Raster Vectorization Using Deep Learning

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Supervisor 1: The main supervisor

Supervisor 2: The co-supervisors (internal and external)

Preface

Here, you give a brief introduction to your work. What it is (e.g., a Master's thesis in RAMS at NTNU as part of the study program xxx and...), when it was carried out (e.g., during the autumn semester of 2021). If the project has been carried out for a company, you should mention this and also describe the cooperation with the company. You may also describe how the idea to the project was brought up.

You should also specify the assumed background of the readers of this report (who are you writing for).

Trondheim, 2012-12-16

(Your signature)

Ola Nordmann

Acknowledgment

I would like to thank the following persons for their great help during . . .

If the project has been carried out in cooperation with an external partner (e.g., a company), you should acknowledge the contribution and give thanks to the involved persons.

You should also acknowledge the contributions made by your supervisor(s).

O.N.

(Your initials)

Remark:

Given the opportunity here, the RAMS group would recognize Professor Emeritus Marvin Rausand for the work to prepare this template. Some minor modifications have been proposed by Professor Mary Ann Lundteigen, but these are minor compared to the contribution by Rausand.

Executive Summary

Here you give a summary of your your work and your results. This is like a management summary and should be written in a clear and easy language, without many difficult terms and without abbreviations. Everything you present here must be treated in more detail in the main report. You should not give any references to the report in the summary – just explain what you have done and what you have found out. The Summary and Conclusions should be no more than two pages.

You may assume that you have got three minutes to present to the Rector of NTNU what you have done and what you have found out as part of your thesis. (He is an intelligent person, but does not know much about your field of expertise.)

Contents

Chapter 1

Introduction

Raster to vector or digitizing is a central part of what GIS specialists do. Digitizing is the task of extracting vector layers from raster maps so that they can be used for further analysis, and is often a time consuming manual process. With the vast amount of raster maps available online, we are losing valuable information because we are unable to process them automatically.

Even though there are multiple software products in the market today concerning the problem of converting a raster image to a vector image such as Scan2Cad [13] and Powertrace [10]. These products only focus on making vectorized boundaries of homogenous color areas, such as those in a logo and do not focus on the problem of digitizing raster maps with spatial data. Problems occur when the raster images not only consists of isolated objects that are easy to distinguish but contains a spatial structure, overlapping geometries, and background layers. The multilayered nature of raster maps in addition to varying image quality makes automatic vectorization a really hard problem.

Deep convolutional neural networks (Deep CNNs), are top performers of semantic image labelling (CITE) and can, therefore, be a possible solution to the digitalization problem. Beeing an instance of supervised learning, deep convolutional networks require proper labelled training data. This is often generated manually for each case. If one could train the networks with some of the digitized raster maps, and then use them to digitize the rest of the maps for us, this would be a great time saver.

In this paper we will look at the state of the art in feature extraction with deep convolutional networks, look at the data needed to train the networks sufficiently, implement a first version of a digitizing network and look at the performance of this.

Chapter 2

Motivation

Digitizing and vectorization is a time consuming and expensive process [18].

In 2009, the Norwegian government made it statutory for all municipalities in Norway to have a digital zoning registers [9]. This has many benefits to society, both for the municipalities, the government, and the private sector. Benefits such as faster insights and sped up proceedings for building projects.

In June 1st, 2017, 354 out of 426 municipalities are registered to have digital zoning registers. The law does however not force the municipalities to vectorize the zoning regulations in detail, only to have them scanned in a digital format such as PDF with the bounding limits of the plan vectorized. The detailed vectorization is then another step that has to be done in order to fully utilize the data in more advanced use cases, such as in GIS. See Figure 2.1 for an example of a zoning regulation in PDF format.

For the municipalities, the digitalization and vectorization is a process that is often done by external contractors. In a project in Telemark and Vestfold, the cost was estimated to be around 3000NOK for each plan, where the whole project consisted of 100 plans [1]. The cost savings in automating the vectorization of digitized zoning plans are thus economically significant.

Since the zoning regulations has to follow strict quality standards, the acccuracy of the output from the deep CNN also has to follow these standards. With many zoning regulations already digitized and vectorized, we potentially have a lot of validated, accurate data that can bee used to generate training data for the deep CNN. This gives us a great oportunity to investigate the performance of deep CNNs for vectorization of scanned maps.

