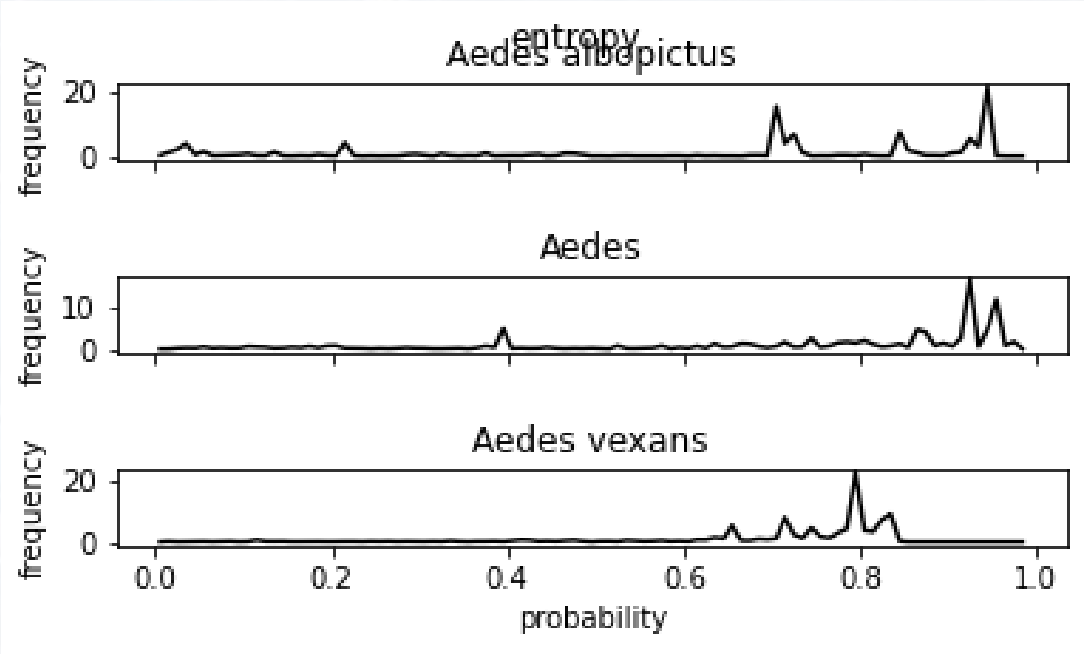
barcode example





for computational reasons:
- **three** classes
- **1k** samples total
- sequences cut to length **500**





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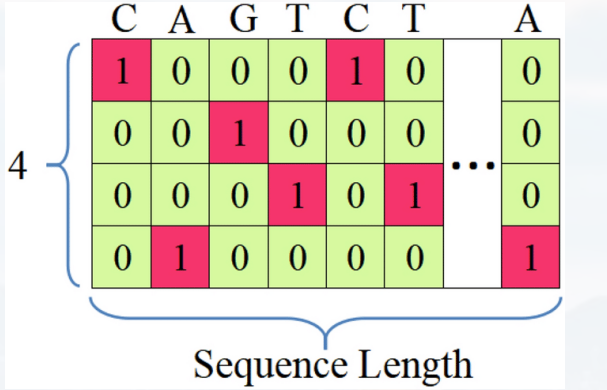
Outline

- LSTM for Classification
- **Bidirectional LSTMs**
- Stacked LSTMs
- LSTM + CNN

LSTM II:

Bidirectional

sometimes, sequences can be read from two directions :




```
from keras.layers import Bidirectional
```

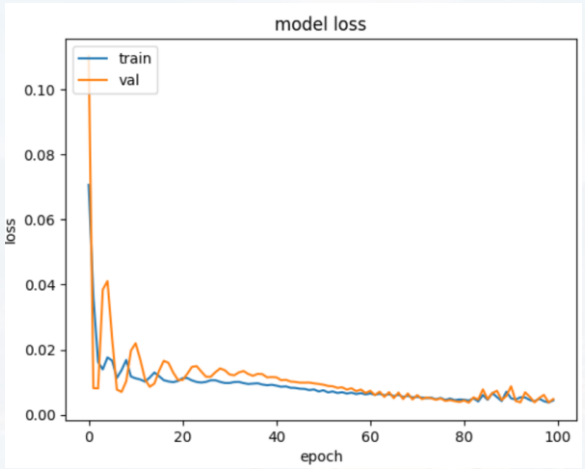
```
model = Sequential()
model.add(Bidirectional(LSTM(n_neurons, activation = 'tanh'),\
                        input_shape = (dt_past, n_features)))
model.add(Dense(dt_futu))

opt = optimizers.Adam()
model.compile(loss = 'mean_squared_error', optimizer = opt)

model.summary()
```

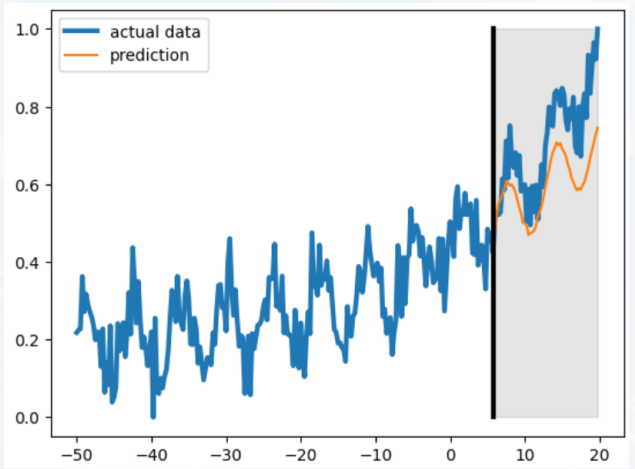
LSTM II:

Bidirectional

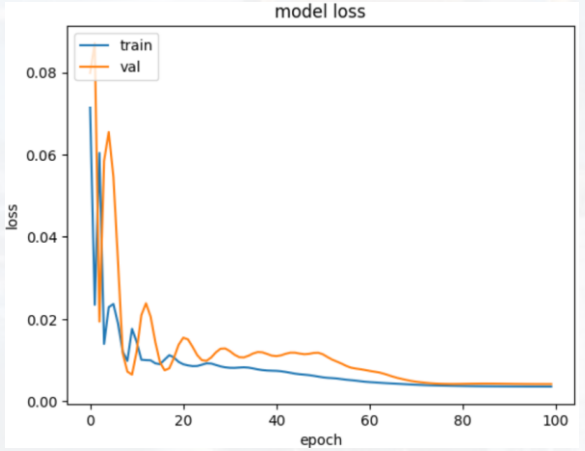
```
model = Sequential()
model.add(Bidirectional(LSTM(n_neurons, activation = 'tanh'), input_shape = (dt_past, n_features)))
model.add(Dense(dt_futu))
opt = optimizers.Adam()
model.compile(loss = 'mean_squared_error', optimizer = opt)
model.summary()
```

