

# VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

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FAKULTA INFORMAČNÍCH TECHNOLOGIÍ  
ÚSTAV POČÍTAČOVÉ GRAFIKY A MULTIMÉDIÍ

FACULTY OF INFORMATION TECHNOLOGY  
DEPARTMENT OF COMPUTER GRAPHICS AND MULTIMEDIA

## IMAGE CAPTIONING WITH RECURRENT NEURAL NETWORKS

SEMESTRÁLNÍ PROJEKT  
TERM PROJECT

AUTOR PRÁCE  
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Bc. JAKUB KVITA

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# **POPIS FOTOGRAFIÍ POMOCÍ REKURENTNÍCH NEU- RONOVÝCH SÍTÍ**

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## **Abstrakt**

Výtah (abstrakt) práce v českém jazyce.

## **Abstract**

Výtah (abstrakt) práce v anglickém jazyce.

## **Klíčová slova**

rekurentní neuronové sítě, RNN, konvoluční neuronové sítě, CNN, popisování obrázků, LSTM, GRU, MS COCO, Torch, hluboké učení

## **Keywords**

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# Image Captioning with Recurrent Neural Networks

## Prohlášení

Prohlašuji, že jsem tento semestrální projekt vypracoval samostatně pod vedením pana Michala Hradiše.

.....

Jakub Kvita  
January 7, 2016

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*Tato práce vznikla jako školní dílo na Vysokém učení technickém v Brně, Fakultě informačních technologií. Práce je chráněna autorským zákonem a její užití bez udělení oprávnění autorem je nezákonné, s výjimkou zákonem definovaných případů.*

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# Chapter 1

## Introduction

Klasicky popis toho co se tady bude dit, jak je to dulezite, atd.

## Chapter 2

# Neural networks

General idea of artificial neural networks emerged after World War II. Perceptron, as a single neuron unit, was created in 1958 by Frank Rosenblatt[34], but became popular only after combination with the backpropagation algorithm[3, 39]. At that time neural nets have not reached massive popularity, not because they are not working, but due to small computing power of machines back then and lack of datasets. Recently (after 2000) neural nets became popular again, under the name of ‘Deep Learning’, to emphasize the use of several layers stacked on top of each other to create deep architectures, which are far more practical than shallow ones. During this reinvention, neural nets have been successfully applied in multiple fields like computer vision[15], speech recognition[13] and natural language modeling[30].

Various useful architectures and algorithms are now introduced almost every month. In this chapter, I will describe only a handful – recurrent neural networks with the LSTM and GRU units, and basics of convolutional neural nets.

### 2.1 Recurrent neural nets

Feedforward neural nets are extremely powerful models, which can be highly parallelized. Despite that, they can be only applied to problems with inputs and outputs, which have fixed dimensionality (e.g. one-hot encoding vectors). This is a serious drawback, as many of the real-world problems are defined as sequences with lengths that are unknown to us in beforehand. Soon recurrent neural networks were introduced and they proved to be very useful to this kind of task. There is vast amount of recurrent neural networks, many not suitable for sequential tasks like Hopfield network, which are very successful in specific tasks, but nevertheless not useful for us now.

Apart from classification, which can be more precise when using sequences, one of the most important tasks is next value prediction. This core task can be then extended very simply to predict arbitrary number of future values. Prediction problems are all around us, from the weather forecast and stock market prediction to the autocomplete in smartphones or web browsers.

We can understand recurrent neural networks as very deep forward nets with shared weights. It is called RNN unrolling and it is described in figure 1. Layers of this very deep net spread in time, together with the input sequence. This is very innovative idea, which enabled training RNN with backpropagation through time. It also shows that, as very deep networks, they have vanishing or exploding gradient problem, which means that the network is not able to learn long-term dependencies, even though in theory it should.



Figure 1: Unrolling of the recurrent neural net.[32]

This is a serious issue, which is caused by iterating many times over the weights and the activation function with derivatives  $> 1$  (exploding gradient) or  $< 1$  (vanishing gradient). Gradient then dies out and learning stops for distant dependencies. Among others this problem has been solved by the LSTM unit described in part 2.1.1, which is most popular now and following research resulting in GRU described in part 2.1.2.

