

Department 07
Master Computer Science



Deep learning - Dog Breed Classification

Realization of an native Android app using deep learning algorithms

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WS 17/18 IG
January 28, 2018

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1. Introduction

In this chapter, a short introduction leads to the subject of Deep learning. Furthermore, the scope of this work and its points of reference are described and localized.

1.1. Deep learning

In 2015, AlphaGo - a computer program developed by Google's DeepMind Group that was trained to play the strategic board game Go - was the first program to defeat the multiple European champion Fan Hui under tournament conditions (DeepMind, 2017). Back then, terms like Artificial Intelligence (AI), Machine Learning and Deep Learning were talked of, because those were the reason why a computer program was able to defeat a human being. One of the most frequent used techniques of AI is Machine Learning. It uses algorithms to parse data, process it and learn from it. The result is a prediction or determination as a conclusion of what was learnt from the dataset (NVIDIA - Michael Copeland, 2016). Deep Learning - which is part of the Machine Learning techniques - sells its application particularly in the field of language and image processing (Wick, 2017).

In 1958, Frank Rosenblatt introduced the concept of the perceptron which is the fundamental idea of all Deep learning approaches. It consists of multiple artificial neurons which are coupled with weights and biases. In the case of a single-layer perceptron, the input nodes are fully connected to one or more output nodes. During the learning process the weights are adapted according to the learning progress. When such a structure is extended with layers, it becomes a multi-layer perceptron (MLP). This basic structure can be found in special neural network architectures e.g. Convolutional Neural Networks (CNN). CNNs which are frequently used for object detection and image/ audio recognition etc. consists of multiple neurons (Wick, 2017). When a neuron receives an input, it performs a dot production and adapts the weights. Because of their special structure, CNNs are able to detect local properties of an image. Basically, the network represents a differentiable score function which is applied on the raw image pixels and computes the class scores as an output (University of Stanford, nd).

1.2. Terms of Reference

The problem of Deep learning architectures is their high performance requirements regarding computational power. Common frameworks for open source development in the field of deep learning which are discussed in section 2.1 introduced several models for the integration in mobile applications.

In order to overcome the above mentioned problem, optimizing methods will be combined with appropriate models which require less computing power and are suitable for mobile application integration. As a result of this work, a dog breed analyzer will be implemented. This mobile app will take a live camera stream as an input and determine the breed of the focused dog. The three highest probabilities of breeds will be shown by the app.

1.3. Recent Work GitHub Repository

The entire work done within this paper can be found in the GitHub repository <https://github.com/awilsee/dl.git>.

2. Methodological fundamentals

This chapter describes the most frequently used frameworks in deep learning for developing applications. Furthermore, common models for deep learning are introduced. The chapter closes listing key requirements for an appropriate dataset which increases the quality of the training results.

2.1. Common Frameworks for Deep Learning Applications

The demands on neural networks increase with the complexity of problems to solve. Concurrently, there's an expanding offer of deep learning frameworks with a variety of features and tools. The most common used ones are represented in the following section.

2.1.1. Tensorflow

In 2015, the Google Brain Team introduced the most popular deep learning API Tensorflow which is an open-source library for numerical computation. Its current version 1.4.1 was released on December 8th, 2017 (TensorFlow, 2017d). Tensorflow is primarily used for machine learning and deep neural network research. Based on the programming language Python, Tensorflow is capable of running on multiple CPUs and GPUs. Furthermore, C++ and R are supported by Tensorflow (Varangaonkar, 2017). Another feature is the possibility to generate models and export them as .pb file which holds the graph definition (GraphDef). The export is done by protocol buffers (protobuf) which includes tools for serializing and processing structured data. When loading a .pb file by protobuf, an graph object is created which holds a network of nodes. Each of these nodes represent an operation and the output is used as input for another operation. This concept enables an user to create self-built tensors (TensorFlow, 2017f). To simplify the usability, Tensorflow developed a high-level wrapper of the native API which is called Tensorflow Slim (TensorFlow, 2017e). Furthermore, in order to run Tensorflow on performance critical devices like e.g. mobile devices, two lightweight solutions of Tensorflow are available: Tensorflow Mobile and Tensorflow Lite. The latter one is an evolution of Tensorflow Mobile and still in developer mode. But both are predestinated for integration in mobile applications (TensorFlow, 2017c).

2.1.2. Keras

In order to simplify the utilization of Tensorflow the Python based interface Keras can be configured to work on top of Tensorflow. It allows building neural networks in a simple way and is part of Tensorflow (Varangaonkar, 2017).

2.1.3. Caffe

Another deep learning library is Caffe which was developed by Berkeley AI Research (BAIR). Based on C++ or Python, it focuses on modeling CNNs. An main advantage of Caffe is the offer of pretrained models available in the Caffe Model Zoo (BAIR, nd).

2.1.4. Torch and PyTorch

Besides Tensorflow and Caffe, Torch is another common deep learning framework. It was developed by Facebook, Twitter and Google. Based on C/C++, Torch supports CUDA for GPU processing. Like above mentioned frameworks, Torch facilitates the building of neural networks. The Python based version of Torch is available through PyTorch (Varangaonkar, 2017).

2.2. Common Models in Deep Learning Applications

State of the art models for image recognition in deep learning applications are based on the CNNs architecture. The most important ones are explained in this section.

The first model was LeNet-5 described in LeCun et al. (1998). As shown in figure 1, it contains seven layers in summary. These are two convolutional layers with a 5×5 filter each followed by a sub-sampling pooling layer. Two fully connected layers complete the architecture of the multi-layer perceptron with its softmax function applied.

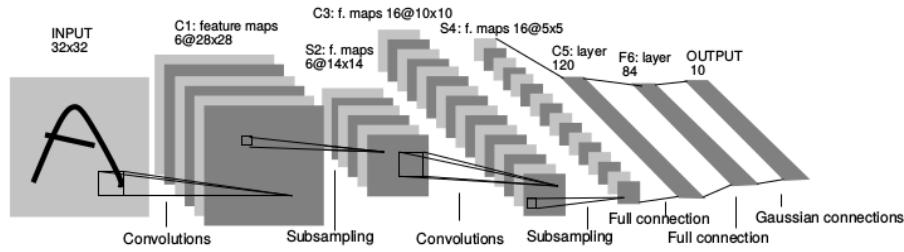


Figure 1: Model architecture of LeNet-5 (LeCun et al., 1998, p. 7)

In 2012, a CNN based network called AlexNet pictured in Krizhevsky et al. (2012) won the ImageNet Large Scale Visual Recognition Challenge (ILSVRC) for the first time (figure 2). From this time, CNN became ubiquitous.

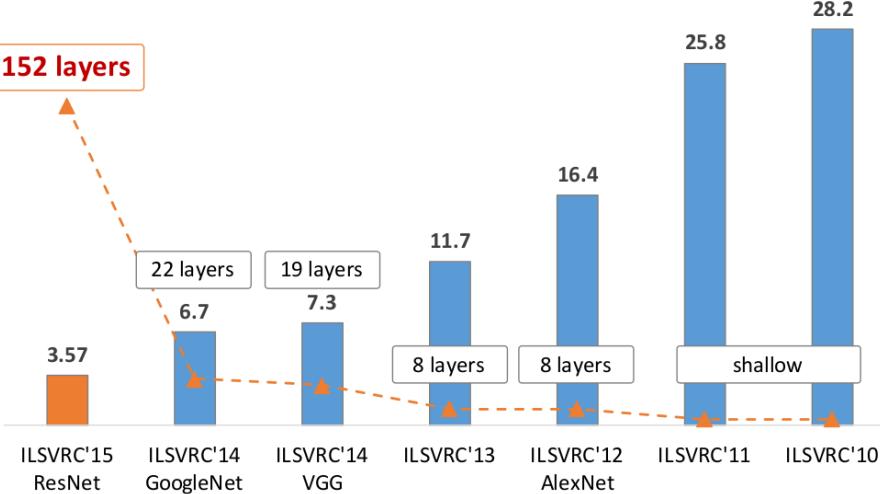


Figure 2: ImageNet Classification top-5 error (%) (He, 2016, p. 6)

Through its immensely improved accuracy the network created new possibilities. This CNN consists of eight layers shown in figure 3. The first convolutional layer has a large 11×11 filter. Furthermore, there is one layer with a 5×5 filter and another three with a 3×3 filter, so in total 5 convolutional layers. Three pooling layers and three fully connected layers complete the architecture. For the first time, a so called Rectified Linear Unit (ReLU) was used which is capable of being spread across two GPUs.

As shown in figure 2, the next improvements were two architectures called VGG as described in Simonyan and Zisserman (2015) and GoogLeNet which is presented in Szegedy et al. (2014). Introduced in 2014, they were considered as very deep neural networks. GoogLeNet is also known

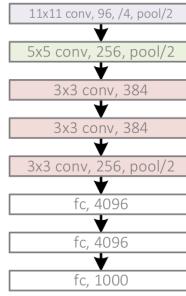


Figure 3: Model architecture of AlexNet (He, 2016, p. 7)

as *InceptionV1*.

VGG comprises 16 or 19 layers in total (figure 4). This network is characterized by its simplicity because it uses convolutional layers with a 3x3 filter which are stacked on top of each other. Size reduction is handled by pooling layers. At the end, there are three fully connected layers with the softmax function followed.

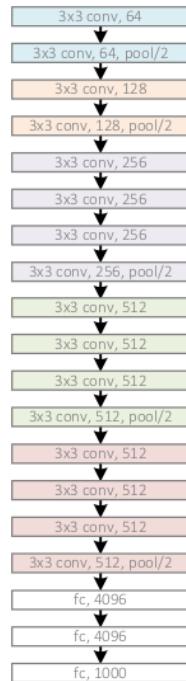


Figure 4: Model architecture of VGG19 (He, 2016, p. 8)

Whereas, GoogLeNet has 22 layers (appendix under section A.1) and was the final winner in 2014. At the beginning, it has two convolutional layers followed by stacked Inception modules. Such modules consists of several parallel convolutional layers with different filter size and in addition one pooling layer as shown in figure 5. On the right side of this figure a convolutional layer with a 1x1 filter is pictured which is used to reduce feature depth. At the end, the output of these modules are concatenated and taken as new input for the next layer. The network ends with one fully connected layer.

Since 2015 it gets very deep with a new architecture named ResNet of He et al. (2015). On ILSVRC this network swept all competitors in classification and detection. The network itself is designed as a 152 layer model. The ResNet consists of many residual network blocks (appendix under section A.2). Each of them has two convolutional layers with a 3x3 filter. Furthermore,

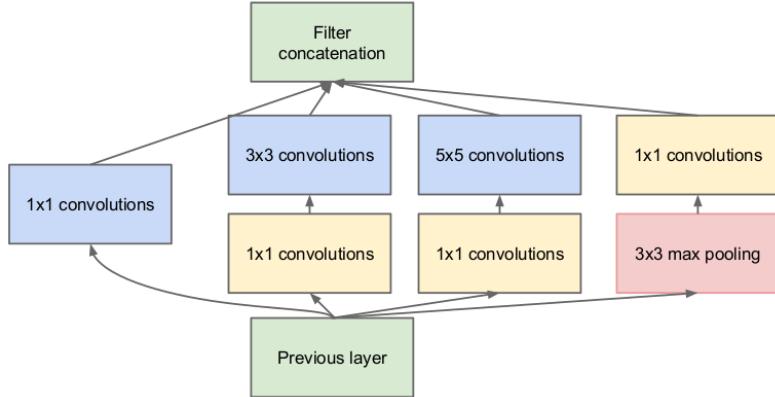


Figure 5: Inception modules (Szegedy et al., 2014, p. 5)

there is a shortcut connection which will be used if the input and output dimension of this block are the same.

Especially for performance critical devices MobileNet was developed by Google as described in Howard et al. (2017). The network structure consists of depthwise seperable convolutional parts but also one standard convolutional layer at the beginning. The depthwise part is separated in a depthwise convolutional layer and a pointwise one which applies a 1x1 convolution. Each of this layers are followed by batchnormalisation and ReLU as shown in figure 6. In the depthwise convolutional section two convolutional layers are splitted in the one for filtering and in the one for combining. As an effect, the computation power and model size are massively reduced which results in better performance on low performance devices.

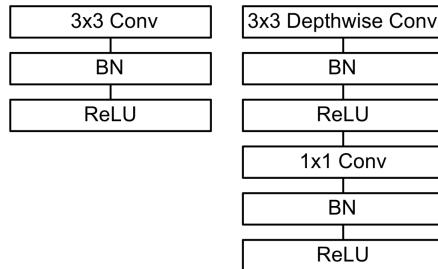


Figure 6: Standard convolution and depthwise seperable convolution (Howard et al., 2017, p. 4)

2.3. Key requirements for an appropriate dataset

Supervised learning tasks such as image recognition are based on operations where an output is taken as an input for the next node. Every raw pixel input is taken to compute an intermediate representation - a vector containing all learned information about the dataset. As a consequence, the training results are only as good as the dataset itself. For better accuracy its important to train a model on a variety of images for each object which should later be classified by the model. It's recommended to take images of an object which were taken at different times, with different devices and at different places. Otherwise, the model will concentrate on other things like for example the background instead of details about the object itself. Therefore, a huge dataset is required especially for non pre-trained models. Training a model from scratch will require a huge dataset, a lot of computing power and time. Whereas pre-trained models only require a small dataset of about hundreds of images. For that reason, a pre-trained model will be used in this work (TensorFlow, 2017a).

3. Concept

First, this chapter describes the selection of the appropriate framework. Furthermore, the structure of the model which was used for classification is explained based on its architecture. The chapter closes with the class diagram of the mobile application.

3.1. Frameworks

As a deep learning framework, Tensorflow was used to retrain the model. This decision was mainly based on recommendations. Even companies like e.g. NVIDIA Corporation, Intel Corporation etc. use Tensorflow. It is one of the common frameworks for deep learning applications and also provides solutions for integration in mobile apps. Furthermore, Tensorflow provides a variety of tutorials for working with neural networks. Beside those advantages, there is a large community about Tensorflow talking about issues and solutions (TensorFlow, 2017d).

To run the tensor within a mobile application, the first approach was to use Tensorflow Lite which is still in development state. But many attempts resulted in corrupt models which caused the app to terminate. Because of this experiences Tensorflow Mobile was used to optimize the model for app integration.