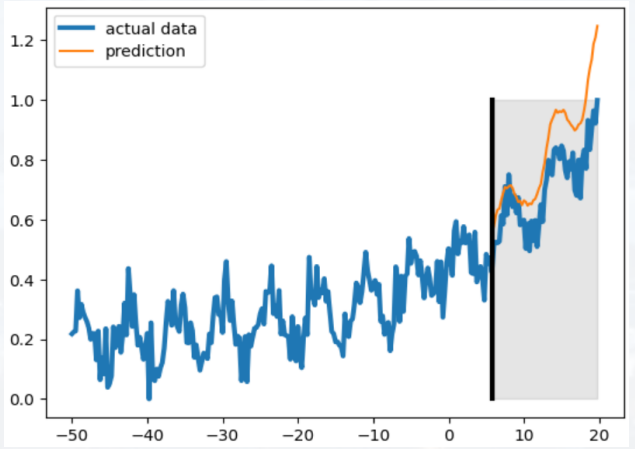
vanilla





bidirectional





Layer (type)	Output Shape	Param #
bidirectional (Bidirectional)	(None, 800)	1286400
dense_1 (Dense)	(None, 8)	6408

Total params: 1292808 (4.93 MB)
Trainable params: 1292808 (4.93 MB)
Non-trainable params: 0 (0.00 Byte)

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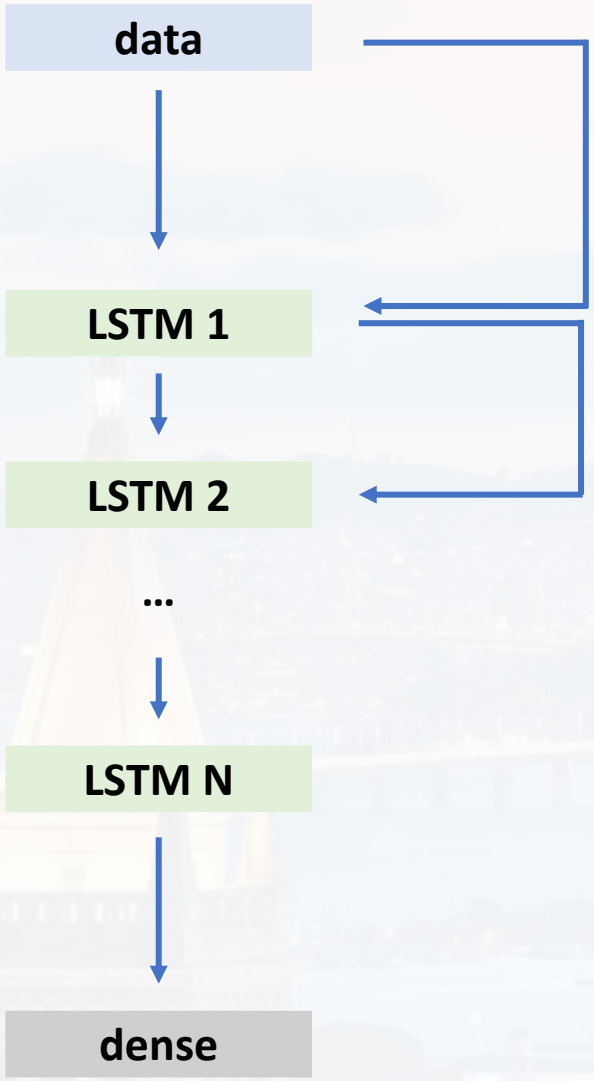
Outline

- LSTM for Classification
- Bidirectional LSTMs
- **Stacked LSTMs**
- LSTM + CNN

LSTM II: Stacked

idea:

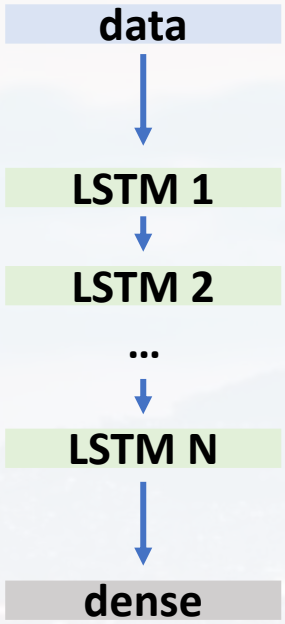



```
shape: (len(y(t)) - dt_past - dt_futu + 1)
          x  dt_past  x features
```

```
shape: (len(y(t)) - dt_past - dt_futu + 1)
          x  dt_past  x hidden state
```

```
return_sequences = True
```

LSTM II: Stacked



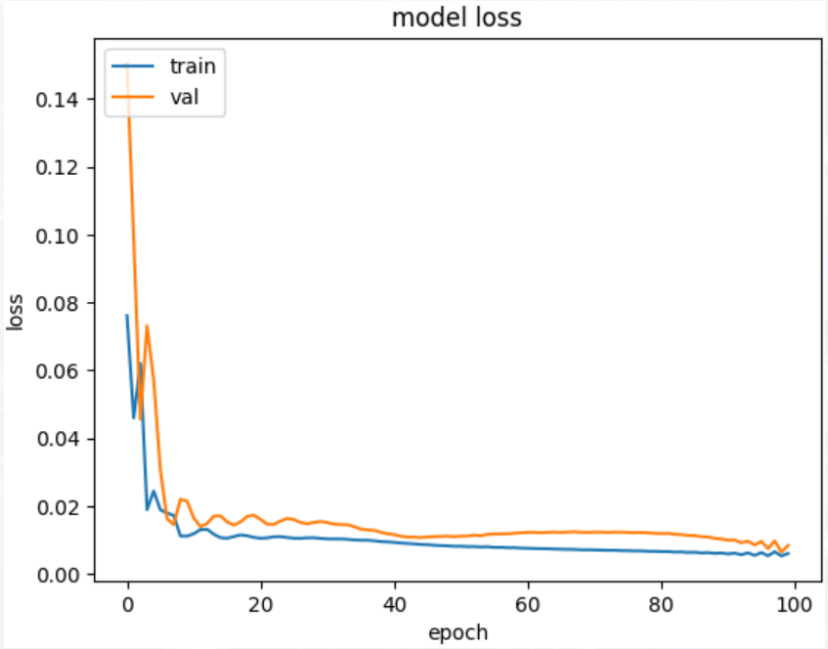

```
model = Sequential()

model.add(LSTM(n_neurons, activation = 'tanh',\
               return_sequences = True, input_shape = (dt_past, n_features)))

model.add(LSTM(2*n_neurons, activation = 'relu',\
               return_sequences = True))

model.add(LSTM(n_neurons, activation = 'relu'))

model.add(Dense(dt_futu))

opt = optimizers.Adam()
model.compile(loss = 'mean_squared_error', optimizer = opt)

model.summary()
```