### 2.1.1 LSTM – Long Short-Term Memory

Long Short-Term Memory nets are special kind of recurrent network, capable of learning long-term dependencies. This architecture was introduced by Hochreiter & Schmidhuber[17] after prior research of vanishing gradient problem[16]. Later architecture was refined and popularized by other researchers[10, 11] and nowadays LSTM is most popular RNN architecture used.

The LSTM unit was designed to remember a value for an arbitrary length of time. It contains gates that determine when the input is significant enough to remember, when it should keep or forget the value, and when it should output the value. To understand the flow of data, see the diagram of a simplified LSTM unit on the figure 2. All the gates can be described by the following series of equations.

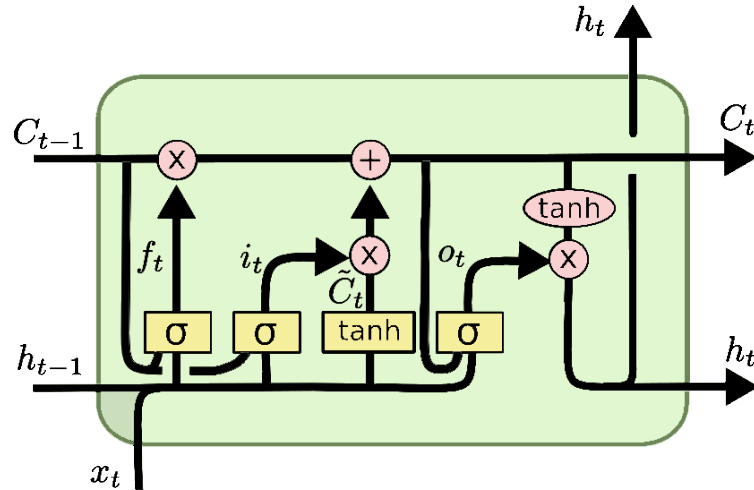


Figure 2: Variation of the LSTM unit.[32]



$$i_t = \sigma(W_{xi}x_t + W_{hi}h_{t-1} + W_{ci}c_{t-1} + b_i) \quad (1)$$

$$f_t = \sigma(W_{xf}x_t + W_{hf}h_{t-1} + W_{cf}c_{t-1} + b_f) \quad (2)$$

$$z_t = \tanh(W_{xc}x_t + W_{hc}h_{t-1} + b_c) \quad (3)$$

$$c_t = f_t \odot c_{t-1} + i_t \odot z_t \quad (4)$$

$$o_t = \sigma(W_{xo}x_t + W_{ho}h_{t-1} + W_{co}c_t + b_o) \quad (5)$$

$$h_t = o_t \odot \tanh(c_t) \quad (6)$$

$$\sigma(x) = \frac{1}{1 + e^{-x}} \quad (7)$$

In each time slice the unit is using current input  $x_t$ , last stored value  $c_{t-1}$  and unit output  $h_{t-1}$  to compute next state  $c_t$  and output  $h_t$ . Variables  $i_t$ ,  $f_t$ ,  $o_t$  denotes value of input, forget and output gates which are used to control the information flow.

LSTM based on these equations is using total of 11 weight matrices and 4 bias vectors for computations and sigmoid function  $\sigma$  defined in the equation (7) and the operation  $\odot$  denotes the element-wise vector product. Equations described in this work are not the only way how to create an LSTM unit, but they will be used later while implementing the proposed model. Some of the versions are omitting ‘peephole connections’, which allows gates to look at stored value  $C_{t-1}$ ,  $C_t$  or include only some of them.

Training of the LSTM based network can be performed effectively by standard methods like stochastic gradient descend in the form of backpropagation through time. Major problem with vanishing gradients during training described earlier is not an issue as back-propagated error is fed back to each of the gates.