3.2. Qualified models for mobile app integration

In Tensorflow Lite only InceptionV3 and MobileNet models are supported. With Tensorflow Mobile it's the same. There are different versions of MobileNet. They differ in the input image size and in the number of parameters which is also proportional to the size and needed computation power of the network.

While the Inception model was well known and established, the MobileNet is relatively new. InceptionV3 models gets an higher accuracy than MobileNets but MobileNets are more optimized on small size, low latency and low-power consumption which are important characteristics for mobile usage. (TensorFlow, nd)

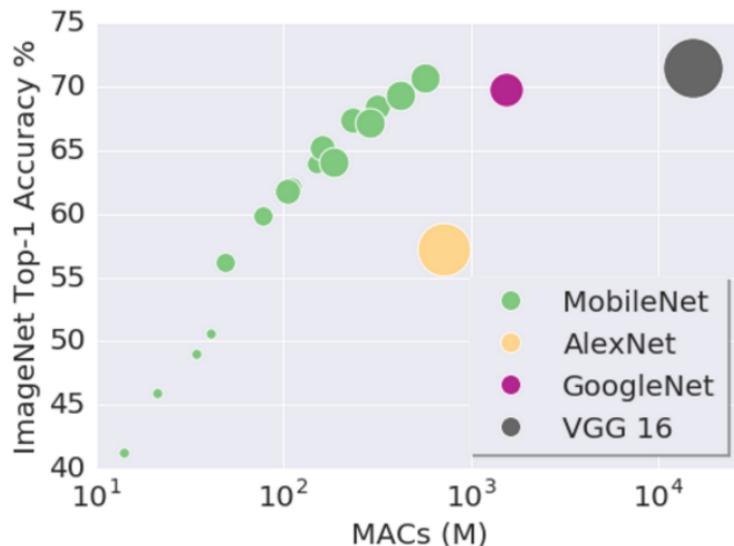


Figure 7: Comparison of popular models (TensorFlow, nd)

In figure 7, the MobileNet and Inception is compared with each other and also with other popular models already mentioned before in section 2.2. It shows the Top-1 accuracy and the Multiply-

Accumulates (MACs) which measures the number of fused multiplication and addition operations. The latter numbers reflect the latency and power consumption of the network and so in result the efficiency. For well comparison reasons between MobileNet and InceptionV1, a MobileNet model with similar accuracy to the Inception one was picked, in order to be more precisely than with the MobileNet_1.0_224. To check out the possibilities of MobileNet, another model, the MobileNet_0.50_244, was selected, too.

3.3. Application based Architecture

This chapter describes the functions to a basic understanding of how the application works based on the application's architecture. It focuses on the important classes and methods of the mobile application.

Tensorflow provides a mobile application for demo purposes (GitHub, 2017). The approach was to understand how the application was implemented regarding the functionality of the camera, image input for the network and background classification besides live camera stream. Then, because of the complexity the application was adapted to our needs.

The ClassifierActivity is set as the launcher activity of the application. It extends the class CameraActivity and loads the CameraFragment which controls the camera view. The CustomTextureView enables the possibility to capture frames from a camera stream and process it. Because of this function, the CustomTextureView is part of the class CameraFragment. If an image is captured, the method onImageAvailable of the class ClassifierActivity is invoked. The classification itself is done by the TensorflowImageClassifier which implements the interface Classifier from the Tensorflow API. The results are displayed by the class RecognitionScoreView which implements the interface ResultsView.

4. Realization

In general, this chapter describes the methodical procedure of solving the problem mentioned in section 1.2. After describing the used dataset all required software and hardware components are explained in detail. Furthermore, the chapter leads through the installation steps of Tensorflow and the setup of Android Studio. Followed by the installation process the retraining of a pre-trained model is depicted. Afterwards, the re-trained model is tested and validated. The chapter ends with the description of the realization of the Android app.

4.1. Dataset

The most famous image dataset is ImageNet which is known from the ILSVRC2012. It contains overall about 14 million Images (ImageNet, 2010). This dataset is also used for nearly all pre-trained models. The dataset includes a set of 120 different dog breeds with about 150 images each breed. This dog dataset can be downloaded from the following Stanford website <http://vision.stanford.edu/aditya86/ImageNetDogs/>.

Another dataset with dogs is from Udacity and can be downloaded from <https://s3-us-west-1.amazonaws.com/udacity-aind/dog-project/dogImages.zip>. It contains 133 dog breeds with a mean of 63 images each breed. The images in this dataset are completely different from the ImageNet dataset.

Because of the reason that the ImageNet dataset is already used to train the pretrained models, the last dataset is used for this project, which is fully unknown for any pretrained model.

4.2. Hardware environment

Different hardware setups are used for this project to compare the performance of the mobile application. At first the lowest one is a notebook with an Intel(R) Core(TM) i7-4720HQ CPU @ 2.60GHz and 16 GB memory. The other one is a powerful desktop computer with an Intel(R) Core(TM) i7-6700K CPU @ 4.4 GHz and 16 GB memory. In this computer there is also a NVIDIA GeForce GTX 980 with CUDA capabilities version 5.2. It has 2048 CUDA cores running @ 1.291 GHz and 4 GB memory.

For good performance comparison of the mobile application also two different mobile phones are used. The first one is a Samsung Galaxy S4 (GT-I9515) with a Qualcomm Snapdragon S600 Quad-Core @ 1.9 GHz (32-bit) and 2 GB memory. The operating system is Android 5.0.1 (API 21) is running. The other one is a Motorola Moto X (2nd Gen, 2014) with a Qualcomm Snapdragon 801 Quad-Core @ 2.5 GHz (32-bit, ARMv7-ISA) and 2 GB memory. Here, the operating system is Android 6.0 (API 23).

4.3. Installation of software

This chapter describes all necessary steps for installing the software environment including Tensorflow.

4.3.1. Prerequisites

The software environment was set up on the Linux distribution Ubuntu 16.04 LTS. To install the software environment for Tensorflow, Python is required. Therefore, the current version of Python 3.6 was installed by default. Tensorflow also supports Bazel which was installed by following command (Bazel, 2018).

```

1 sudo apt-get install openjdk-8-jdk
2
3 echo "deb [arch=amd64] http://storage.googleapis.com/bazel-apt stable jdk1.8" | sudo
   tee /etc/apt/sources.list.d/bazel.list
4 curl https://bazel.build/bazel-release.pub.gpg | sudo apt-key add -
5
6 sudo apt-get update && sudo apt-get install bazel
7
8 sudo apt-get upgrade bazel

```

Listing 1: Bazel Installation

Futhermore, the package and environment management tool Anaconda was installed by the following steps: First, the Anaconda installer was downloaded from <https://www.anaconda.com/download/#linux>. During the installation process the prompts were answered by the default suggestions except the following prompt: "Do you wish the installer to prepend the Anaconda3 install location to PATH in your /home/aw/.bashrc ? [yes—no]". "yes" was typed in and conda was tested using the "conda list" command (Anaconda, 2017).

In the development of native Android Apps, Java is used as the programming language. Within the installation of Anaconda, the JDK in the version 8 was installed.

For using Tensorflow with GPU support, further NVIDIA software must be installed which is the so called Compute Unified Device Architecture (CUDA) and the CUDA Deep Neural Network library (cuDNN). The requirements will be decribed in the following, otherwise check out https://www.tensorflow.org/install/install_linux#nvidia_requirements_to_run_tensorflow_with_gpu_support.

To use TensorFlow with GPU support, the older CUDA Toolkit in version 8.0 and cuDNN in version 6.0 must be installed.

The first step is to validate that the GPU card support at least CUDA Compute Capability 3.0 which can be seen on <https://developer.nvidia.com/cuda-gpus>.

Next, CUDA Toolkit 8.0 GA2 must be downloaded from <https://developer.nvidia.com/cuda-downloads>. Correct target settings must be set and the debian-file must be downloaded. An installation guide can also be downloaded, however all relevant steps are described here.

The kernel headers and development packages for the currently running kernel has to be installed using following command (listing 2).

```
1 sudo apt-get install linux-headers-$ (uname -r)
```

Listing 2: Installation of linux-headers

The installation of CUDA is shown in listing 3.

```
1 sudo dpkg -i cuda-repo-ubuntu1604-8-0-local-ga2_8.0.61-1_amd64.deb
2 sudo apt-get update
3 sudo apt-get install cuda-8-0
```

Listing 3: Installation of CUDA

If a newer version of CUDA is already installed, it can be removed by the prompts depicted in listing 4

```
1 sudo apt-get remove cuda
2 sudo apt-get autoremove
3 sudo apt-key remove /var/cuda-repo-..../....pub #fill in correct path/file
```

Listing 4: Removing newer CUDA version

To verify the installation, the verification environment must be set up by following commands (refer to listing 5).

```
1 export PATH=/usr/local/cuda-8.0/bin${PATH:+:${PATH}}
2
3 #To change the environment variables for 32-bit operating systems:
4 export LD_LIBRARY_PATH=/usr/local/cuda-8.0/lib\$ ${LD_LIBRARY_PATH:+:${LD_LIBRARY_PATH}}
5 #To change the environment variables for 64-bit operating systems:
6 export LD_LIBRARY_PATH=/usr/local/cuda-8.0/lib64\$ ${LD_LIBRARY_PATH:+:${LD_LIBRARY_PATH}}
7
8 cuda-install-samples-8.0.sh <dir> #fill in directory for downloaded samples
```

Listing 5: Setup CUDA verification environment

The downloaded samples were renamed to *NVIDIA_CUDA-8.0_Samples* and compiled by *make*.

Thereafter, *deviceQuery* was executed which is placed in the directory *NVIDIA_CUDA-8.0_Samples/bin/*. The output is shown in figure 8. The important outcomes are that a device was found and that the final test passed.

In order to check if the system and the CUDA device are able to communicate with each other correctly, *bandwidthTest* was executed. The output is shown in figure 9.

For downloading cuDNN from <https://developer.nvidia.com/cudnn>, a registration for the NVIDIA Developer Program is needed. The three debian-files were downloaded from *cuDNN 6.0 for CUDA 8.0* according to the corresponding platform environment. Afterwards the installation was done by the following prompts shown in listing 6.

```
aw@tux:~/Downloads/NVIDIA_CUDA-8.0_Samples/bin/x86_64/linux/release$ ./deviceQuery
./deviceQuery Starting...

CUDA Device Query (Runtime API) version (CUDART static linking)

Detected 1 CUDA Capable device(s)

Device 0: "GeForce GTX 980"
  CUDA Driver Version / Runtime Version      9.0 / 8.0
  CUDA Capability Major/Minor version number: 5.2
  Total amount of global memory:             4096 MBytes (4224909312 bytes)
  (16) Multiprocessors, (128) CUDA Cores/MP:
  GPU Max Clock rate:                      1291 MHz (1.29 GHz)
  Memory Clock rate:                       3505 Mhz
  Memory Bus Wdthb:                         256-bit
  L2 Cache Size:                           2097152 bytes
  Maximum Texture Dimension Size (x,y,z):  1D=(65536), 2D=(65536, 65536), 3D=(4096, 4096, 4096)
  Maximum Layered 1D Texture Size, (num) layers: 1D=(16384), 2048 layers
  Maximum Layered 2D Texture Size, (num) layers: 2D=(16384, 16384), 2048 layers
  Total amount of constant memory:          65536 bytes
  Total amount of shared memory per block:   49152 bytes
  Total number of registers available per block: 65536
  Warp size:                               32
  Maximum number of threads per multiprocessor: 2048
  Maximum number of threads per block:       1024
  Max dimension size of a thread block (x,y,z): (1024, 1024, 64)
  Max dimension size of a grid size (x,y,z): (2147483647, 65535, 65535)
  Maximum Memory pitch:                     2147483647 bytes
  Texture alignment:                        512 bytes
  Concurrent copy and kernel execution:    Yes with 2 copy engine(s)
  Run time limit on kernels:               Yes
  Integrated GPU sharing Host Memory:     No
  Support host page-locked memory mapping: Yes
  Alignment requirement for Surfaces:      Yes
  Device has ECC support:                 Disabled
  Device supports Unified Addressing (UVA): Yes
  Device PCI Domain ID / Bus ID / location ID: 0 / 1 / 0
  Compute Mode:
    < Default (multiple host threads can use ::cudaSetDevice() with device simultaneously) >

deviceQuery, CUDA Driver = CUDART, CUDA Driver Version = 9.0, CUDA Runtime Version = 8.0, NumDevs = 1, Device0 = GeForce GTX 980
Result = PASS
```

Figure 8: CUDA Verification - valid results from deviceQuery

```
aw@tux:~/Downloads/NVIDIA_CUDA-8.0_Samples/bin/x86_64/linux/release$ ./bandwidthTest
[CUDA Bandwidth Test] - Starting...
Running on...

Device 0: GeForce GTX 980
Quick Mode

Host to Device Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes)      Bandwidth(MB/s)
  33554432                  12908.5

Device to Host Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes)      Bandwidth(MB/s)
  33554432                  13218.3

Device to Device Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes)      Bandwidth(MB/s)
  33554432                  159783.0

Result = PASS
NOTE: The CUDA Samples are not meant for performance measurements. Results may vary when GPU Boost is enabled.
```

Figure 9: CUDA Verification - valid results from bandwidthTest

```

1 sudo dpkg -i libcudnn6_6.0.21-1+cuda8.0_amd64.deb
2 sudo dpkg -i libcudnn6-dev_6.0.21-1+cuda8.0_amd64.deb
3 sudo dpkg -i libcudnn6-doc_6.0.21-1+cuda8.0_amd64.deb

```

Listing 6: Installation of cuDNN

To verify that cuDNN is working correctly, mnistCUDNN was compiled and executed with the following commands (listing 7).

```

1 cp -r /usr/src/cudnn_samples_v6/ $HOME
2 cd $HOME/cudnn_samples_v6/mnistCUDNN
3 make clean && make
4 ./mnistCUDNN

```

Listing 7: Verification of cuDNN

At the end, the outcome *Test passed!* occurred.