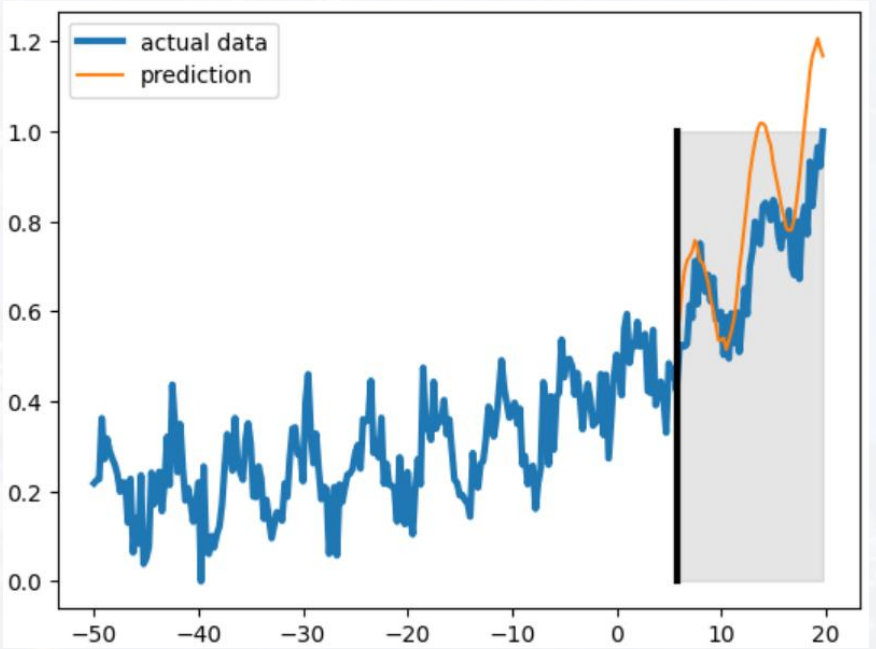
all LSTMs, **except the last** stack needs `return_sequences = True`

LSTM II: Stacked

Layer (type)	Output Shape	Param #
lstm_2 (LSTM)	(None, 20, 400)	643200
lstm_3 (LSTM)	(None, 20, 800)	3843200
lstm_4 (LSTM)	(None, 400)	1921600
dense_2 (Dense)	(None, 8)	3208

Total params: 6411208 (24.46 MB)
Trainable params: 6411208 (24.46 MB)
Non-trainable params: 0 (0.00 Byte)





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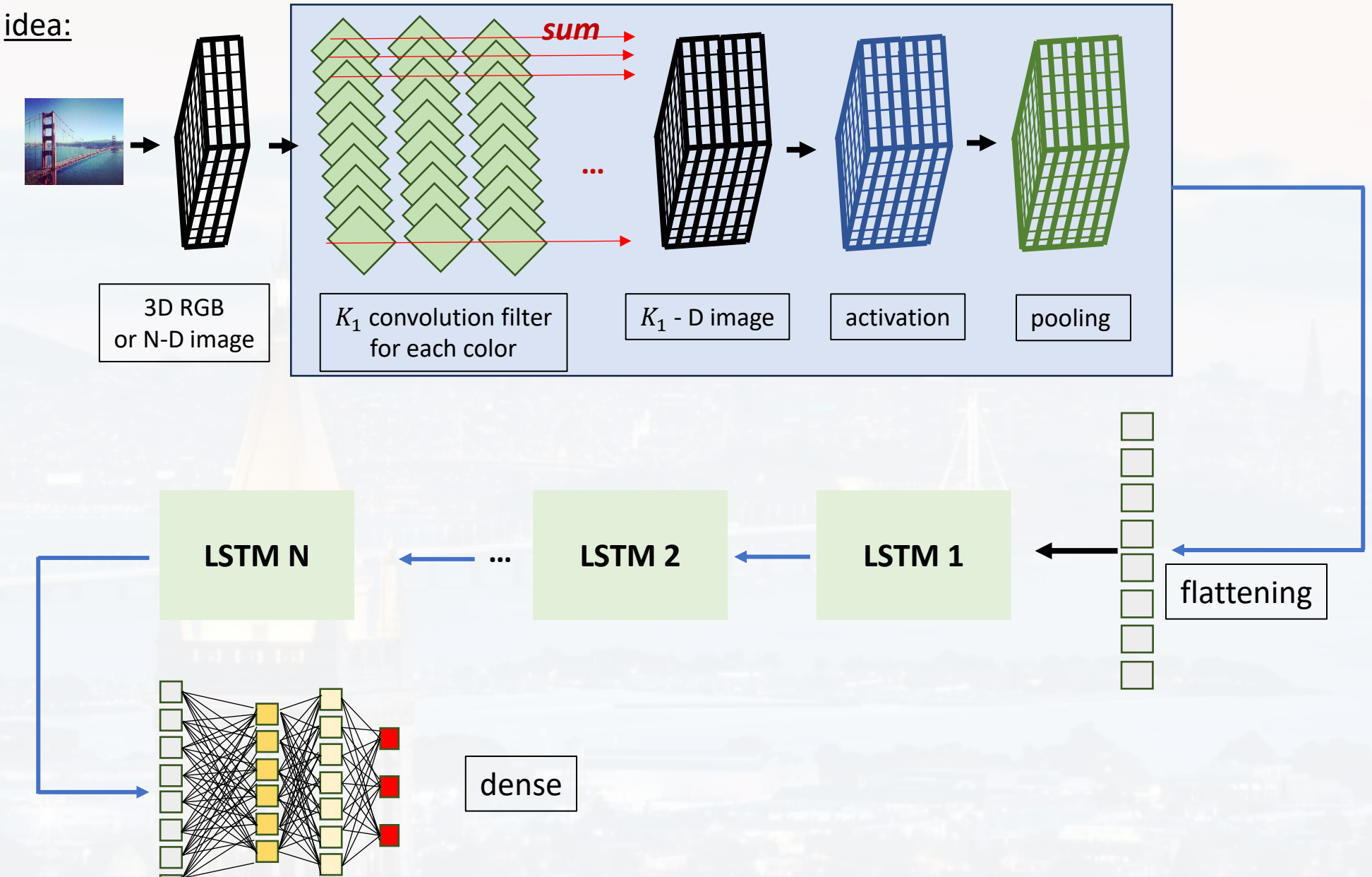
Outline

- LSTM for Classification
- Bidirectional LSTMs
- Stacked LSTMs

- LSTM + CNN

LSTM II:

idea:

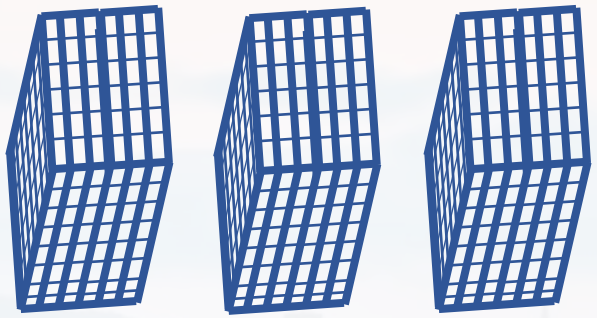

sum
...
3D RGB
or N-D image
K_1 convolution filter
for each color
K_1 - D image
activation
pooling
flattening
LSTM 1
...
LSTM 2
LSTM N
dense