### 2.1.2 GRU – Gated Recurrent Unit

Gated Recurrent Unit[5] is slightly more dramatic variation on the LSTM theme. It combines hidden state of the unit  $h_t$  with the saved value  $C_t$ , merges input and forget gates into one update gate and removes peephole connections. These changes are simplifying standard LSTM models, but not at the expense of performance, and cause rapid growth in popularity. Diagram of the GRU unit is on the figure 3.

$$r_t = \sigma(W_{xr}x_t + W_{hr}h_{t-1} + b_r) \quad (8)$$

$$z_t = \sigma(W_{xz}x_t + W_{hz}h_{t-1} + b_z) \quad (9)$$

$$\tilde{h}_t = \tanh(W_{xh}x_t + W_{hh}(h_{t-1} \odot r_t) + b_h) \quad (10)$$

$$h_t = (1 - z_t) \odot \tilde{h}_t + z_t \odot h_{t-1} \quad (11)$$

$$\sigma(x) = \frac{1}{1 + e^{-x}} \quad (12)$$

Equations describe a version of GRU unit used in this work, with sigmoid function  $\sigma$  defined in equation (12). The operation  $\odot$  again denotes the element-wise vector product.

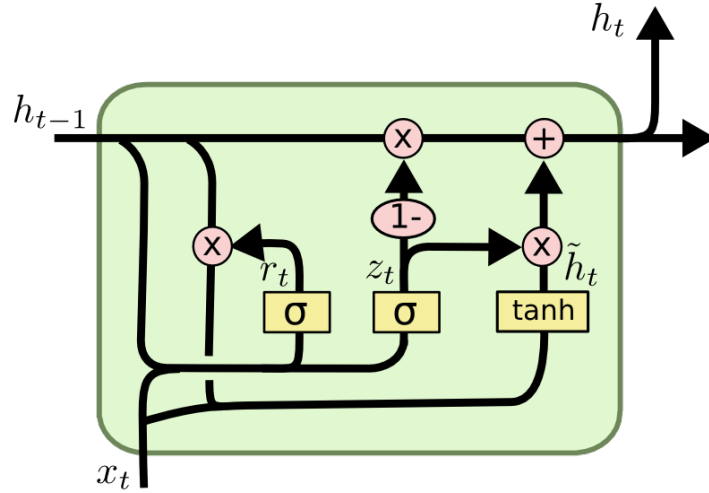


Figure 3: Variation of a GRU unit.[32]

While it is using only 4 weight matrices, 3 biases and just 1 state variable, researchers studied whether this can achieve at least same performance as previous LSTM unit.

Last year, study by Chung[6] was done, where different types of recurrent units were compared on the polyphonic music datasets. In this task LSTM and GRU were significantly better than all the other architectures, with GRU slightly in the lead. Generally, researchers agree that most of the LSTM variations, including GRU, are roughly on the same performance level. According to [14] GRU is an average variation, slightly better than vanilla LSTM, with much simpler architecture.

In paper [22], which emphasized variety of tasks and the data, GRU outperformed LSTM unit on all tasks with the exception of language modeling. There are multiple approaches to model languages and in this work I will explore different type than the one mentioned in Jozefowicz’s paper[22]. More will be explained in following chapters. Interestingly they also found that LSTM nearly matched the GRU’s performance, when its forget gate bias was initialized to 1 and not to naive initialization around 0. It is also worth mentioning that Jozefowicz in his paper discovered several architectures similar to GRU, but with slightly better general performance. They were found by evolutionary algorithm working on candidate architectures represented by the computational graph.

### 2.1.3 Language modeling and word embeddings

With the addition of LSTM units, recurrent neural nets quickly showed good performance in many different types of sequence processing like speech recognition from sound waves, signal prediction and language modeling. These result were further improved when researchers started stacking LSTMs on top of each other like pancakes.

Text is represented by discrete values and is usually presented to network in form of input vectors with one-hot encoding<sup>1</sup>. If we have a task with  $K$  classes, class  $i$  will be represented by a vector  $V$  of length  $K$ . All the entries of  $V$  will be switched off to 0, except  $V_i$ , which will have the value of 1. Vector  $V$  is simultaneously a degenerated multinomial probability distribution of the current input. If the output has the same shape as input,

<sup>1</sup>One-hot encoded vector has exactly one high ('1') value and all the others low ('0').

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it can be simply created by softmax function at the output layer. Result will be proper multinomial distribution of next value, given current value.