As a last step, the libcupti-dev library was installed and exported by the following commands listing 8.

```

1 sudo apt-get install cuda-command-line-tools
2 export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/usr/local/cuda/extras/CUPTI/lib64

```

Listing 8: Verification of cuDNN

4.3.2. Tensorflow based on Python

First, there are some necessary dependencies to install before the actual installation can begin (refer to listing 9).

```
1 sudo apt-get install python3-numpy python3-dev python3-pip python3-wheel
```

Listing 9: Installing the dependecies for Tensorflow based on Python 3.n

In order to install Tensorflow with Anaconda, an Anaconda environment must be created using following command (refer to listing 10).

```
1 conda create -n tensorflow python=3.6
```

Listing 10: Creating an Anaconda environment

This command depends on the version of Python installed on the computer. Next, the created environment is activated through following line (listing 11).

```
1 source activate tensorflow
```

Listing 11: Activating the Anaconda environment

Futhermore, Tensorflow was installed through the Anaconda environment for CPU only by the following command (refer to listing 12).

```
1 pip install --ignore-installed --upgrade https://storage.googleapis.com/tensorflow/
    linux/cpu/ tensorflow-1.4.1-cp36-cp36m-linux_x86_64.whl
```

Listing 12: Installing Tensorflow through Anaconda

For GPU the tfBinaryURL was changed to https://storage.googleapis.com/tensorflow/linux/gpu/tensorflow_gpu-1.4.1-cp36-cp36m-linux_x86_64.whl.

In order to validate the installation, a following short Python script was executed in the Anaconda environment (refer to listing 13).

```

1 # Python
2 import tensorflow as tf
3 hello = tf.constant('Hello, TensorFlow!')
4 sess = tf.Session()
5 print(sess.run(hello))

```

Listing 13: Installing Tensorflow through Anaconda

If the output is 'Hello, TensorFlow!', the installation was conducted sucessfully. Each time when working with Tensorflow, the environment has to be activated using the command in listing 11. As a consequence, the environment has to be deactivated when the work is done using the command 'deactivate' (TensorFlow, 2017b).

4.3.3. Tensorflow based on Bazel

Another way of working with Tensorflow is using Bazel. In order to install, refer to listing 1. After the Bazel installation is completed, the Tensorflow repository can be cloned by following command (refer to listing 14).

```

1 git clone https://github.com/tensorflow/tensorflow

```

Listing 14: Cloning the tensorflow repository

Now, the installation can be configured. The configuration and its prompts are shown in section A.3. If GPU usage is desired, some configurations might differ from the shown configuration steps. The differences are explained in section 4.3.1.

Furthermore, the Android SDK and NDK must be added to the workspace of Bazel. This is done by removing the comments in the WORKSPACE file which is located in the source directory of the Tensorflow repository and adapting the PATH variable according to the location of the SDK and NDK. NDK 16 which was released on November 2017 is incompatible with Bazel.

Then, the Tensorflow pip package can be built by Bazel using the command shown in listing 15 which also enables Streaming SIMD Extensions 2 introduced by Intel Corporation to process data with doubled accuracy. For GPU support the option '--config=cuda' was added to the build command (GitHub, 2018).

```

1 bazel build -c opt --copt=-msse4.2 //tensorflow/tools/pip_package:build_pip_package
2 bazel-bin/tensorflow/tools/pip_package/build_pip_package /tmp/tensorflow_pkg

```

Listing 15: Building the Tensorflow pip package

Finally, the pip package is installed by executing the following command listing 16.

```

1 sudo pip install --upgrade /tmp/tensorflow_pkg/tensorflow-*.whl

```

Listing 16: Installing the pip package

Instead of using the placeholder '-*', the version can also be specified. Which Tensorflow version is used, can be determined by executing 'pip list |grep tensorflow' depending on the Python version. The version of Tensorflow used in this work is 1.4.1. The validation of the installation is done by executing the command shown in listing 13 (TensorFlow, 2018).

4.3.4. Installing Android Studio and its Delevopment Kit

As an app development environment the free IDE Android Studio in its version 3.0.1 was installed by downloading from <https://developer.android.com/studio/index.html>. After the archive file was extracted, the script studio.sh was executed. Required dependencies are installed by Android Studio itself. Futhermore, Android Studio automatically installs the necessary SDK and NDK. So, the SDK in the version 26.1.1 and the NDK in its version 16.1 were used.

If Android Studio doesn't install the necessary Development Kits, the appropriate SDK and NDK version can be installed by selecting the SDK and NDK in the section File - Settings - Appearance and Behaviour - System Settings - Android SDK. Thereby, in order to avoid any collapses when running the app, it's important to check the used Tensorflow version in the dependency which has to correspond to the Tensorflow version which was used to retrain the model.

4.4. Building the models

In this section the whole build and re-/training process is described. Additionally, several comparisons of the execution time on different hardware setups are done.

After setting up the entire software environment independent of a Python/ Bazel/ GPU/ CPU based setup, the models can be retrained. For several reasons as already explained in section 2.3 and section 4.1 pretrained models are used for this project. The script used for retraining will automatically download the desired pretrained model.

In general, all existing weights of the pretrained model will be left untouched except for the final layer which is retrained from scratch. Thus, the pretrained model trained on its original task and labels can be adapted to a new task and new labels, even if the task and the labels are completely different. This technique is called transfer learning. (TensorFlow, 2017a)

For easier use some variables have been defined which are shown in listing 17. Some of them have to be changed depending on the used model, others are optionally.

All of these variables are used in the entire project for every execution of a python script or an executable built by bazel.

```

1 #for InceptionV3 models use:
2 INPUT_SIZE=299           #size of input layer
3 ARCHITECTURE=inception_v3 #name of architecture
4 INPUT_LAYER=Mul          #name of input layer
5 #OUTPUT_LAYER=softmax    #name of output layer (only pretrained model)
6 OUTPUT_LAYER=final_result #name of output layer (after retraining)
7
8 #for MobileNet models use:
9 INPUT_SIZE=224           #size of input layer
10 VERSION=0.50             #version of MobileNet
11 ARCHITECTURE=mobilenet_${VERSION}_${INPUT_SIZE} #name of architecture
12 INPUT_LAYER=input         #name of input layer
13 #OUTPUT_LAYER=MobilenetV1/Predictions/Reshape_1 #name of output layer (only
   pretrained model)
14 OUTPUT_LAYER=final_result #name of output layer (after retraining)
15
16 #optional
17 DOG_PATH=${HOME}/dog_photos  #path with images for retraining
18 RETRAIN_PATH=${HOME}/MobileInceptionRetrained  #path for all output data
19 TRAINING_STEPS=500          #how many training steps
20 LEARNING_RATE=0.01          #learning rate

```

Listing 17: Defining terminal variables

To retrain a model the python script *code/scripts/retrain.py* from the github repository of this project is used and executed as shown in listing 18. This script is taken from (GitHub, 2017) and is extended with some time measuring markers. All relevant parameters are explained later in this section. However, for retraining the following command was used *python -m scripts.retrain -h*.

```

1 python -m scripts.retrain \
2   --bottleneck_dir=${RETRAIN_PATH}/bottlenecks_${ARCHITECTURE} \
3   --how_many_training_steps=${TRAINING_STEPS} \
4   --model_dir=${RETRAIN_PATH}/models_${ARCHITECTURE}/ \
5   --summaries_dir=${RETRAIN_PATH}/training_summaries/${ARCHITECTURE}_${TRAINING_STEPS} \
6   ${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE} \
7   --output_graph=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/ \
retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
8   --output_labels=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/ \
retrained_dog_labels_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.txt \
9   --architecture=${ARCHITECTURE} \
10  --image_dir=${DOG_PATH} \
11  --learning_rate=${LEARNING_RATE}

```

Listing 18: Call of *retrain.py*

For the alternative execution method with the binary built by bazel, see listing 19.

```

1 bazel build tensorflow/examples/image_retraining:retrain && \
2 bazel-bin/tensorflow/examples/image_retraining/retrain \
3   --bottleneck_dir=${RETRAIN_PATH}/bottlenecks_${ARCHITECTURE} \
4   --how_many_training_steps=${TRAINING_STEPS} \
5   --model_dir=${RETRAIN_PATH}/models_${ARCHITECTURE}/ \
6   --summaries_dir=${RETRAIN_PATH}/training_summaries/${ARCHITECTURE}_${TRAINING_STEPS} \
${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE} \
7   --output_graph=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/ \
retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
8   --output_labels=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/ \
retrained_dog_labels_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.txt \
9   --architecture=${ARCHITECTURE} \
10  --image_dir=${DOG_PATH} \
11  --learning_rate=${LEARNING_RATE}

```

Listing 19: Build and call of *retrain*

The first parameter called *bottleneck_dir*, describes the path for caching bottleneck values in files. The option *how_many_training_steps* defines the quantity of training steps. *model_dir* is the directory, where the pretrained model should be downloaded and extracted. *summaries_dir* is the path, where additionally visualization data will be stored. In *output_graph* and *output_labels* the path and name of the new graph respectively new labels are defined. *architecture* represents the desired architecture. *image_dir* is the location of the image to retrain on. *learning_rate* specifies the learning rate during training.

First, this script downloads the pretrained model from TensorFlow if it doesn't already exist. Then it loads the model info of the pretrained graph and internally sets up the graph.

Afterwards the function *create_image_lists* is called, which separates all images from the image directory for training, validation and testing sets. The separation depends on the label name, because the script calculates a hash of it and according to the calculated hash it gets its corresponding label. The benefit is, that all existing images are kept in the same set, even if later files are added.

After this preparatives, bottleneck values for all images are calculated and cached on disk. Bottlenecks are mostly used for the layer just before the final result layer. Because of reusing every image multiple times during training, it saves a lot of time using the cached values, thus the first part, until the bottleneck, is constant. (TensorFlow, 2017a)

This process takes some time depending on the hardware setup and on the chosen model, which is indicated in figure 10. Of course the setup with GPU is the fastest, with about 50 seconds for MobileNets and 300 seconds for InceptionV3. At this point a GPU is a great benefit.

On average the powerful desktop-CPU takes four times longer and the notebook even takes six times longer as with the GPU setup. On an average, the notebook takes 1.4 times longer than the desktop-CPU although the desktop-CPU theoretically is 1.6 times faster.

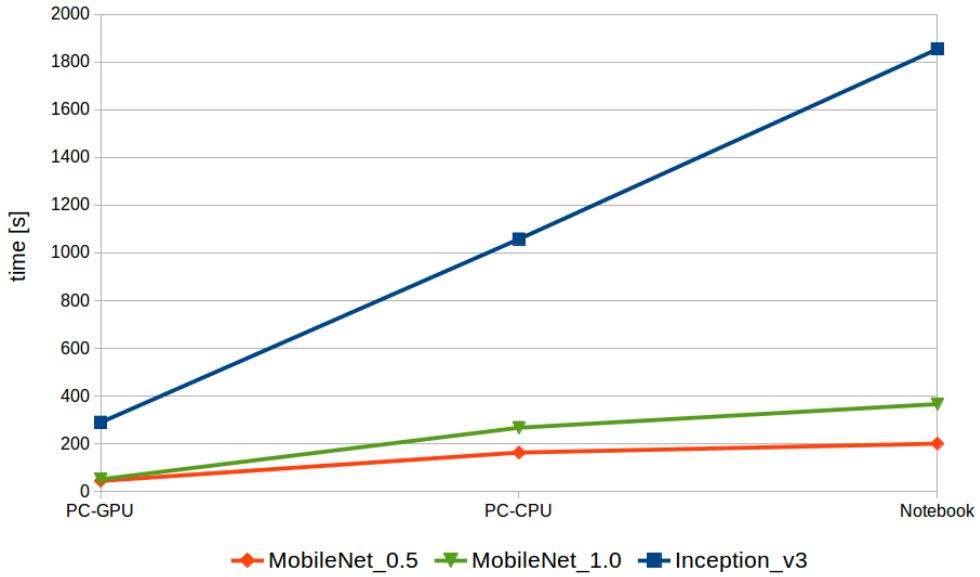


Figure 10: Total time creating bottlenecks

Listing 20 shows the workload of the GPU during calculation which can be produced by executing `nvidia-smi -l 1`. It works at 38% capacity and uses about 3160 MiB memory. Whereas the CPU is only utilized at 110% of the maximum 800% because of four cores with hyper threading which can be seen in the upper part of figure 11. The lower part of this figure shows about 470% workload if calculating everything with the desktop-CPU only.

```

1 nvidia-smi -l 1
2 | GPU Name Persistence-M| Bus-Id Disp.A | Volatile Uncorr. ECC |
3 | Fan Temp Perf Pwr:Usage/Cap| Memory-Usage | GPU-Util Compute M. |
4 |=====+=====+=====+=====+=====+=====+=====|
5 | 0 GeForce GTX 980 Off | 00000000:01:00.0 On | N/A |
6 | 1% 30C P2 68W / 196W | 3873MiB / 4029MiB | 38% Default |
7 +-----+-----+-----+-----+-----+
8 | Processes:                                     GPU Memory |
9 | GPU PID Type Process name                   Usage   |
10|=====+=====+=====+=====+=====+=====+=====|
11| 0 1065 G /usr/lib/xorg/Xorg           584MiB |
12| 0 1675 G compiz                      83MiB  |
13| 0 12867 G ...-token=A79FC92A8A549F181FB5DBE83D71EFC2 31MiB |
14| 0 26527 C python                     3159MiB |

```

Listing 20: Build and call of *retrain*

Once finished with creating the bottleneck values, training of the final layer begins. In each step, random images of the training set will be fed into the final layer to get predictions. Those predictions are now used to update the final layer weights through the back-propagation process. The script outputs the *train accuracy*, *cross entropy* and the *validation accuracy* each 10th step. This can be seen on listing 21, which is a shortened output. At the end a final test evaluation with the testing image set is run which results in the *final test accuracy*. Furthermore, some time measurings are printed out. (TensorFlow, 2017a)

```

GPU calculating
top - 13:52:11 up 2 days, 2:19, 1 user, load average: 0,52, 0,50, 0,70
Tasks: 242 gesamt, 1 laufend, 241 schlafend, 0 gestoppt, 0 Zombie
%CPU(s): 14,8 be, 0,9 sy, 0,0 ni, 84,2 un, 0,0 wa, 0,0 hi, 0,1 si, 0,0 st
KiB Spch : 16381648 gesamt, 488276 frei, 5314092 belegt, 10579280 Puff/Cache
KiB Swap: 974844 gesamt, 974844 frei, 0 belegt. 10501708 verfü Spch

  PID USER      PR  NI    VIRT    RES    SHR S %CPU %MEM     ZEIT+ BEFEHL
17880 aw        20   0 31,781g 1,254g 396376 S 110,6 8,0    0:20.41 python
1065 root      20   0 1137300 366304 88180 S 16,6 2,2   60:10.97 Xorg

CPU calculating all
top - 13:54:33 up 2 days, 2:21, 1 user, load average: 1,05, 0,62, 0,71
Tasks: 245 gesamt, 2 laufend, 243 schlafend, 0 gestoppt, 0 Zombie
%CPU(s): 59,0 be, 0,9 sy, 0,0 ni, 40,0 un, 0,0 wa, 0,0 hi, 0,0 si, 0,0 st
KiB Spch : 16381648 gesamt, 1172768 frei, 4503052 belegt, 10705828 Puff/Cache
KiB Swap: 974844 gesamt, 974844 frei, 0 belegt. 11375376 verfü Spch

  PID USER      PR  NI    VIRT    RES    SHR S %CPU %MEM     ZEIT+ BEFEHL
22270 aw        20   0 1760060 245380 49108 S 473,7 1,5   0:44.93 python
1065 root      20   0 1137300 366304 88180 R 7,0 2,2   60:23.61 Xorg