LSTM II:

idea:

input expected by CNN (images):

```
(N_images,      N_x, N_y, N_color)
```

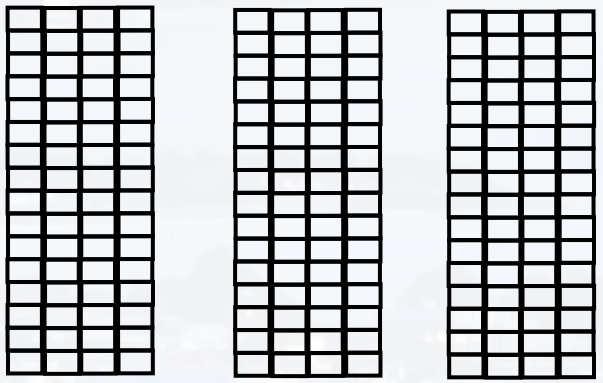


input expected by CNN (videos):

```
(N_videos,      N_t, N_x, N_y, N_color)
```

input expected by LSTM (sequences):

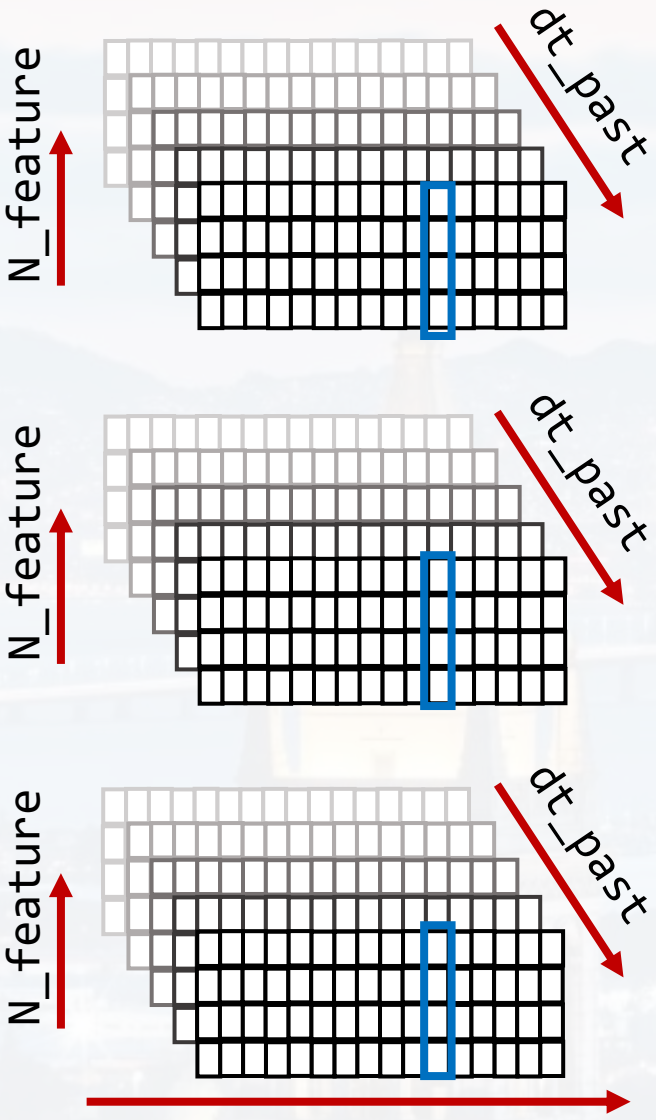
```
(N_sequences,  N_t, N_feature)
```

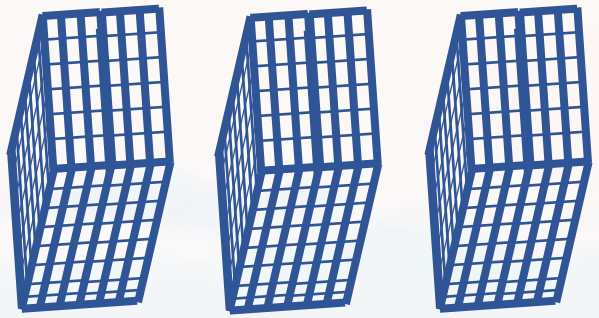


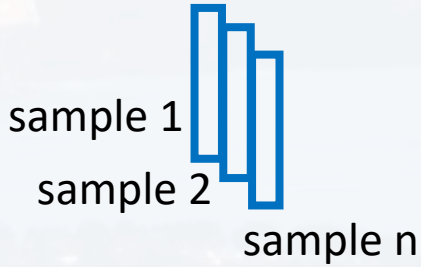
None

LSTM II:

(N_images, N_x, N_y, N_color)



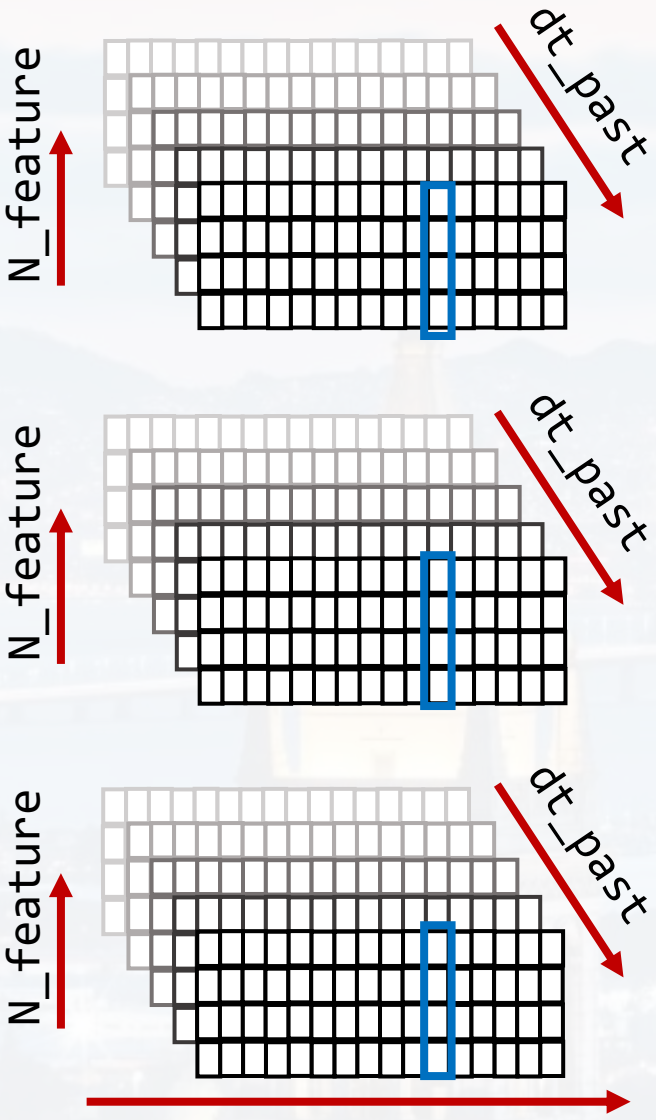


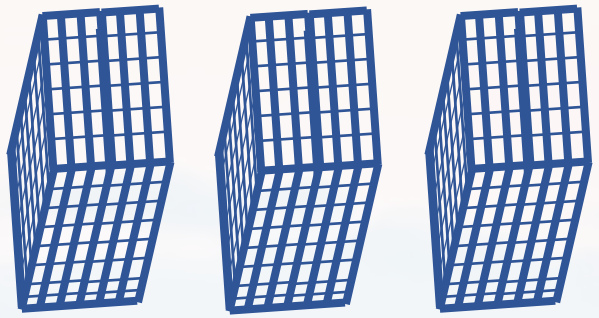


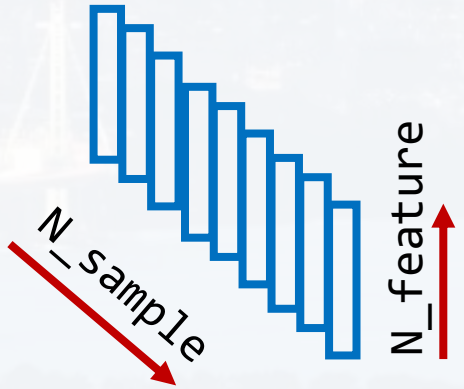
LSTM II:

LSTM + CNN

(N_images, N_x, N_y, N_color)





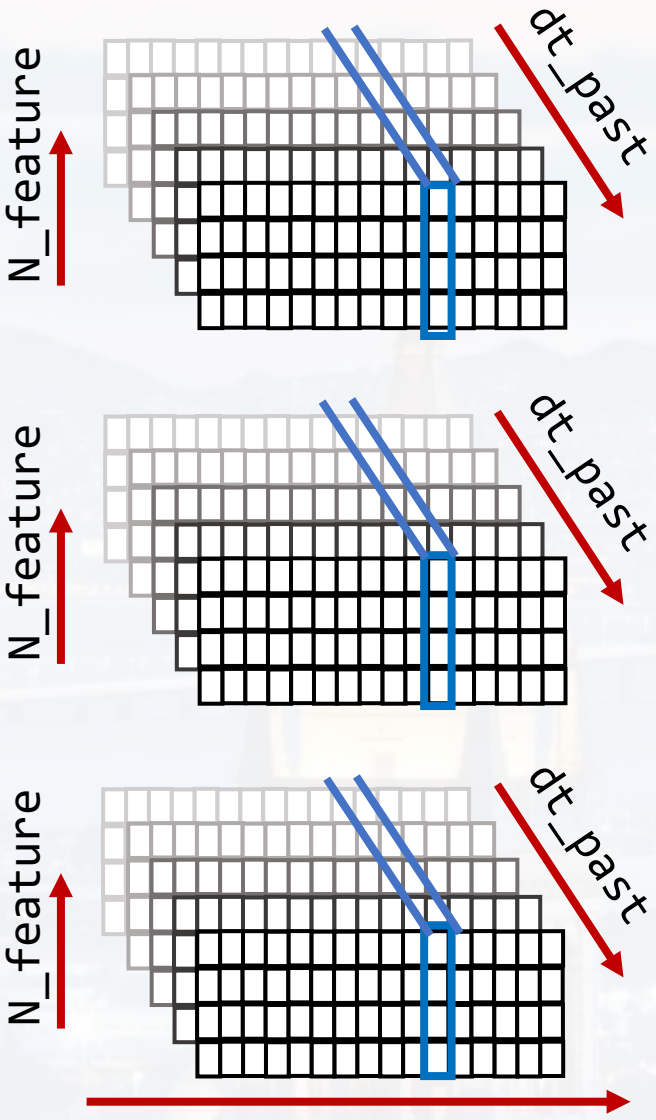


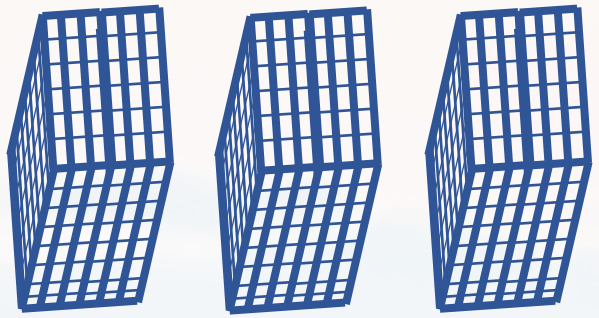
for **one** timepoint t

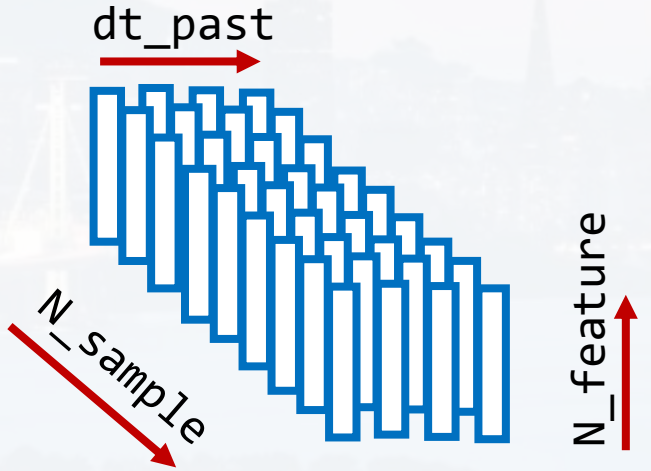
LSTM II:

LSTM + CNN

(N_images, N_x, N_y, N_color)

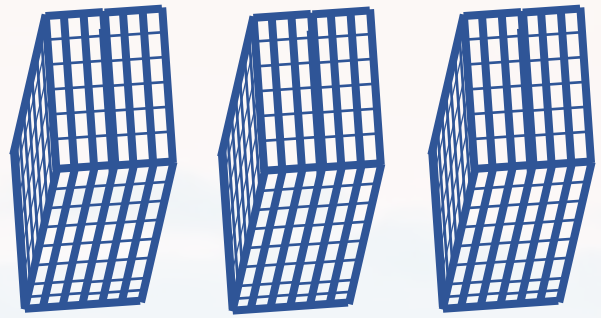


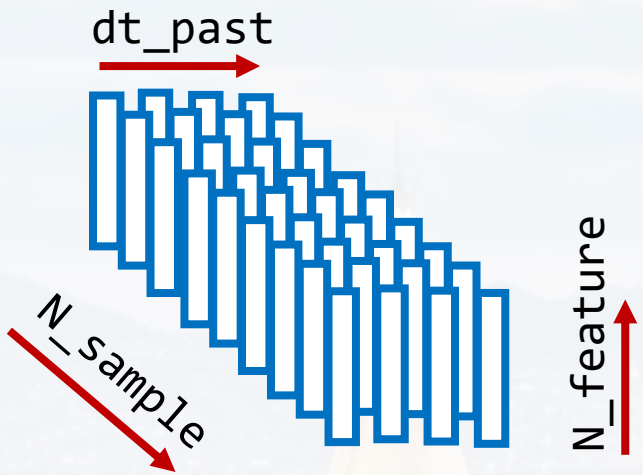




for **one** timepoint t

(N_images, N_x, N_y, N_color)





for **one** timepoint t

regression: **one** sample of N_features and dt_past

```
X = X.reshape((X.shape[0], N_samples, dt_past, n_features))
```