At this point it is necessary to decide what will classes and defined vectors represent. In most cases, text prediction is performed at the word level.  $K$  is hence the number of words in the dictionary. This can cause some problems, as in bigger tasks dictionary often exceeds 100 000 records. This many classes require huge amount of training data to properly cover all the cases and high computational cost of the softmax layer is also an issue. This text representation cannot be used for texts not containing separate words, like multi-digit numbers. Nevertheless, state-of-the-art models have been using word-level representation. One of the advantages is no need to teach the net proper forms of the words. The net does not have to remember, how to spell the words properly and can learn other, more useful, features.

To solve the problem with extremely long input vectors, set of techniques called *word embedding* were developed. They map words from the vocabulary to suitable vectors of real numbers in high dimensional space (around 50–1000 dimensions). Chosen vectors cannot be random, they are meaningful in order of performing some following task. For example Skip-gram model[29] mapped 783 millions words to vectors of 300 real numbers, while creating reasonable relationships between them.

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Character level modeling has been considered and used as an alternative to word-level, but so far had slightly worse performance. Regardless, it is still considered as an option, because it has much simpler representation of input and output. Consider roughly 45 characters in English text and over 50000 words created from them. Character level network is also more suited for Czech or Russian and other fusional<sup>2</sup> languages, which heavily use prefixes and suffixes to create new words. This is also an ability, which cannot be overlooked, as it is not available for word level. Character level models have usually smaller vocabulary size and have to be trained longer, as they need to learn spelling of the words on top of the same features of word level. With the properly trained character level model we can benefit from its much greater generative abilities, than we can achieve with word-level.

## 2.2 Convolutional neural nets

Feed-forward neural nets together with backpropagation algorithm showed very useful for range of tasks and it has even been proven[7, 19] they can approximate any continuous function. However, they were not very good in recognizing objects presented visually. As every unit is connected to large amount of units in the next layer (or all of them in fully-connected layers), the number of weights grows rapidly with the size of the problem and even more with the dimensionality. All these problems are manifesting even in image processing with only two dimensions. Convolutional neural nets (CNN) were introduced as a solution to reduce the number of parameters involved, while exploiting spatial constraints in the input.

Ideas of convolutional nets took inspiration from neurobiology, more precisely from the organisation of neurons in visual cortex of the cat. They were first used in the work of Homma[1] to process temporal signal. Later their design was improved by LeCun et al. [28]. Different CNN architecture was proposed by Graupe[12] for decomposition of one-dimensional EMG signals. Convolutional nets can be also used to natural language

<sup>2</sup>Fusional language is a type of language distinguished by its tendency to overlay many morphemes to denote grammatical, syntactic, or semantic change.

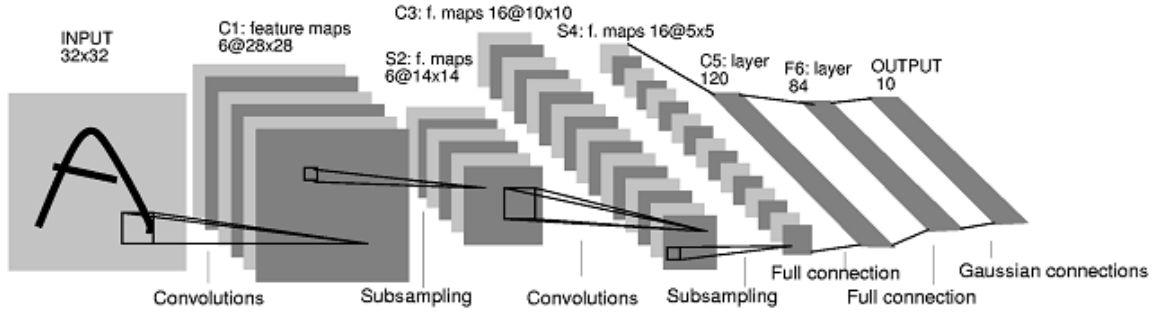


Figure 4: LeNet-5 architecture.[28]

processing[26] and to analysis of three-dimensional data like videos[21] or volumetric data (eg. 3D medical scans), but that is not as common as image processing.