```

Figure 11: CPU usage creating bottlenecks - Top: GPU - Bottom: CPU only

```

1 INFO:tensorflow:2018-01-23 18:49:46.730940: Step 0: Train accuracy = 34.0%
2 INFO:tensorflow:2018-01-23 18:49:46.731069: Step 0: Cross entropy = 4.808121
3 INFO:tensorflow:2018-01-23 18:49:46.839474: Step 0: Validation accuracy = 4.0%
4 INFO:tensorflow:2018-01-23 18:49:47.309740: Step 10: Train accuracy = 27.0%
5 INFO:tensorflow:2018-01-23 18:49:47.309843: Step 10: Cross entropy = 4.646721
6 INFO:tensorflow:2018-01-23 18:49:47.356538: Step 10: Validation accuracy = 15.0%
7 INFO:tensorflow:2018-01-23 18:49:47.828190: Step 20: Train accuracy = 50.0%
8 INFO:tensorflow:2018-01-23 18:49:47.828293: Step 20: Cross entropy = 4.465392
9 INFO:tensorflow:2018-01-23 18:49:47.875599: Step 20: Validation accuracy = 32.0%
10 #### shortened ####
11 INFO:tensorflow:2018-01-23 18:53:15.319134: Step 3990: Train accuracy = 91.0%
12 INFO:tensorflow:2018-01-23 18:53:15.319235: Step 3990: Cross entropy = 0.282067
13 INFO:tensorflow:2018-01-23 18:53:15.369910: Step 3990: Validation accuracy = 89.0%
14 INFO:tensorflow:2018-01-23 18:53:15.796850: Step 3999: Train accuracy = 96.0%
15 INFO:tensorflow:2018-01-23 18:53:15.796950: Step 3999: Cross entropy = 0.204091
16 INFO:tensorflow:2018-01-23 18:53:15.844287: Step 3999: Validation accuracy = 89.0%
17 INFO:tensorflow:Final test accuracy = 91.0% (N=818)
18 INFO:tensorflow:Froze 2 variables.
19 Converted 2 variables to const ops.
20
21 bottleneck time: 290.75745s
22 Evaluation training time: 48.22647s
23 Evaluation total time: 209.29127s

```

Listing 21: Output of *retrain.py*

For explanation, *train accuracy* shows the percentage of correctly labeled images in the current training batch. The *validation accuracy* is also the percentage of correctly-labeled images but now on random images from the validation set. *Cross entropy* is a loss function that indicates how well the learning process is progressing. (TensorFlow, 2017a)

If during training, the error "Label xxx has no images in the category validation" occur, renaming this label names, solves this issue because another hash will be calculated and the separation of the sets changes.

If using Python and Bazel, the same version of TensorFlow has to be chosen, otherwise compatibility issues can occur.

During the retraining process the accuracy, cross entropy and some more data are written to the summaries directory and can be visualized with TensorBoard which is automatically installed with TensorFlow. In order to start the board, following command is executed listing 22.

```

1 tensorboard --logdir ${RETRAIN_PATH}/training_summaries/${ARCHITECTURE}_${{
  TRAINING_STEPS}/ &

```

Listing 22: Build and call of *retrain*

To validate the retrained model, see section 4.5.

The graph of the model can also be visualized in TensorBoard. The retrained graph of the MobileNet model including the training nodes is depicted in figure 12. In the appendix section ??, there is a more detailed overview with all convolutional layer. In section ??, the depthwise convolution containing its depthwise and pointwise convolutional layers can be found as described in section 2.2.

The retrained graph of the MobileNet model is depicted in figure 12 including the training nodes. In the appendix under section A.5 is a more detailed one with all convolutional layer and under section A.6 the view on the depthwise convolution containing its depthwise and pointwise convolutional layers as described in section 2.2.

The whole retrained graph of the InceptionV3 model is depicted in the appendix under section A.7. Furthermore, under section A.8 a detailed view on a mixed_layer and under section A.9 it's specific operations within a convolutional layer are shown.

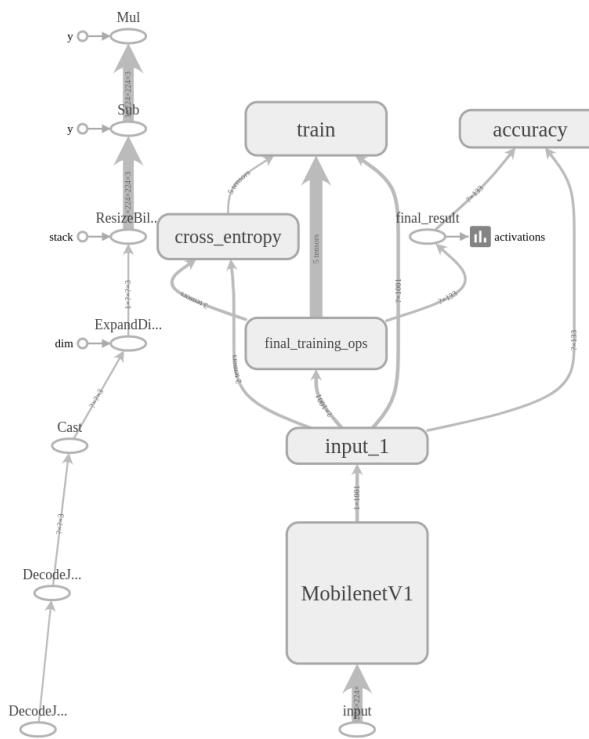


Figure 12: MobileNet retrained graph

Varying the parameters `how_many_training_steps` and `learning_rate` can improve accuracy. To measure the performance of the network, the validation accuracy is a good indicator, because these images aren't used for training. Even better for proving the performance of the classification task is the evaluation test at the end of the retraining process, as those images are entirely unknown to the model. Overfitting the network occurs, when the train accuracy is high, but the validation accuracy remains low, so particular features in the training images are memorized which in general is not helpful. (TensorFlow, 2017a)

In figure 13 the differences of retraining the InceptionV3 model with 5000 training steps and different learning rates is shown. For MobileNets it behaves similar. The final results experimenting with different training steps and learning rates are described in section 5.

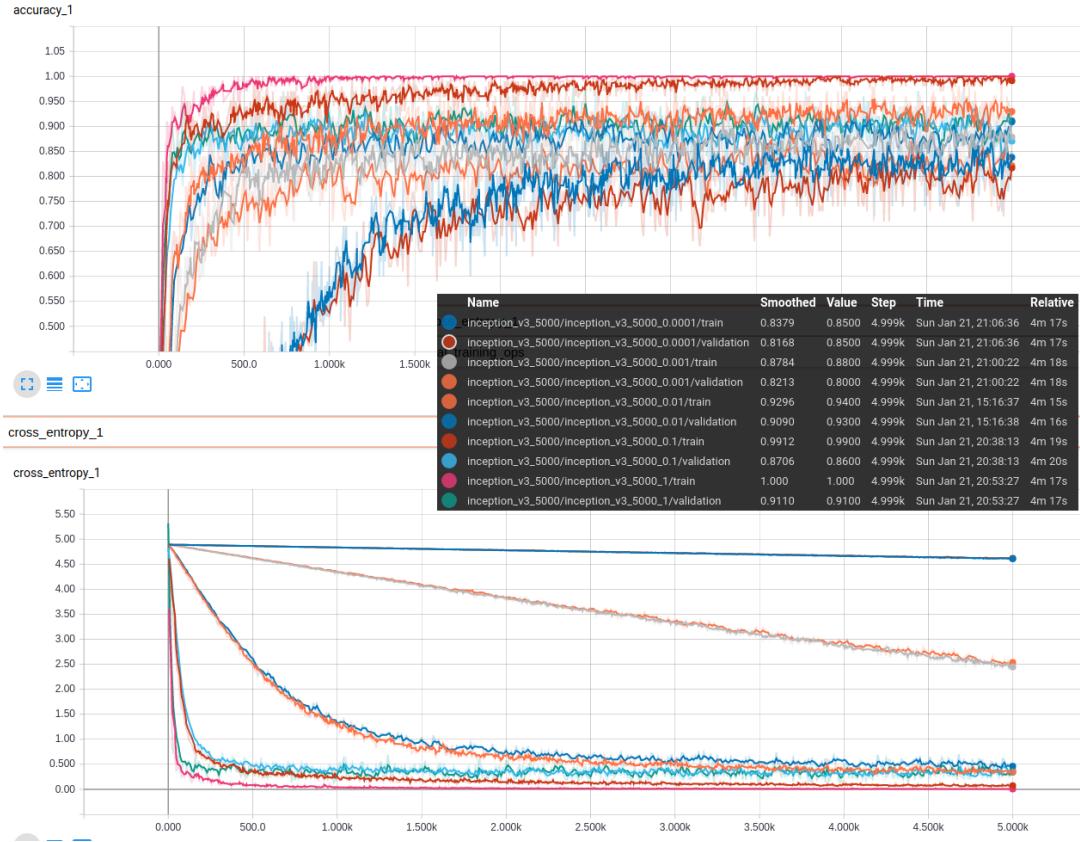


Figure 13: InceptionV3 with 5000 training steps and different learning rates

As result of the retraining process the model is saved in the predefined file. So theoretically the models are now ready to use for inference.

However, to use the model in the mobile app, the DecodeJpeg Operation has to be stripped from the retrained model, because the Inference Interface of TensorFlow Mobile currently doesn't support it. This could be done by the `strip_unused.py`-script of the official tensorflow github repository.

Nevertheless it is recommend to optimize the pretrained graph for mobile inference to achieve the best tradeoff between accuracy, latency, size and performance. There are several ways and different options to do the optimization.

The first option, which will be called in following as *opt1*, is only for running the `optimize_for_inference`-script of the official tensorflow github repository. The corresponding call is shown in listing 23. This script removes all nodes that aren't needed anymore like all training operations. Furthermore, it strips unused parts, removes debug informations, folds batch normalization ops into the pre-calculated weights and fuses common operations into unified versions.

```

1 python -m tensorflow.tools.optimize_for_inference \
2   --input=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
3   retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
4   --output=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
5   opt1_retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
6   --input_names=${INPUT_LAYER} \
7   --output_names="final_result"

```

Listing 23: Call of `optimize_for_inference.py`

The next attempt is to use the already optimized graph of *opt1* and additionally quantizes it by

rounding the weights. The *quantize_graph.py*-script of (GitHub, 2017) can be called as shown in listing 24. This will make the model compressible, which will reduce the model size significantly. Thus every mobile app compresses the package before distribution.

```

1 python -m scripts.quantize_graph \
2   --input=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
3   opt1_retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
4   --output=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
5   opt2_retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
--output_node_names=final_result \
--mode=weights_rounded

```

Listing 24: Call of *quantize_graph.py*

To compare the improvement, use the gzip command in listing 25 on the model of *opt1* and also on the new one.

```

1 gzip -c ${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb > ${
RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/retrained_dog_graph_${{
ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb.gz
2
3 gzip -1 ${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb.gz

```

Listing 25: Call of gzip

The detailed result of both graphs is shown in listing 26. So, the *opt2* model is 65,4% lower in size. This is also independent of the model. In the example of an InceptionV3 model the size is dropped from about 88 MB to only 24 MB which is a great improvement.

```

1 compressed uncompressed ratio uncompressed_name
2 81839945 88222145 7,20% /home/aw/MobileInceptionRetrained/graphs/inception_v3_4000/
  opt1_retrained_dog_graph_inception_v3_4000_0.03.pb
3
4 compressed uncompressed ratio uncompressed_name
5 24164803 88224397 72,60% /home/aw/MobileInceptionRetrained/graphs/inception_v3_4000
  /opt2_retrained_dog_graph_inception_v3_4000_0.03.pb

```

Listing 26: Output of gzip

These first two ways of optimization are described in the tensorflow-for-poets-2-tutorial. (GitHub, 2017)

The next two attempts are using *transform_graph* of the official tensorflow github repository. Unfortunately, there exists none Python version of that tool, so it has to be built with Bazel first.

The tool *transform_graph* has a parameter called *transforms* which defines all operations to be executed.

Calling the commands in listing 27 strips all unused nodes and folds batch normalization ops, so very similar to *opt1*. In the following content this will be *opt3*.

```

1 bazel build tensorflow/tools/graph_transforms:transform_graph && \
2 bazel-bin/tensorflow/tools/graph_transforms/transform_graph \
3 --in_graph=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
  retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
4 --out_graph=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
  opt3_retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
5 --inputs=${INPUT_LAYER} \
6 --outputs='final_result:0' \
7 --transforms=
8   strip_unused_nodes(type=float, shape="1,${INPUT_SIZE},${INPUT_SIZE},3")
9   remove_nodes(op=Identity, op=CheckNumerics)
10  fold_old_batch_norms'

```

Listing 27: Build and call of *transform_graph*

With *opt4* the command in listing 28 has been extended by *fold_old_batch_norms*, *round_weights* and *sort_by_execution_order*. Thus, it rounds the weights. It is also compressible, which is similar

to the *opt2* one.

```

1  bazel build tensorflow/tools/graph_transforms:transform_graph && \
2  bazel-bin/tensorflow/tools/graph_transforms/transform_graph \
3  --in_graph=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
   retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
4  --out_graph=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
   opt4_retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb \
5  --inputs=${INPUT_LAYER} \
6  --outputs=final_result:0 \
7  --transforms='
8    strip_unused_nodes(type=float, shape="1,${INPUT_SIZE},${INPUT_SIZE},3")
9    remove_nodes(op=Identity, op=CheckNumerics)
10   fold_batch_norms
11   fold_old_batch_norms
12   round_weights(num_steps=256)
13   sort_by_execution_order'
```

Listing 28: Build and call of *transform_graph*

The results experimenting with optimization are described in section 5.