LSTM II:


```
X = X.reshape((X.shape[0], N_samples, dt_past, n_features))


model = Sequential()
model.add(TimeDistributed(Conv1D(filters = 64, kernel_size = 3,\
                                 activation = 'relu'),\
                                 input_shape = (None, dt_past, n_features)))

model.add(TimeDistributed(MaxPooling1D(pool_size = 2)))

model.add(TimeDistributed(Flatten()))

model.add(LSTM(n_neurons, input_shape = (dt_past, n_features),\
                                 activation = 'tanh'))
model.add(Dense(dt_futu))

opt = optimizers.Adam()
model.compile(loss = 'mean_squared_error', optimizer = opt)

model.summary()
```

1D filter along time coordinate

takes care of maintaining matrix orientation

actual input is (None, None, dt_past, n_features)

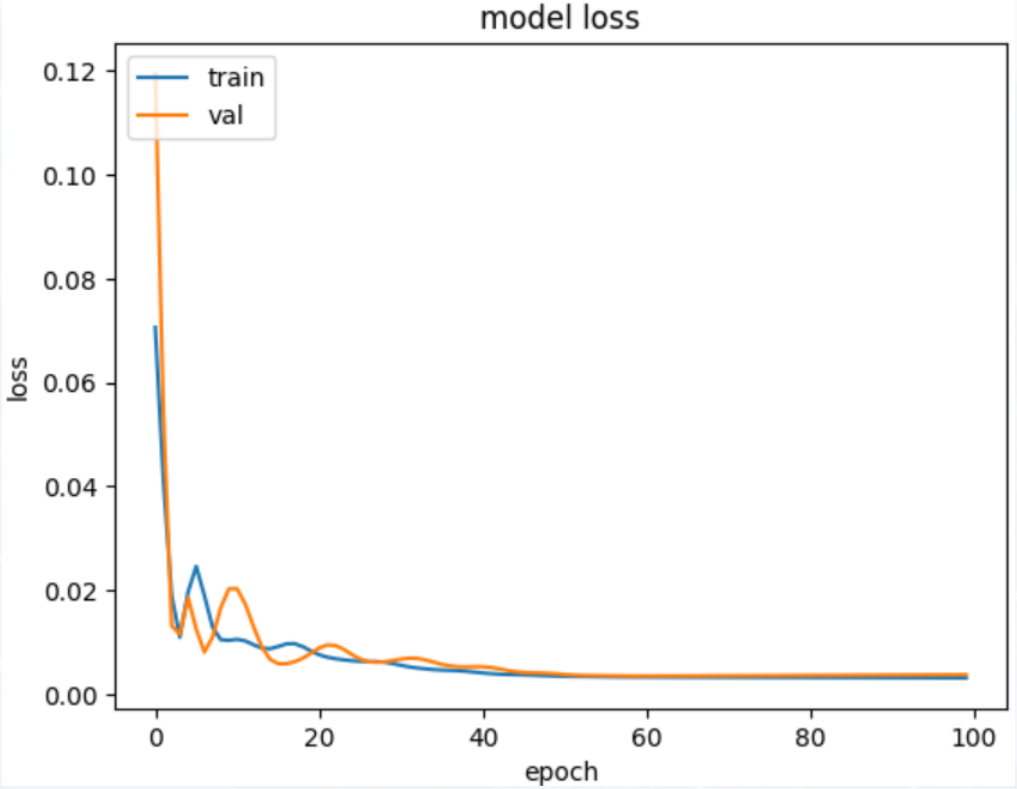
LSTM II:

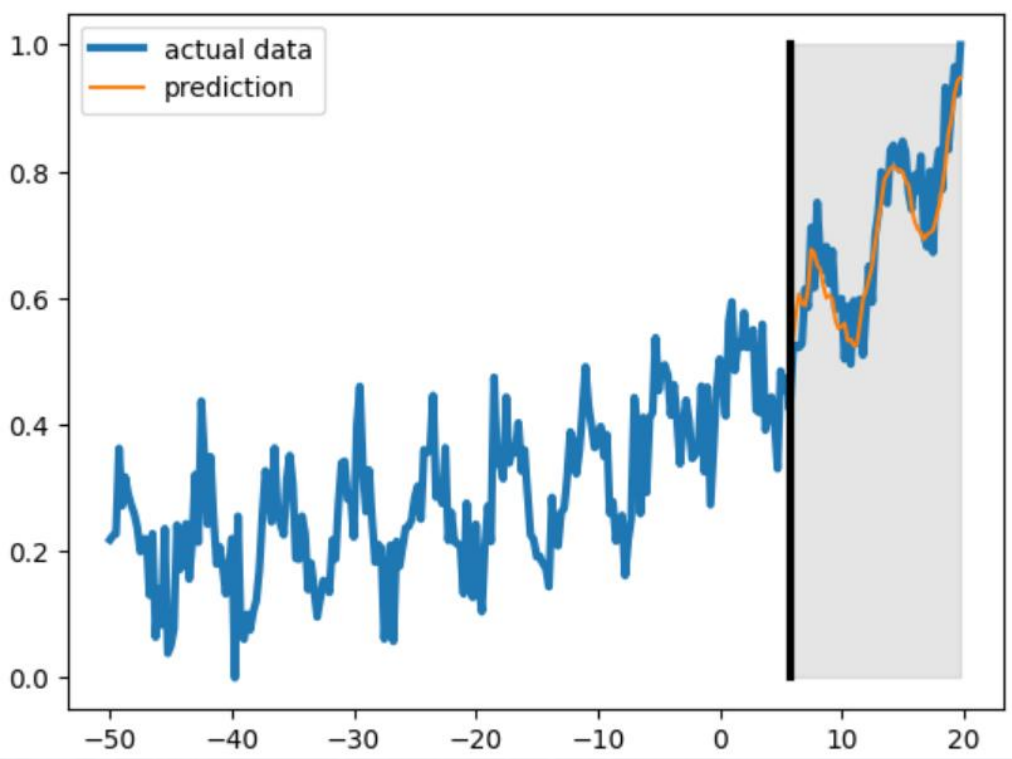

```
 Layer (type)                 Output Shape              Param #
=================================================================
 time_distributed (TimeDist   (None, None, 18, 64)      256
 ributed)

 time_distributed_1 (TimeDi   (None, None, 9, 64)       0
 stributed)

 time_distributed_2 (TimeDi   (None, None, 576)         0
 stributed)

 lstm_5 (LSTM)                (None, 400)               1563200

 dense_3 (Dense)              (None, 8)                 3208

=================================================================
Total params: 1566664 (5.98 MB)
Trainable params: 1566664 (5.98 MB)
Non-trainable params: 0 (0.00 Byte)
```

actual input is (None, None, dt_past, n_features)

LSTM II:

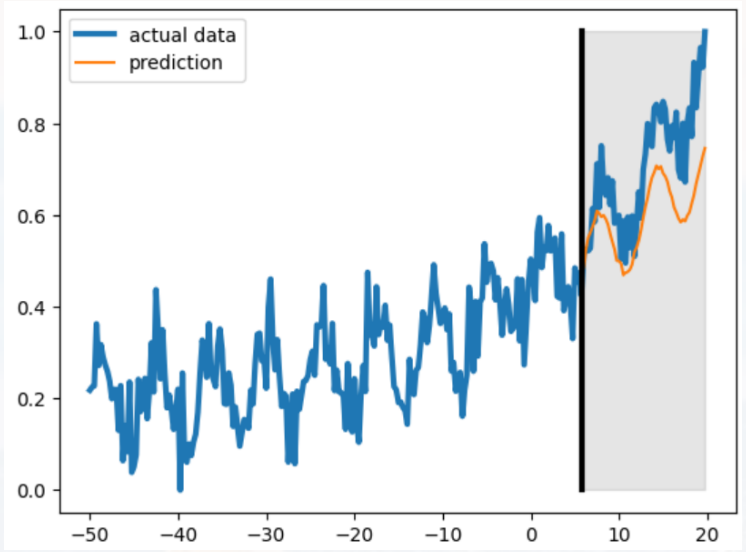
LSTM + CNN



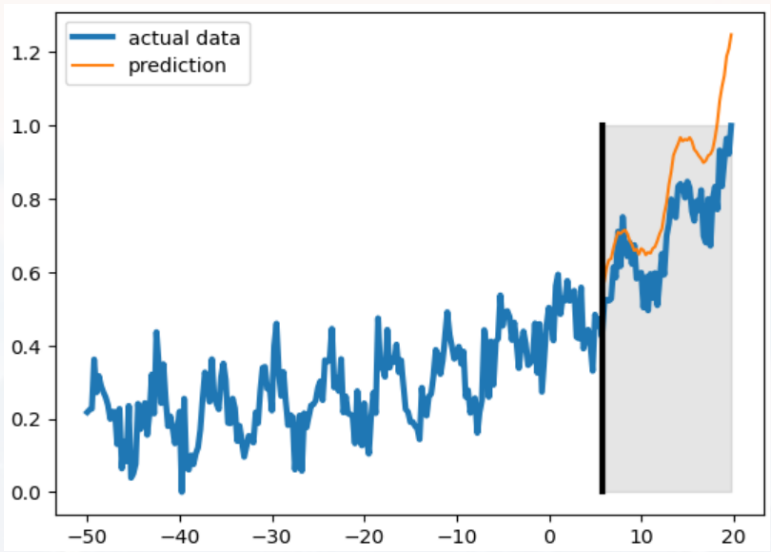


LSTM II:

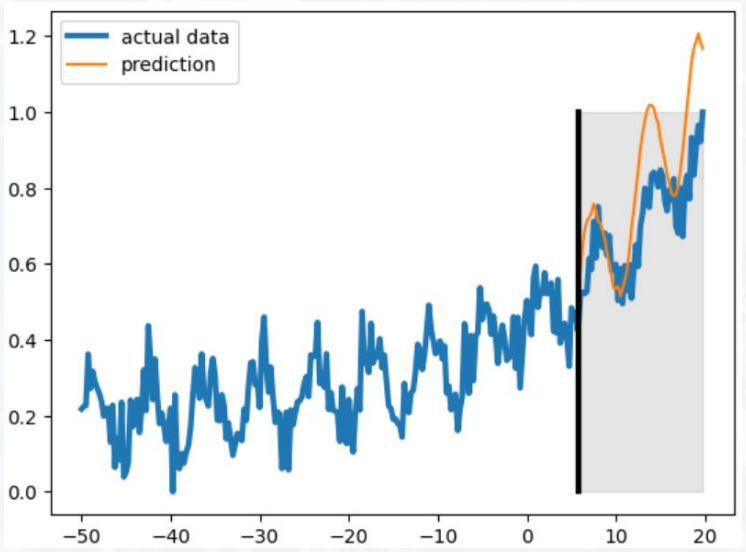
vanilla



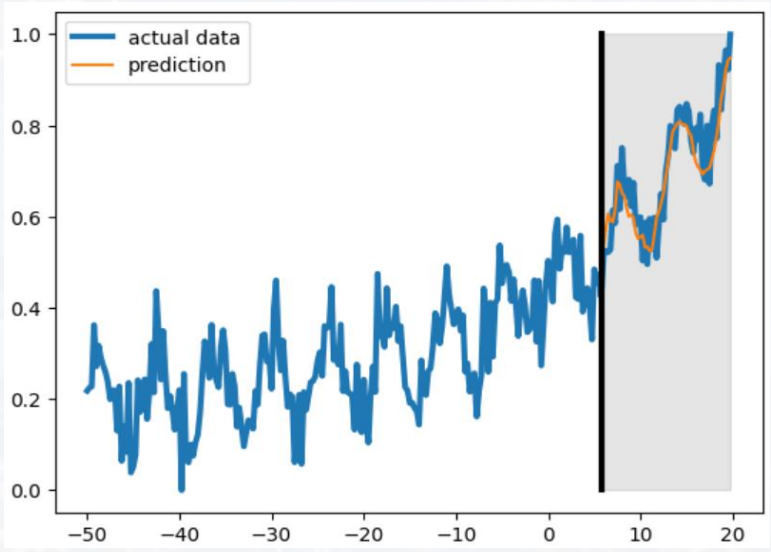
bidirectional



stacked



LSTM + CNN



LSTM II:

classification: **N** samples of N_features and dt_past = Length_Seq

```
[N_sample, LengthSeq, N_features] = X.shape

model = Sequential()
model.add(Conv1D(filters = 64, kernel_size = 3, activation = 'relu',\
                                 input_shape = (LengthSeq, N_features)))

model.add(MaxPooling1D(pool_size = 2))


model.add(LSTM(n_neurons, activation = 'tanh'))

model.add(Dense(Nclass, activation = 'softmax'))

opt = optimizers.Adam()
model.compile(loss = 'categorical_crossentropy', optimizer = opt,\
                                 metrics = ['accuracy'])

model.summary()
```

1D filter along time coordinate = LengthSeq

LSTM II:

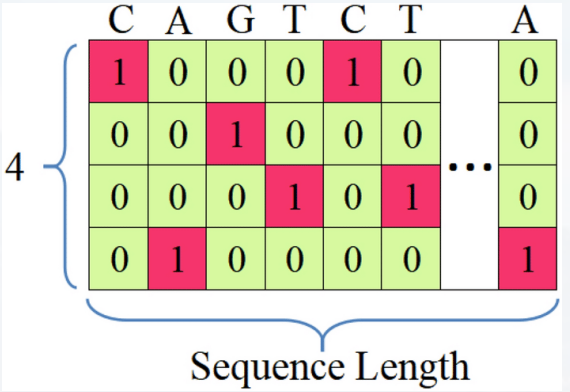
classification: **N** samples of `N_features` and `dt_past = Length_Seq`

`[N_sample, LengthSeq, N_features] = X.shape`

Layer (type)	Output Shape	Param #
conv1d_8 (Conv1D)	(None, 498, 64)	832
max_pooling1d_7 (MaxPooling1D)	(None, 249, 64)	0
lstm_7 (LSTM)	(None, 100)	66000
dense_4 (Dense)	(None, 3)	303