Basic architecture of CNN can be described as the following process:

1. Convolve several small filters on the input.
2. Subsample this space of filter activations.
3. Repeat steps 1 and 2 until you are left with a sufficiently high level features.
4. Use a standard feed-forward neural net to solve the task, using the features as input.

Convolutional layer, which is most important and gave CNN their name is essentially the same as mathematical convolution used elsewhere. Here it means to apply a 'filter' over an input at all possible offsets. This filter - in image processing and computer vision called kernel - has a layer of connection weights with the same dimensionality as the input, but with much smaller size. Despite the fact that there is many connections, which are even overlapping, the weights are tied together and during training only handful of parameters per filter need to be updated. It is also possible to stack filters on top of each other to create more powerful architectures, but as they do not reduce dimensionality significantly, output has the same size as the input. Second type of a layer has been introduced to improve it - subsampling.

Subsampling, or max pooling in this version, is a simple operation that takes small non-overlapping grid of the input tensor and outputs the maximum value of each part. By putting this operation in between the convolutional layers, we can detect higher level features than without it.

Last type of unit commonly used in CNN is rectified linear unit (ReLU), which provides nonlinearity and improves overall performance[20, 31]. One of the first and most famous examples of convolutional neural net is LeNet<sup>3</sup>[28], which recognize handwritten digits from the MNIST database<sup>4</sup>. Architecture of LeNet-5 is on the figure 4.

<sup>3</sup>Demos and examples of LeNet: <http://yann.lecun.com/exdb/lenet/>

<sup>4</sup>MNIST database website: <http://yann.lecun.com/exdb/mnist/>

## Chapter 3

# Image caption generation

Scene understanding is one of the fundamental and most difficult tasks of computer vision. Being able to automatically generate image or video captions in regular text could have great effect. However, it is much more complicated than simple classification or object recognition, because the model also need to understand relations between the recognized objects and capture that correctly in the captions.

In this chapter I will do an overview of approaches to this task and more closely describe latest papers on which is this work based (section 3.1). Following parts cover datasets (3.2) and evaluation procedures (3.3) most commonly used for this task.

### 3.1 Related Work

Currently, neural networks are most heavily used to generate captions. Before them two main approaches were common. The first one used caption templates, which were filled by detected objects and relations. Second was based on retrieving similar captions from database and modifying them to fit current image. Question of similarity ranking has been addressed by many papers, which are based on the idea of joint embedding vector space for both images and captions[25]. Similar descriptions are in this space close to each other.

Both approaches above usually included generalization step to remove information relevant only to current image, for example names. They are quite successful in describing images, but they are heavily hand-designed and their text-generation power is fixed on the database/embedding and is not able to describe previously unseen compositions of objects. Over time these approaches fell out of favor to now dominant neural network methods.

Many of the methods using neural nets are inspired by successes in training of recurrent nets for machine translation. It is worth mentioning Sutskevers work [35], which studied general sequence to sequence mapping by converting input sequence to vector of fixed length. Vector is then decoded to output sequence. This encoder–decoder architecture is closely related to autoencoders and work of Kalchbrenner and Blunsom[23], who were first to map the entire input sequence to vector.

The introduced encoder–decoder architecture is important to the captioning task, because we can interpret image description problem as a translation from an image to a sentence. In this case, encoder part of the model is usually convolutional neural net, as they are excellent in the image classification[36]. Decoder part is similar as in machine translation models – type of a RNN or LSTM, as the output for both tasks is essentially same.

One of the most interesting event in this field is MS COCO Captioning Challenge<sup>1</sup> in which many of the state-of-the-art researchers compete directly against each other. Most of the works described further have participated in this challenge.

### 3.1.1 Show and Tell: A Neural Image Caption Generator

Clanek z Coco od Googlu.

[38]

### 3.1.2 Show, Attend and Tell: Neural Image Caption Generation with Visual Attention

Clanek z Coco z Montrealu/Toronta

[40]

### 3.1.3 From Captions to Visual Concepts and Back

Clanek z Coco od Microsoftu, mrknout se i na pokracovani v druhem clanku

[9]

### 3.1.4 Long-term Recurrent Convolutional Networks for Visual Recognition and Description

Clanek z Coco z berkeley

[8]

## 3.2 Datasets

Big datasets are necessary requirement in training recurrent neural nets, together with sufficient computing power. As access to machines and hardware suitable for training has been made extremely easy, obtaining enough data become the biggest problem. All the descriptions in the image captioning datasets have to be human generated, which is very expensive. This is one of the reasons, not many specialized datasets are created.