There are several helper tools, two of them are introduced here.

The first one, is the *graph_pb2tb.py*-script, again from (GitHub, 2017). It generates a summary file which contains only the data of the graph for visualization with TensorBoard. So after optimizing the graph and calling the command of listing 29 the graph of the MobileNet model should look like depicted in figure 14 which is completely stripped of unused nodes as the training stuff and thus optimized for inference. The InceptionV3 model is shown in the appendix under section A.10.

```

1  python -m scripts.graph_pb2tb ${RETRAIN_PATH}/training_summaries/${ARCHITECTURE}_${{
   TRAINING_STEPS}/${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}/retrained \
2  ${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/retrained_dog_graph_${{
   ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb
```

Listing 29: Call of *graph_pb2tb.py*

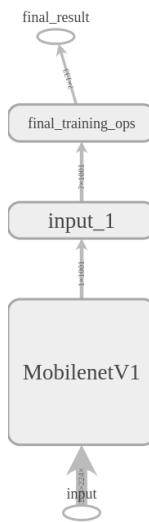


Figure 14: Optimized graph of a MobileNet model

Another tool is *summarize_graph* of the official tensorflow github repository, which has to be built by bazel. After building and calling command of listing 30 a short summary of the model is printed out which includes useful information like the shape, the name of input and output layers or quantity of constants. An example with the optimized retrained InceptionV3 model is shown in listing 31.

```

1  bazel build tensorflow/tools/graph_transforms:summarize_graph && \
2  bazel-bin/tensorflow/tools/graph_transforms/summarize_graph \
3      --in_graph=${RETRAIN_PATH}/graphs/${ARCHITECTURE}_${TRAINING_STEPS}/
        retrained_dog_graph_${ARCHITECTURE}_${TRAINING_STEPS}_${LEARNING_RATE}.pb

```

Listing 30: Build and call of *summarize_graph*

```

1 Found 1 possible inputs: (name=Mul, type=float(1), shape=[1,299,299,3])
2 No variables spotted.
3 Found 1 possible outputs: (name=final_result, op=Softmax)
4 Found 22040882 (22.04M) const parameters, 0 (0) variable parameters, and 0
  control_edges
5 Op types used: 202 Const, 94 BiasAdd, 94 Conv2D, 94 Relu, 11 Concat, 9 AvgPool, 5
  MaxPool, 1 Add, 1 MatMul, 1 Placeholder, 1 PlaceholderWithDefault, 1 Reshape, 1
  Softmax

```

Listing 31: Output of *summarize_graph* on a retrained and optimized InceptionV3 model

4.5. Output Tests and Validation

In order to test and validate the output of the model regardless of whether the pretrained, retrained or optimized one is used the python script named *label_image.py* of (GitHub, 2017) was applied. The variables defined in section 4.4 in listing 17 has to be used depending on the model.

```

1 python -m scripts.label_image \
2 --graph=${HOME}/retrained_graph.pb \
3 --labels=${HOME}/retrained_labels.txt \
4 --output_layer=final_result \
5 --input_layer=${INPUT_LAYER} \
6 --image=${HOME}/dl/label_image_pics/Affenpinscher_00001.jpg \
7 --input_width=${INPUT_SIZE} \
8 --input_height=${INPUT_SIZE}

```

Listing 32: Call of *label_image.py*

The corresponding command based on Bazel is shown in listing 32 where again the three variables need to be specified. The call itself is fundamentally the same. However, the executable binary has to be built before which is shown in listing 33.

```

1  bazel build tensorflow/examples/label_image:label_image && \
2  bazel-bin/tensorflow/examples/label_image/label_image \
3      --graph=${HOME}/retrained_graph.pb \
4      --labels=${HOME}/retrained_labels.txt \
5      --output_layer=final_result \
6      --input_layer=${INPUT_LAYER} \
7      --image=${HOME}/dl/label_image_pics/Affenpinscher_00001.jpg \
8      --input_width=${INPUT_SIZE} \
9      --input_height=${INPUT_SIZE}

```

Listing 33: Build and call of *label_image*

If retraining of the model was conducted successfully, the output of *label_image* consists of five labels containing the highest values and corresponding accuracy which are returned by the model (refer to listing 34).

```

1 Evaluation time (1-image): 0.350s
2
3 001 affenpinscher 0.9940035
4 038 brussels griffon 0.002003342
5 042 cairn terrier 0.0008437461
6 100 lowchen 0.00018292216
7 099 lhasa apso 0.00012668292

```

Listing 34: Output of *label_image.py*

4.6. Implementation of an native Android App

This subchapter describes the processing of the camera input stream and classifying the particular images. Because of the vast extent of the application, the focus lies on the explanation of how the app works and on its important implementation parts.

When clicking on the icon of the app, a camera view showing results in the bottom part is loaded figure 15. In the background, the ClassifierActivity is set as the launcher activity in the AndroidManifest.xml which is a file containing all configuration settings for the app. When an activity is loaded for the first time, the onCreate method is invoked. Because the ClassifierActivity extends the CameraActivity the onCreate method of the CameraActivity is executed and loads the layout activity_camera.xml consisting of a container and a result field. Next, the setFragment method of the class CameraActivity is invoked if permission for the camera is given. This causes the replacement of the container with the adapted fragment according to the actual size and orientation of the screen. When the size is set, the method onPreviewSizeChosen is invoked where a TensorFlowImageClassifier is instantiated with following input parameters: MODEL_FILE, LABEL_FILE, INPUT_SIZE, IMAGE_MEAN, IMAGE_STD, INPUT_NAME, OUTPUT_NAME. Details about the classification itself follow later in the section.

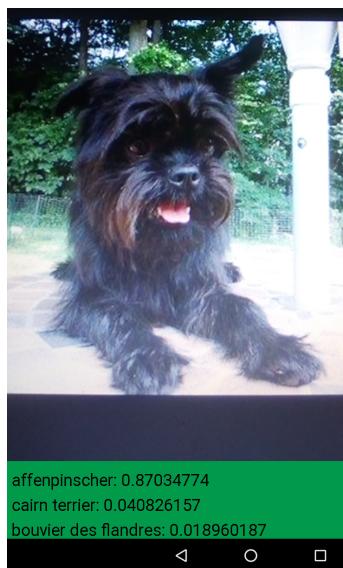


Figure 15: Camera View of the mobile application showing the classification

When the fragment was replaced by the CameraActivity, an instance of the class CameraFragment was created. Next, the method onViewCreated of the class CameraFragment is called and a texture view is created. The latter class is part of the Android API and used for frame capturing from an image stream as OPENGL ES texture. Thereby, the most recent image is stored within a texture object. This object is observed by a listener which invokes the method onSurfaceTextureAvailable when the texture object is available. Within this method the camera is opened by the method openCamera(width, height) given the width and height of the camera preview (Android, 2017). First, the method openCamera sets the camera parameters within setUpCameraOutputs e.g. sensorOrientation, previewSize, cameraId etc. In order to classify a given OPENGL ES texture, the coordinate column vectors of the texture must be transformed into the proper sampling location in the streamed texture. So, the matrix has to be prepared with the correct configuration which happens in the method configureTransform. The next important step is done by the camera manager which opens the camera by invoking the method openCamer(cameraId, stateCallback, backgroundHandler). The id represents the specific camera device whereas the stateCallback is

necessary to manage the life circle of the camera device and to handle different states of the camera device. The `backgroundHandler` ensures that the classification is done in background mode. When the camera is opened, the camera preview is started by the method `createCameraPreviewSession`. Within this method the preview reader is initialized and set to read images from the `ImageListener` which observes whether an image is available. Therefore, an `ImageListener` which was instantiated by the `CameraActivity` is transferred to the `CameraFragment`.

When an image is available the method `onImageAvailable` of the class `ClassifierActivity` is invoked. The image is read by the preview reader and stored in an object. First, the image is preprocessed meaning transferred into planes, stored as bytes, cropped and stored as a `Bitmap` which is an Android graphic. Google provides an Tensorflow Mobile API to run tensors on a performance critical device such as mobile devices. To use this API, the dependency has to be added to the `build.gradle` file as shown in listing 35.

```

1 allprojects {
2     repositories {
3         jcenter()
4     }
5 }
6
7 dependencies {
8     compile 'org.tensorflow:tensorflow-android:+'
9 }
```

Listing 35: Tensorflow API in build.gradle

When including the API, Tensorflow's class `Classifier` can be used to classify images. Therefore, the `TensorFlowImageClassifier` which was initialized before invokes the method `recognizeImage(croppedBitmap)` on the preprocessed image. Within this method, the image data is transferred from int to float (refer to listing 39). Then, the previous initialized object of the `TensorflowInferenceInterface` calls the method `feed` to pass the float values to the input layer of the model. Afterwards, the `InferenceInterface` invokes the method `run` with the specified output layer in order to process the classification. Subsequently, the output data is fetched by calling `fetch` on the output layer which is depicted in listing 36.

```

1 // Copy the input data into TensorFlow.
2 Trace.beginSection("feed");
3 inferenceInterface.feed(inputName, floatValue, 1, inputSize, inputSize, 3);
4 Trace.endSection();
5
6 // Run the inference call.
7 Trace.beginSection("run");
8 inferenceInterface.run(outputNames, logStats);
9 Trace.endSection();
10
11 // Copy the output Tensor back into the output array.
12 Trace.beginSection("fetch");
13 inferenceInterface.fetch(outputName, outputs);
14 Trace.endSection();
```

Listing 36: Classifying images by the `inferenceInterface` (GitHub, 2017)

Afterwards, the results are reordered according to the highest probability and returned to the result field for displaying the output.

4.7. Deployment and Validation

In order to get the model running in the application, a few things must be adapted. First, the model in the format of a .pb file and its retrained labels as a text file must be imported. Therefore, a assets folder was created where the model and labels were placed. Next, the path of the model and the labels file must be specified like pictured in listing 37.

```

1 // Input shapes
2 private static final int INPUT_SIZE = 224;
3 private static final int IMAGE_MEAN = 128;
4 private static final float IMAGE_STD = 128.0f;
5
6 // Input Layer
7 private static final String INPUT_NAME = "input";
8
9 // Output Layer
10 private static final String OUTPUT_NAME = "final_result";
11
12 // Model Name from Assets
13 private static final String MODEL_FILE = "file:///android_asset/
14 opt4_retrained_dog_graph_mobilenet_0.50_224_700_0.007.pb";
15
16 // Label Name from Assets
17 private static final String LABEL_FILE = "file:///android_asset/
18 retrained_dog_labels_mobilenet_0.50_224_700_0.007.txt";

```

Listing 37: Including the model in the mobile application

For MobileNet models the default settings are shown in the mentioned listing. Otherwise, if an InceptionV3 is used, the settings must be adapted like shown in listing 38.

```

1 private static final int INPUT_SIZE = 299;
2 private static final int IMAGE_MEAN = 128;
3 private static final float IMAGE_STD = 128.0f;
4 private static final String INPUT_NAME = "Mul:0";
5 private static final String OUTPUT_NAME = "final_result";

```

Listing 38: Setup for InceptionV3

The input size defines the size of the input layer of InceptionV3 which is 'Mul'. Whereas the input layer for MobileNet is specified as 'input'. The IMAGE_MEAN and IMAGE_STD values are needed for converting the image data from integer into float values. The conversion is shown in listing 39.

```

1 for (int i = 0; i < intValues.length; ++i) {
2     final int val = intValues[i];
3     floatValues[i * 3 + 0] = (((val >> 16) & 0xFF) - imageMean) / imageStd;
4     floatValues[i * 3 + 1] = (((val >> 8) & 0xFF) - imageMean) / imageStd;
5     floatValues[i * 3 + 2] = ((val & 0xFF) - imageMean) / imageStd;
6 }

```

Listing 39: Conversion of image data integer to float

Futhermore, the output layer has to be specified. For MobileNet and InceptionV3, this was set to 'final_result'.

After setting up the application with appropriate values, the application can be built and run. If the application is running successfully and doesn't terminate, the settings are correct. If the result view contains results, everthing's working. If the results are below 0.1, the threshold in the class TensorflowImageClassifier has to be adapted. It's default setting is 0.1f which means only relevant results higher than 0.1 are shown in the result field. As a consequence, bad results given by the network aren't shown in general. So the threshold was set to 0.01f.

5. Evaluation

As described in section 4.4 the accuracy can be improved by playing around with the training steps and the learning rate. It's a tradeoff between good results and overfitting, so that the model is too specialized on the training set.

The best values for the MobileNet0.5 model are achieved with 700 training steps and a learning rate of 0.007.

For the MobileNet1.0 model it was hard to find really well values. So the best here are 500 training steps and a learning rate of 0.01.

The final Inception model was retrained with 4000 training steps and a learning rate of 0.03.

For all models the *accuracy*- and *cross entropy*-diagram from TensorBoard is depicted in the appendix under section A.11 (figure 26 till figure 29). Exact these models are now used for further work.

In oder to compare the different optimization attempts, a bash script named *eval_label-image.sh* was written. It's placed in the github repository of this project in the directory *code/scripts*. The script takes a choosen set of 20 images (works/Evaluierung/eval_label_image_pics) and calls internally the *label_image.py* script to label them. The images, which partly are very difficult to classify, are picked from both dog datasets mentioned in section 4.1. In an Excel-sheet the results are averaged which is depicted in detail in the appendix under section A.12 (table 2 till table 4) and graphically in figure 16.