Total params: 67135 (262.25 KB)
Trainable params: 67135 (262.25 KB)
Non-trainable params: 0 (0.00 Byte)

barcode example



for computational reasons:
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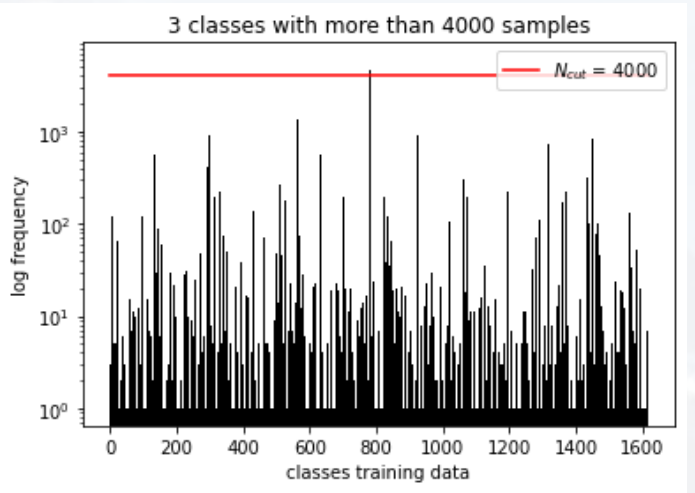
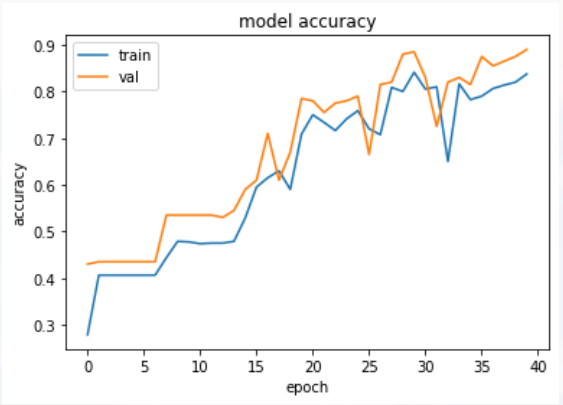
- **1k** samples total
- sequences cut to length **500**

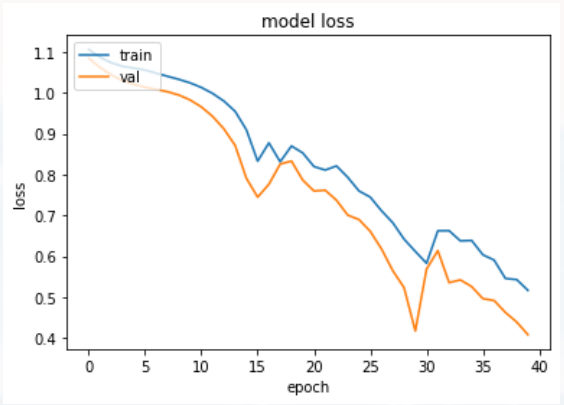


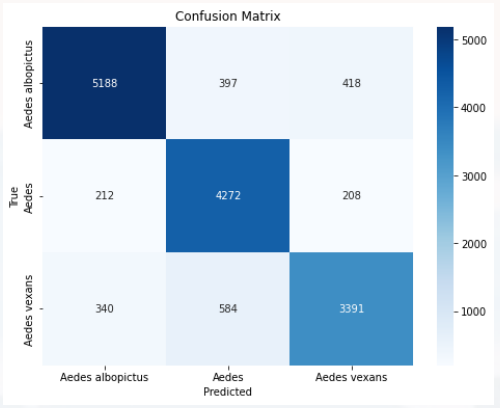
LSTM II:

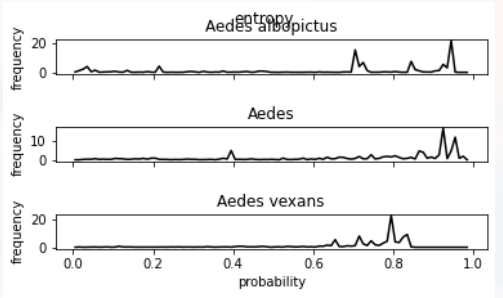
LSTM + CNN

LSTM

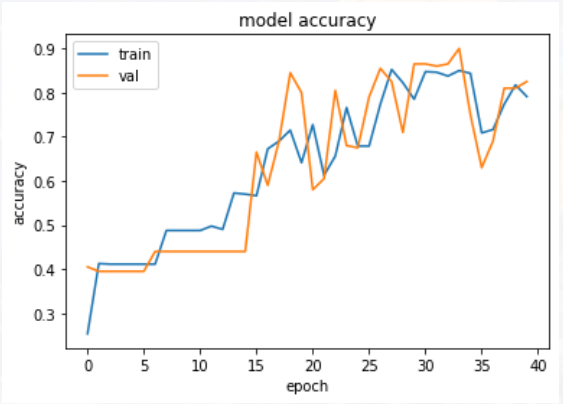


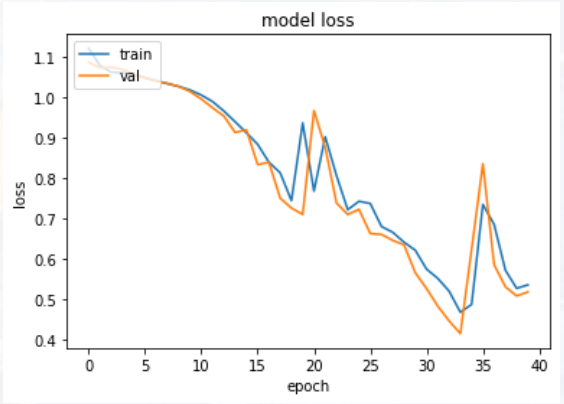


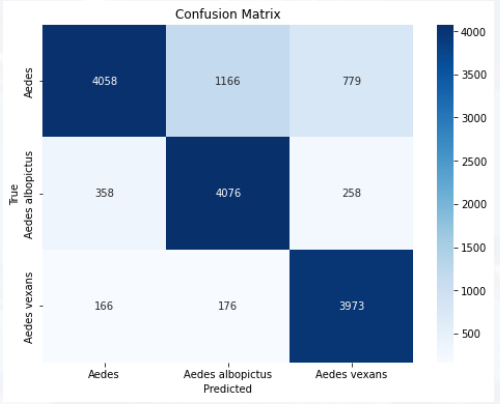


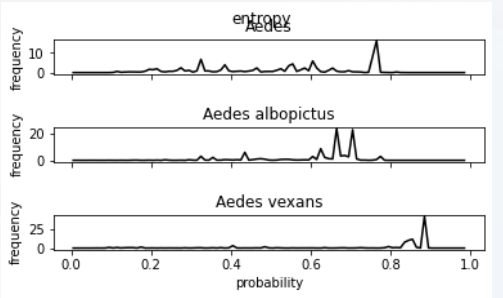


LSTM+CNN









Thank you for your attention!