There are two main options how to get images and captions. First, using user-generated data from an online service, most commonly Flickr. However, captions are not made specifically for the task and could be prone to error. Second option is to create captions directly for use in the dataset. Amazon Mechanical Turk<sup>2</sup> is heavily used for this task. All datasets mentioned here are created this way.

Flickr8k[18] was one of the first datasets created for this purpose. It has been later expanded into Flickr30k[41]. MS COCO[4] is dataset created by Microsoft for their captioning challenge. CIDEr[37] datasets PASCAL-50S, ABSTRACT-50S are youngest mentioned, designed specifically for evaluation with the CIDEr metric.

---

<sup>1</sup>MS COCO Challenge: <http://mscoco.org/dataset/#captions-challenge2015>

<sup>2</sup>Amazon Mechanical Turk is crowdsourced Internet marketplace to perform tasks that computers are currently unable to do.

Table 1: Image captioning datasets.

Name	Images	Captions per image	Note
Flickr8k <sup>3</sup>	8 092	5	Focused on people or animals (mainly dogs) performing some specific action.
Flickr30k <sup>4</sup>	31 783	5-6	An extension of Flickr8k dataset.
MS COCO <sup>5</sup>	120 000	5	Images are divided - 80 000 for training and 40 000 for testing purposes.
PASCAL-50S <sup>6</sup>	1 000	50	Built upon images from the UIUC Pascal Sentence Dataset.
ABSTRACT-50S <sup>7</sup>	500	50	Built upon images from the Abstract Scenes Dataset. No photos.

### 3.3 Evaluation

Recent progress in fields like machine translation, which are very similar to image captioning, caused spike of interest in evaluating regular text output accuracy. Although it is sometimes not clear if a description of an image is best option available, some degree of assessment is possible. The best results can be obtained by asking live raters to give a score on the usefulness of each description. Subjective scores can vary, but it can be averaged by giving same description to multiple raters. However this method consumes tremendous amount of time and usually external raters are necessary. Tools like Amazon Mechanical Turk can be used to great extent, but need for automated tools is evident.

#### 3.3.1 Automated metrics

Assuming that one has access to human generated captions, which is ground truth in our case, completely automated metrics exists. Even though all of them compute how alike are generated to human descriptions, different approaches are used. One metric can use several different settings with slight changes in the algorithm. This raises the question, how can we compare results of different works, despite using the ‘same’ evaluation method. Microsoft group of researchers addresses this issue in [4]. They created an evaluation server<sup>8</sup> which

<sup>3</sup>Flickr8k project: <http://nlp.cs.illinois.edu/HockenmaierGroup/8k-pictures.html>

<sup>4</sup>Flickr30k project: <http://shannon.cs.illinois.edu/DenotationGraph/>

<sup>5</sup>MS COCO project: <http://mscoco.org/dataset/>

<sup>6</sup>PASCAL-50S and ABSTRACT-50S: <http://ramakrishnavedantam928.github.io/cider/>

<sup>7</sup>See footnote 6.

<sup>8</sup>MS COCO evaluation server: <http://mscoco.org/dataset/#captions-upload>.

has many automated metrics, with several configurations, including all mentioned here. It will serve as a reference point for comparing image captioning models.

The most commonly used metric has been BLEU (Bilingual Evaluation Understudy)[33], which was created in 2002 to evaluate quality of machine translated text from one language to another. Scores are computed on individual segments, usually sentences. BLEU has high correlation with human judgments and is still highly popular even for captioning tasks. However, it is becoming outdated as automatic methods are now outperforming humans. Four different variations of BLEU are used in MS COCO evaluation server.

METEOR (Metric for Evaluation of Translation with Explicit ORdering)[27] is another metric for the evaluation of machine translation from 2007. It was designed to fix some problems of the BLEU metric and it can also look for synonyms and perform stemming on input words.