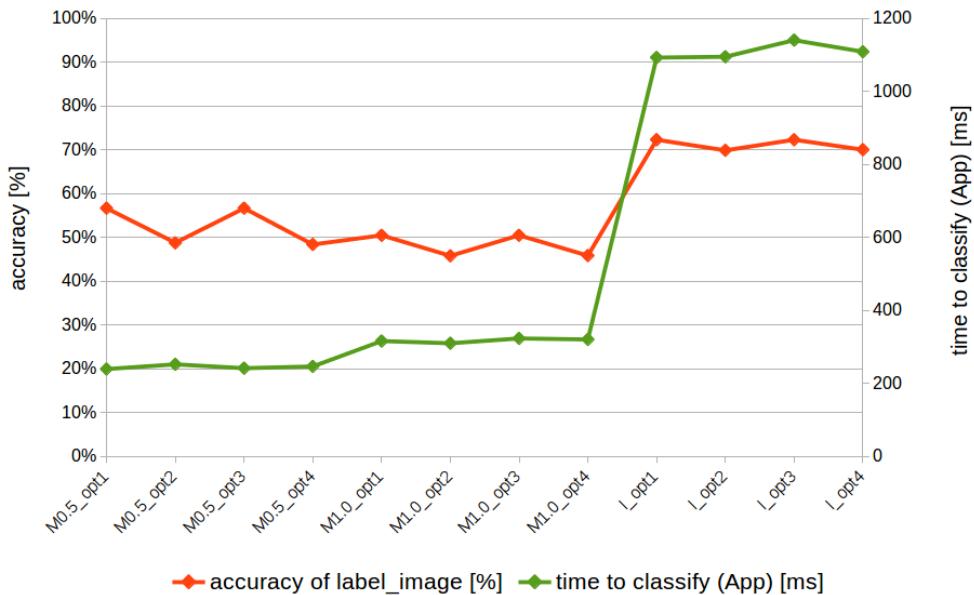


Figure 16: Accuracy and time to classify of different optimization attempts

Because of the great benefit with the compression (refer to section 4.4) and the fact that the accuracy and the classification time of *opt2* and *opt4* isn't dramatically worser in contrast to the others, these two attempts are a good choice. Looking exactly at the tables, *opt4* is a little bit more accurate, so this is the best one and will be used for further comparisons.

For evaluating the different model architectures the last chart (figure 16) was represented as a scatter plot, which is shown in figure 17. So in this plot the upper left corner would be the best tradeoff between accuracy and performance of the mobile app. Thus one of the two MobileNets would be selected.

However for a more accurate evaluation of the models, some more facts have to be considered, which is shown in table 1 in numbers and graphically in figure 18.

The table contains the overall accuracy, the quantity of how many images are classified with a wrong label, how long the *label_image* on the computer took, how long it takes to load the model on the app, how long the classification on the app took and finally the compressed model size.

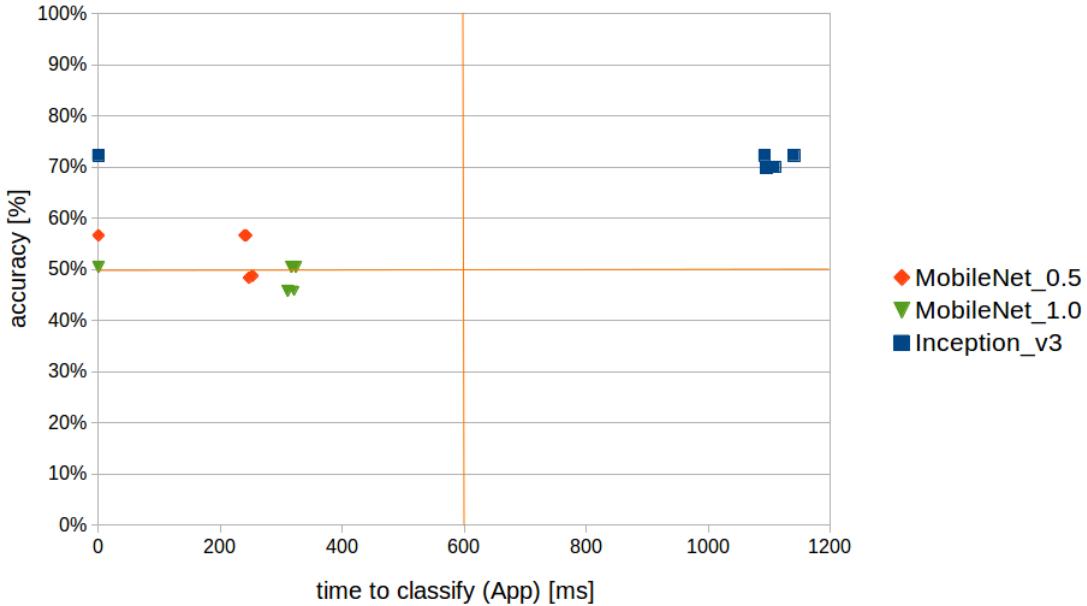


Figure 17: Accuracy in relation to classification time of different models

Model	accuracy [%]	misclassified	labelImage [ms]	LoadModelApp [ms]	classifyApp [ms]	size [MB]
MobileNet0.5	48%	8	45	70	247	1.8
MobileNet1.0	46%	8	76	120	321	4.8
InceptionV3	70%	3	285	491	1108	24.1

Table 1: Values for final evaluation of model architecture

Except the quantity of misclassified images and the model size, all values are shown in the graph.

As expected the InceptionV3 model is the most accurate one, indeed it need a lot of performance, too.

A little surprise was the results between both MobileNets because the MobileNet_0.5 with less parameters is more accurate, has a smaller model size and further is in all tasks about 1.7 times faster than the other one.

The differences between MobileNet_0.5 and InceptionV3 are essential. On the one side InceptionV3 is about 1.4 times more accurate and classifies all images correctly except three images. On the other side the model size is much more higher. Furthermore Inception lags all the time because it's about six times slower, which is a disaster for responsiveness and usability. Especially for a mobile app it's more significant to run well on many devices even if the accuracy suffers a little bit. Additionally InceptionV3 also needs more time for retraining (refer to section 4.4).

All in all the MobileNet_0.5 is with this hardware setup the best tradeoff between accuracy and latency, model size and performance.

6. Conclusion

At the beginning, a lot of research was done to answer the general question of 'how can a network be integrated in a mobile application and run on a performance critical device'. During the research, Tensorflow Lite was chosen as an API which enables running a network on an Android mobile phone. Because Tensorflow supports the models MobileNet and Inception specifically for

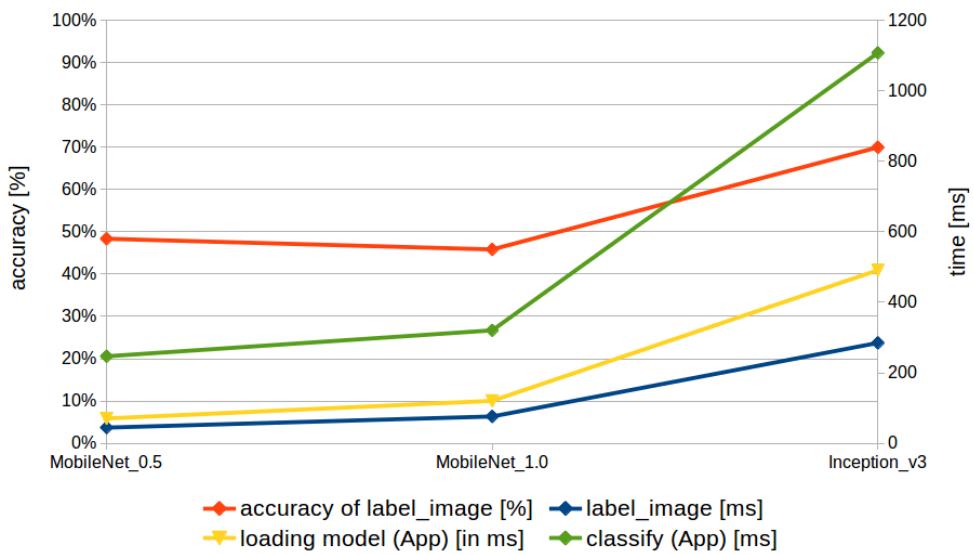


Figure 18: Graph for final evaluation of model architecture

mobile application usage, both were chosen. Based on this decision, both models were investigated and a comparison of both of them was incorporated into this work. After determining which framework and models are suitable for mobile application support, the installation began. Because of a good documentation the installation of Tensorflow and its necessary dependencies was done quickly. Following the tutorials the models were retrained on dog images. For a first, the optimization of the models to its full degree was omitted and the focus was to include the optimized models in the mobile application for running. Therefore, Tensorflow Lite was used to convert the .pb file to a .tflite file. The conversion was conducted successfully, but the produced .tflite file caused the app to terminate. After proving the versions of all used APIs and reconverting the models several times, the app still collapsed without throwing an error. Even after optimizing, rounding, quantizing the models with different commands, the app failed to run. In addition, the tutorials and documentation are kept short on this subject. Because of this behaviour, Tensorflow Mobile was used instead of Tensorflow Lite which is still in development mode. After integration of the .pb file and its corresponding label file, the Tensorflow version had to be adapted. If adding '+' in the dependency section for Tensorflow instead of the specified version, Android Studio installs the most recent one. Furthermore, after integrating an InceptionV3 model, no results were displayed while the app was running. Therefore, the threshold was adapted to a lower value in order to display low results from the network. Next, the models were optimized to their full degree based on varying the learning rate in relation to the training steps. Afterwards, the models were comprised and loaded into the mobile application. The result are two applications, one including MobileNet and another containing InceptionV3. In the last step, the models were compared based on performance, time expenditure for producing an optimized model and quality in accuracy. Especially for the time related evaluation, marker were placed in the scripts to measure the time needed for creating the bottlenecks, training on images and evaluating an image. The expectation was that the InceptionV3 was the most accurate model, but the one with the most required performance classifying an image in the mobile application. Furthermore, the MobileNet 1.0 was expected to be the most fastest and accurate model, whereas the MobileNet 0.50 might be accurate, but slower than its successor. It turned out contrary to expectations that the MobileNet 0.50 is the most accurate one with lowest performance required (refer to section 5). As a last surprise, the app was running more smoothly on the Samsung S4 device than on the newer Motorola Moto X which contains a better processor.

7. Apportionment of work

The parallel work on the entire task results in a uniform division of work. Therefore, there is no distinct apportionment of work. Here, an overview of a rough work-sharing is given by the following.

- Introduction (Alice)
- Methodological fundamentals (Andreas)
- Concept (Alice)
- Realization (Alice and Andreas)
- Evaluation (Andreas)
- Conclusion (Alice and Andreas)

References

- He, K. (2016). Deep residual networks.
- He, K., Zhang, X., Ren, S., and Sun, J. (2015). Deep residual learning for image recognition.
- Howard, A. G., Zhu, M., Chen, B., Kalenichenko, D., Wang, W., Weyand, T., Andreetto, M., and Adam, H. (2017). Mobilenets: Efficient convolutional neural networks for mobile vision applications.
- Krizhevsky, A., Sutskever, I., and Hinton, G. E. (2012). Imagenet classification with deep convolutional neural networks.
- LeCun, Y., Bottou, L., yoshua Bengio, and Haffner, P. (1998). Gradient-based learning applied to document recognition.
- Anaconda (2017). Installing on linux. Website. <https://conda.io/docs/user-guide/install/linux.html>. Accessed on January 28, 2018.
- Android (2017). Surfacetexture. <https://developer.android.com/reference/android/graphics/SurfaceTexture.html>. Accessed on January 26, 2018.
- BAIR (n.d.). Caffe. Website. <http://caffe.berkeleyvision.org/>. Accessed on January 28, 2018.
- Bazel (2018). Installing bazel on ubuntu. Website. <https://docs.bazel.build/versions/master/install-ubuntu.html>. Accessed on January 28, 2018.
- DeepMind (2017). Alphago. Website. <https://deepmind.com/research/alphago/>. Accessed on January 28, 2018.
- GitHub (2017). tensorflow-for-poets-2. Website. <https://github.com/googlecodelabs/tensorflow-for-poets-2>. Accessed on January 28, 2018.
- GitHub (2018). build-tensorflow-from-source. Website. <https://gist.github.com/Brainiac7/6d6c3f23ea057775b72c52817759b25c>. Accessed on January 28, 2018.
- ImageNet (2010). Imagenet - summary and statistics. <http://www.image-net.org/about-stats>. Accessed on January 26, 2018.
- NVIDIA - Michael Copeland (2016). What's the difference between artificial intelligence, machine learning, and deep learning? <https://blogs.nvidia.com/blog/2016/07/29/whats-difference-artificial-intelligence-machine-learning-deep-learning-ai/>. Accessed on January 22, 2018.
- TensorFlow (2017a). How to retrain inception's final layer for new categories. https://www.tensorflow.org/tutorials/image_retraining. Accessed on January 22, 2018.
- TensorFlow (2017b). Installing tensorflow on ubuntu. Website. https://www.tensorflow.org/install/install_linux. Accessed on January 26, 2018.
- TensorFlow (2017c). Mobile - overview. Website. <https://www.tensorflow.org/mobile/>. Accessed on January 28, 2018.
- TensorFlow (2017d). Tensorflow. Website. <https://www.tensorflow.org/>. Accessed on January 28, 2018.

- TensorFlow (2017e). Tensorflow-slim. Website. <https://github.com/tensorflow/tensorflow/tree/master/tensorflow/contrib/slim>. Accessed on January 28, 2017.
- TensorFlow (2017f). A tool developer's guide to tensorflow model files. https://www.tensorflow.org/extend/tool_developers/. Accessed on January 22, 2018.
- TensorFlow (2018). Installing tensorflow from sources. Website. https://www.tensorflow.org/install/install_sources. Accessed on January 28, 2018.
- TensorFlow (n.d.). Mobilenet_v1. https://github.com/tensorflow/models/blob/master/research/slim/nets/mobilenet_v1.md. Accessed on January 22, 2018.
- University of Stanford (n.d.). Deep learning. Website. <http://deeplearning.stanford.edu/>. Accessed on January 28, 2018.
- Simonyan, K. and Zisserman, A. (2015). Very deep convolutional networks for large-scale image recognition.
- Szegedy, C., Liu, W., Jia, Y., Sermanet, P., Reed, S., Anguelov, D., Erhan, D., Vanhoucke, V., and Rabinovich, A. (2014). Going deeper with convolutions.
- Varangaonkar, A. (2017). Top 10 deep learning frameworks. <https://datahub.packtpub.com/deep-learning/top-10-deep-learning-frameworks/>. Accessed on January 22, 2018.
- Wick, C. (2017). *Deep Learning*.

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A. Appendix

A.1. GoogLeNet - InceptionV1 architecture

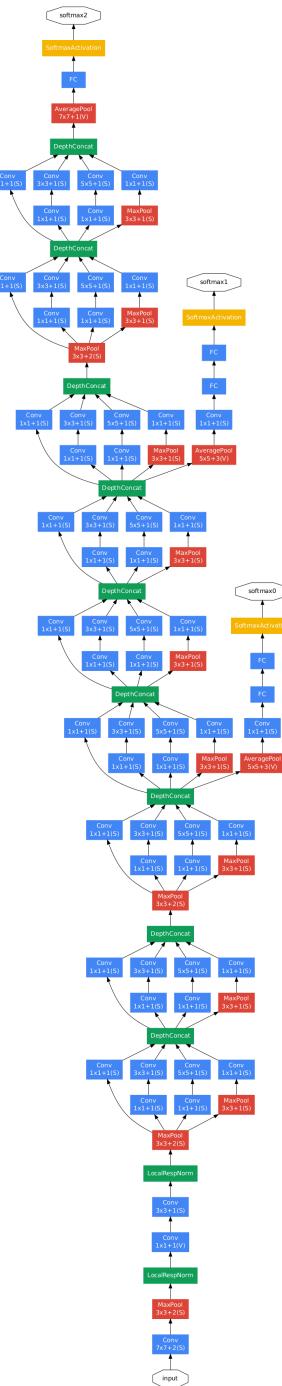


Figure 19: Model architecture of GoogLeNet (Szegedy et al., 2014, p. 7)

A.2. ResNet architecture

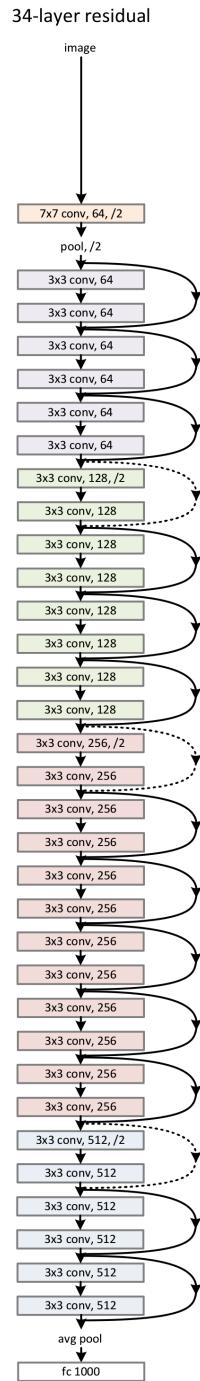


Figure 20: ResNet block (He et al., 2015, p. 4)

A.3. Configure Bazel for Tensorflow

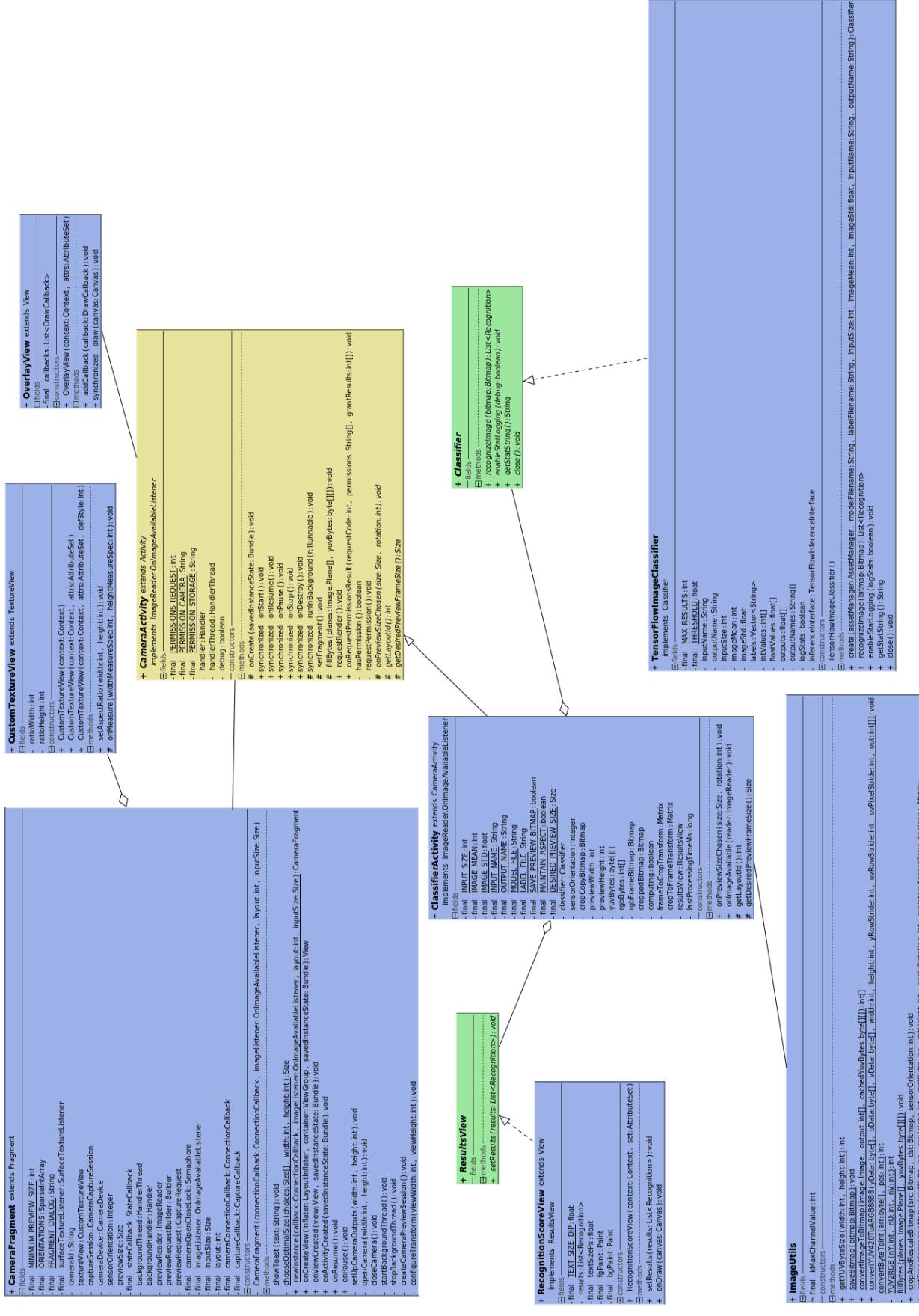
```

1 $ cd tensorflow # cd to the top-level directory created
2 $ ./configure
3 Please specify the location of python. [Default is /usr/bin/python]: /usr/bin/python3
.6
4 Found possible Python library paths:
5   /usr/local/lib/python3.6/dist-packages
6   /usr/lib/python3.6/dist-packages
7 Please input the desired Python library path to use. Default is [/usr/lib/python3.6/
dist-packages]
8 Using python library path: /usr/local/lib/python3.6/dist-packages
9 Do you wish to build TensorFlow with MKL support? [y/N]
10 No MKL support will be enabled for TensorFlow
11 Please specify optimization flags to use during compilation when bazel option "--
config=opt" is specified [Default is -march=native]:
12 Do you wish to use jemalloc as the malloc implementation? [Y/n] n
13 No jemalloc as malloc support will be enabled for TensorFlow.
14 Do you wish to build TensorFlow with Google Cloud Platform support? [y/N] n
15 No Google Cloud Platform support will be enabled for TensorFlow
16 Do you wish to build TensorFlow with Hadoop File System support? [y/N] n
17 No Hadoop File System support will be enabled for TensorFlow
18 Do you wish to build TensorFlow with the XLA just-in-time compiler (experimental)? [y
/N] n
19 No XLA support will be enabled for TensorFlow
20 Do you wish to build TensorFlow with Amazon S3 File System support? [Y/n]: n
21 No Amazon S3 File System support will be enabled for TensorFlow.
22 Do you wish to build TensorFlow with GDR support? [y/N]: n
23 No GDR support will be enabled for TensorFlow.
24 Do you wish to build TensorFlow with VERBS support? [y/N] n
25 No VERBS support will be enabled for TensorFlow
26 Do you wish to build TensorFlow with OpenCL support? [y/N] n
27 No OpenCL support will be enabled for TensorFlow
28 Do you wish to build TensorFlow with CUDA support? [y/N] Y
29 CUDA support will be enabled for TensorFlow
30 Please specify the Cuda SDK version you want to use, e.g. 7.0. [Leave empty to
default to CUDA 8.0]: 8.0
31 Please specify the location where CUDA 8.0 toolkit is installed. Refer to README.md
for more details. [Default is /usr/local/cuda]:
32 Please specify the cuDNN version you want to use. [Leave empty to default to cuDNN
6.0]: 6
33 Please specify the location where cuDNN 6 library is installed. Refer to README.md
for more details. [Default is /usr/local/cuda]:
34 Please specify a list of comma-separated Cuda compute capabilities you want to build
with.
35 You can find the compute capability of your device at: https://developer.nvidia.com/
cuda-gpus.
36 Please note that each additional compute capability significantly increases your
build time and binary size.
37 [Default is: 5.2]: 5.2
38 Do you want to use clang as CUDA compiler? [y/N] n
39 nvcc will be used as CUDA compiler
40 Please specify which gcc should be used by nvcc as the host compiler. [Default is /
/usr/bin/gcc]:
41 Do you wish to build TensorFlow with MPI support? [y/N] n
42 MPI support will not be enabled for TensorFlow
43 Configuration finished

```

Listing 40: Configure bazel for Tensorflow

A.4. Mobile Application Architecture in the form of a Class Diagram



A.5. MobileNet retrained graph - detailed



Figure 21: MobileNet retrained graph - detailed

A.6. MobileNet retrained graph - depthwise

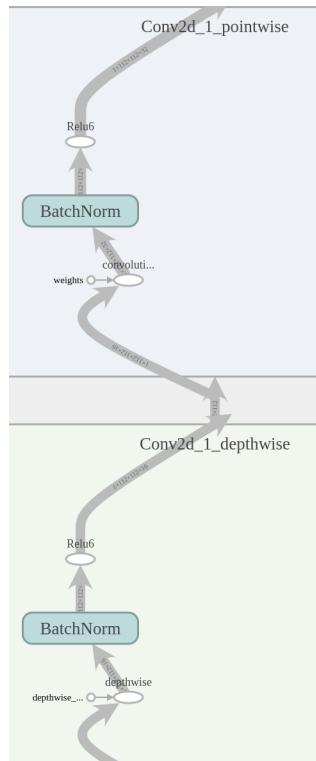


Figure 22: MobileNet retrained graph - depthwise

A.7. InceptionV3 retrained graph

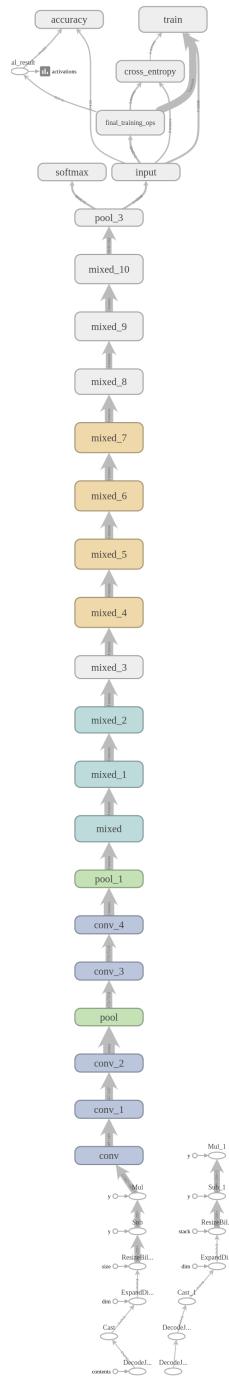
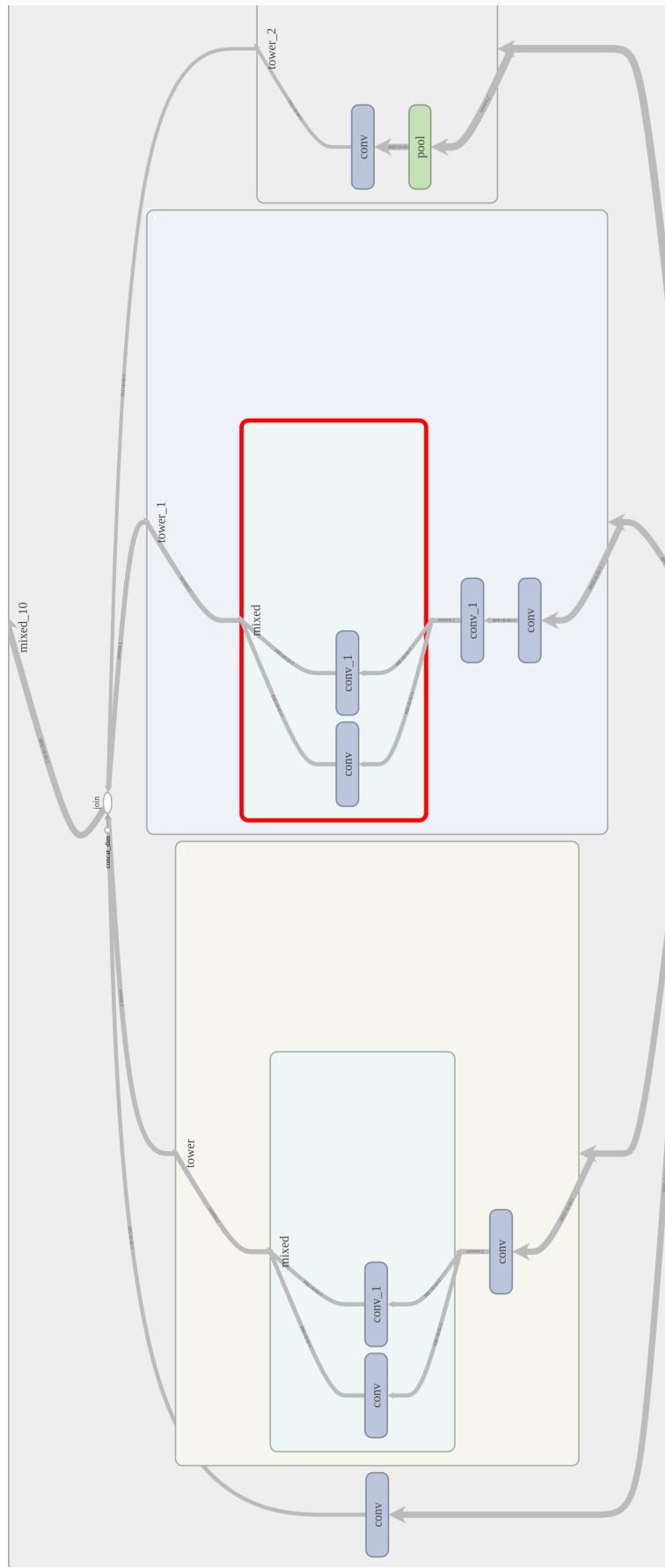