Last year, metric designed directly to caption evaluation called CIDEr (Consensus-based Image Description Evaluation)[37] was introduced. This is still new metric, but with growing popularity as it correlate well with human judgment. Main idea of this metric is that given enough captions for the same image, metrics perform better. This can be seen in datasets introduced with it (see part 3.2).



## Chapter 4

# Tools and Experiments

In this chapter I will describe tools and frameworks, which are used to implement deep learning models. *Torch* will be discussed separately in its own section as it was a tool I used for experimenting with language modeling - predicting next character in text, which is second part of this chapter.

One of the tools most academic researchers in deep learning rely on is *Theano*<sup>1</sup>[2], which is Python library that works with mathematical expressions and matrices. It is built upon *NumPy* to handle multidimensional arrays and compiles expressions before use for efficient computation. Theano can be quite intimidating and non-intuitive for some people, as it is focused on researchers and creating new architectures. For this reason, many packages and libraries has been created on top of Theano to simplify and streamline development of standard models. Among most popular are *Keras*<sup>2</sup>, *Lasagne*<sup>3</sup>, *Blocks*<sup>4</sup>, which are open-source and available on GitHub, and *PyLearn2*<sup>5</sup>.

Next Python library, independent of Theano, is *TensorFlow*<sup>6</sup>, a tool from Google, released last year. It is used to process symbolic data flow graphs on many different types of machines, ranging from multiple GPU computers to smartphones. Interesting feature is ability to perform partial subgraph computation, which allows distributed training of the neural network. TensorBoard is a tool worth mentioning, as it provides visualisations of training and evaluation of the model, tool missing in most of the other libraries.

Python tools with the engine implemented in C/C++ are not the only ones. *Caffe*<sup>7</sup> is well-known and widely used library with API in C++. It performs very well in image classification with neural nets and can be used as a source of many pre-trained models hosted on the Model Zoo<sup>8</sup> site. It is also possible to use *Deeplearning4j*<sup>9</sup>, which is deep-learning library written for Java and Scala, and a lot of others. Nowadays, libraries are introduced almost every month as this field is very live, which also means not everything is implemented in every framework and users need to follow news about their tools.

---

<sup>1</sup>Theano: <http://deeplearning.net/software/theano/>

<sup>2</sup>Keras: <https://github.com/fchollet/keras>

<sup>3</sup>Lasagne: <https://lasagne.readthedocs.org/en/latest/>

<sup>4</sup>Blocks: <https://github.com/mila-udem/blocks>

<sup>5</sup>PyLearn2: <http://deeplearning.net/software/pylearn2/>

<sup>6</sup>TensorFlow: <https://www.tensorflow.org/>

<sup>7</sup>Caffe: <http://caffe.berkeleyvision.org/>

<sup>8</sup>Caffe Model Zoo: <https://github.com/BVLC/caffe/wiki/Model-Zoo>

<sup>9</sup>Deeplearning4j: <http://deeplearning4j.org/>

## 4.1 Torch

Torch se zrecykluje do diplomky.

Udelat tady tabulku o ruznych balicich co torch ma

Jak funguji rekurentni site v Torchi.

Nacitani modelu z Caffe, ukladani v Torchi...

### 4.1.1 nn, nngraph

Linky na knihovny.

### 4.1.2 rnn

### 4.1.3 Other packages

loadcaffe, optim,...

## 4.2 Predicting next character in sequence

Implementace sekce Language modeling, jak se to konkretne dela.

Jak jsem to udelal, co to dela, ukazky.

Karpathyho char-rnn

[24]

# Chapter 5

## Model

Do semestrálního projektu nebo až na diplomku?

Design modelu, co chci použít, jaké metody chci zkusit.

Položit si principiální otázku a zjistit, jestli to nějak pomůže, jak to funguje.

### 5.1 Architecture

Architektura modelu, jaké matematické modely jsem použil, bez implementačních detailů.

### 5.2 Training details

Popis pomocí jakého algoritmu jsme trénovali, s jakými parametry, minibatches, datasety.

## Chapter 6

# Conclusion

Udelat jeden zaver pro semestralni projekt, pak ho prepsat pro diplomku.

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