Figure 23: InceptionV3 retrained graph

A.8. InceptionV3 retrained graph - mixed_layer



A.9. InceptionV3 retrained graph - conv layer

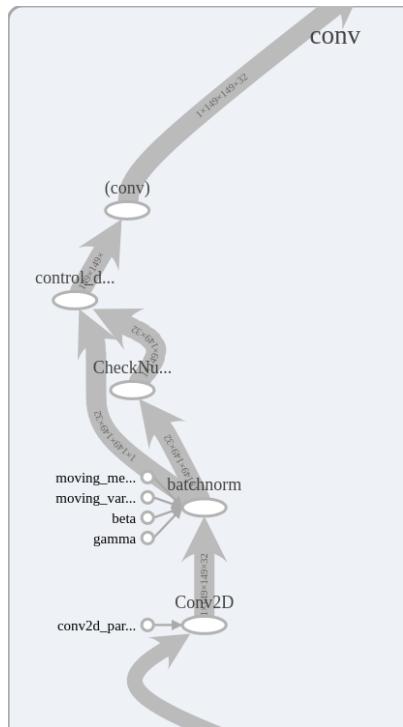


Figure 24: InceptionV3 retrained graph - conv layer

A.10. InceptionV3 retrained graph - optimized



Figure 25: InceptionV3 retrained graph - optimized

A.11. TensorBoard - optimal achieved accuracy of the different models

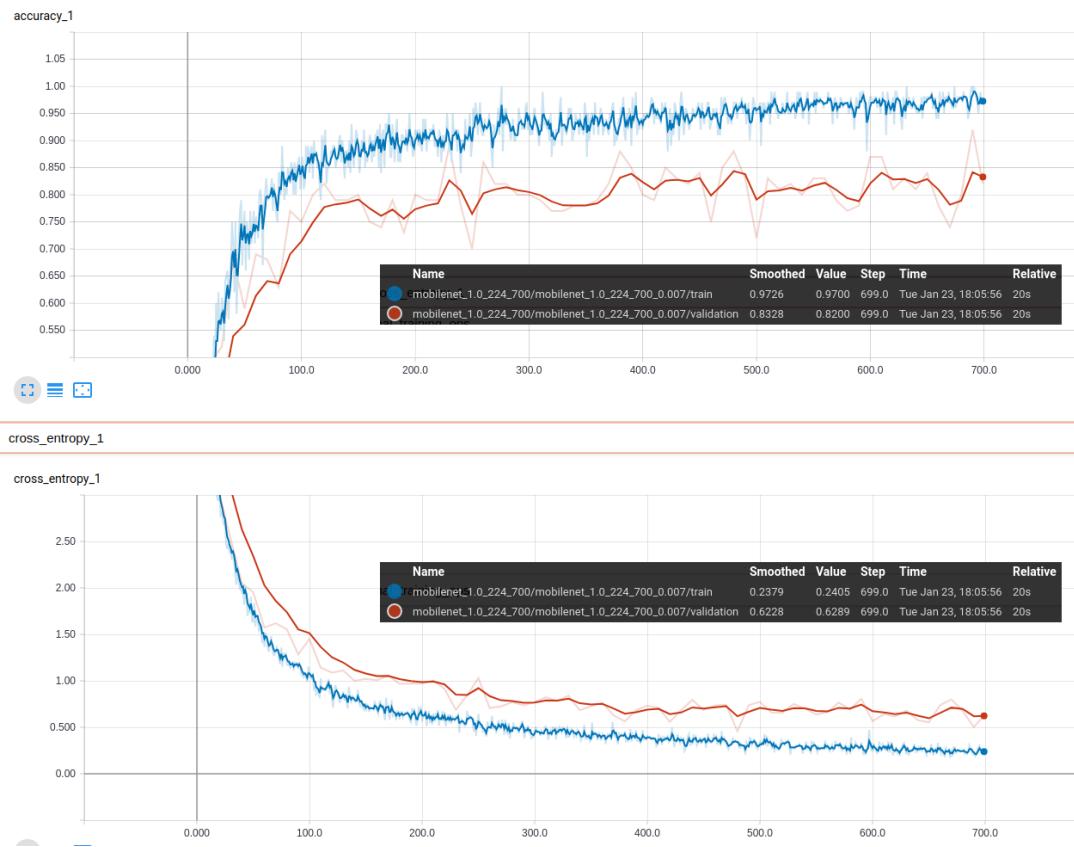


Figure 26: TensorBoard - optimal achieved accuracy of MobileNet_0.5

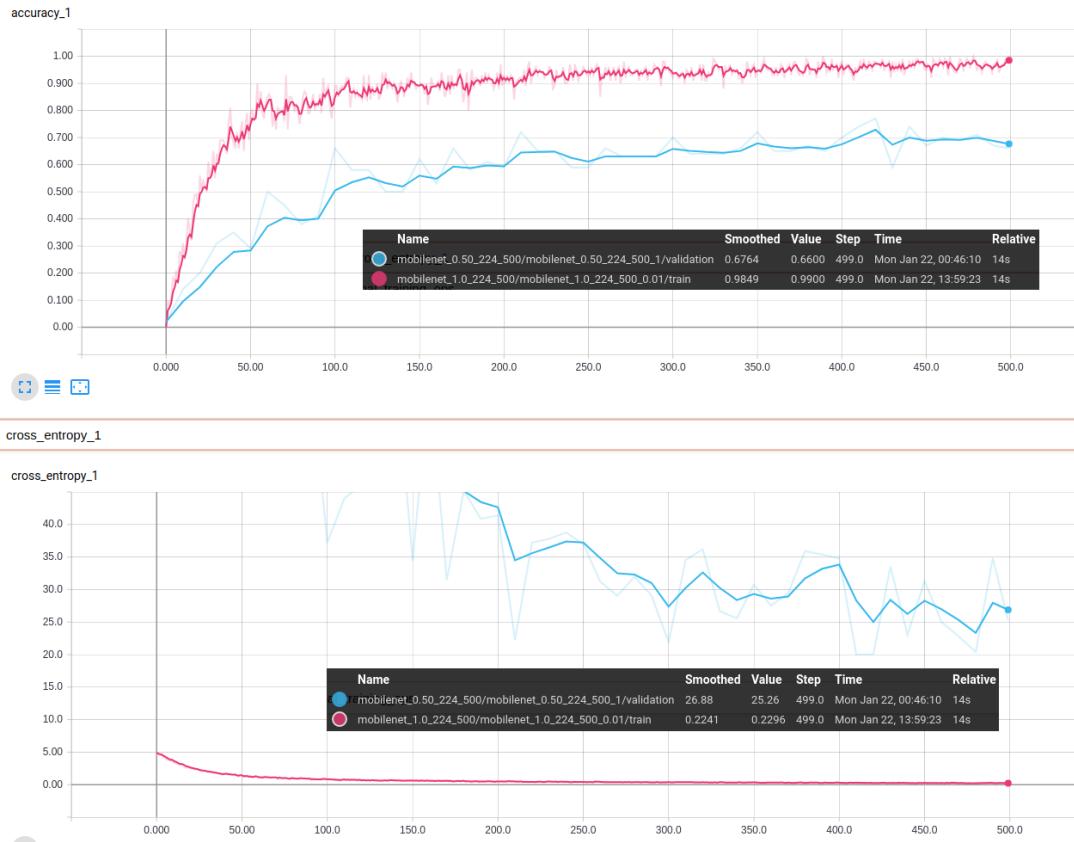


Figure 27: TensorBoard - optimal achieved accuracy of MobileNet_1.0

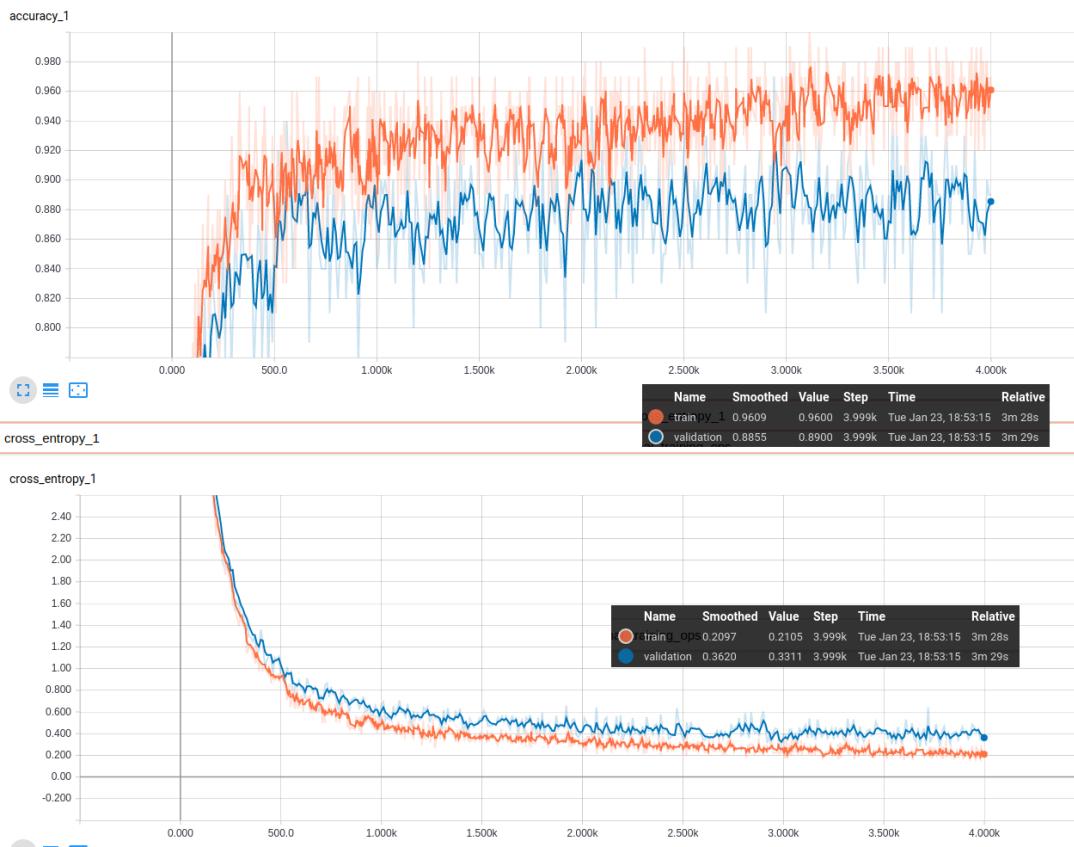


Figure 28: TensorBoard - optimal achieved accuracy of InceptionV3

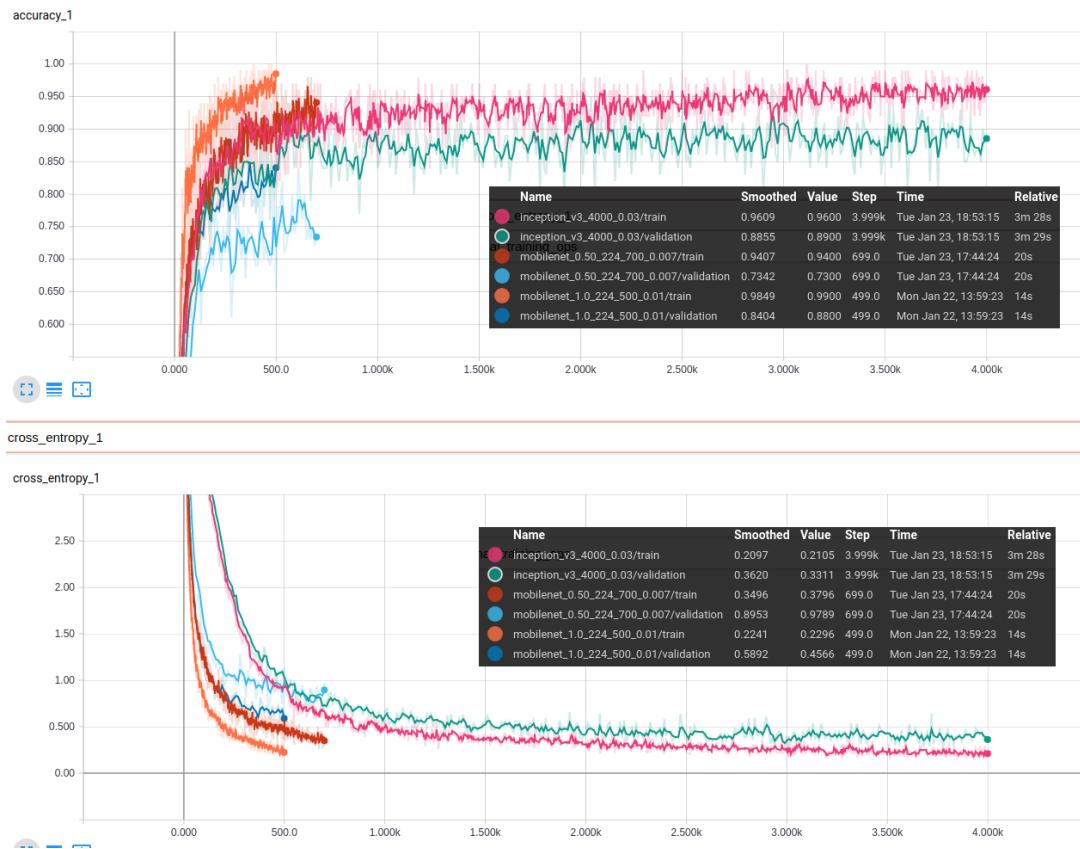


Figure 29: TensorBoard - optimal achieved accuracy of all models

A.12. Evaluation of optimization attempts

opt attempt	accuracy	misclassified	time to classify (App) [ms]
retrained	0,566641033	5	0
opt1	0,566641033	5	239,6
opt2	0,487681977	8	252,5
opt3	0,566641033	5	241,9
opt4	0,483819713	8	246,8

Table 2: MobileNet_0.5

opt attempt	accuracy	misclassified	time to classify (App) [ms]
retrained	0,504834563	7	0
opt1	0,504834563	7	316,2
opt2	0,458024049	8	310,2
opt3	0,504834563	7	323,4
opt4	0,458474453	8	320,6

Table 3: MobileNet_1.0

opt attempt	accuracy	misclassified	time to classify (App) [ms]
retrained	0,722748141	2	0
opt1	0,722748250	2	1092,2
opt2	0,698508064	3	1094,4
opt3	0,722748137	2	1139,9
opt4	0,700055786	3	1108,2

Table 4: InceptionV3