There are a lot of approaches and network architectures that need to be examined and reviewed for this specific problem. This research will be the basis of the author's master thesis, where a practical implementation of the theory found in this research will be done.

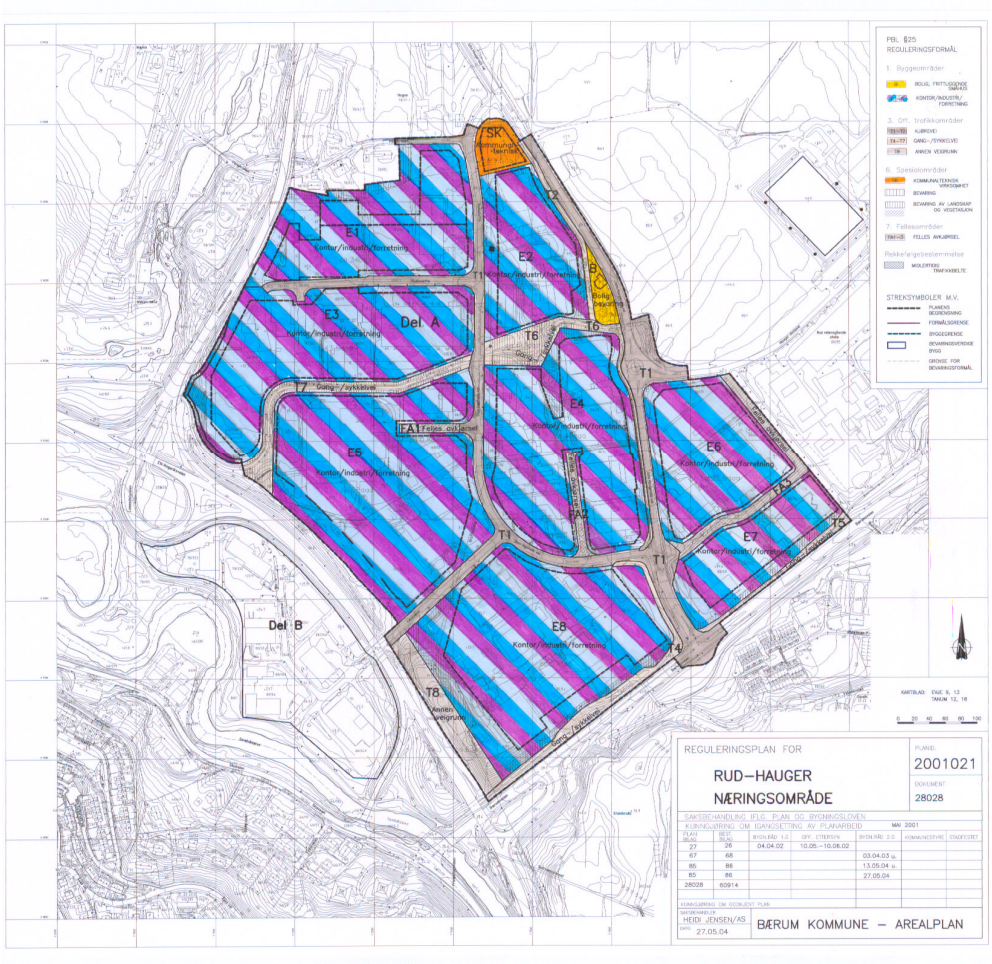

Figure 2.1: Scanned zoning regulation in PDF format from Bærum municipality.

Chapter 3

Vectorization

Vectorization, raster-to-vector conversion or image tracing is the conversion of raster graphics to vector graphics. To understand the reason for converting from raster to vector we need to look at some of the properties of both storage techniques.

Raster data is structured as an array of grid cells, also referred to as pixels. Each cell in a raster can be addressed by its position in the array, by row and column number. Since each pixel has it's own value, a raster can represent a range of spatial objects. A point can be represented by a single pixel, an arc represented by a sequence of pixels and an area as a collection of continuous pixels. Vector data is structured as a finite straight line segment defined by its endpoints. The location, or coordinates, of the endpoints, are given with respect to a coordinatization of the plane. The vector representation is not discretized in a grid space the same way as a raster but does follow an implicit grid structure as a result of the nature of computer arithmetic. Like the raster, the vector structure can represent multiple spatial structures. A point is given by its coordinates, an arc represented as a sequence of line segments, each consisting of start and end coordinates and an area represented by its boundary consisting of a collection of vectors.

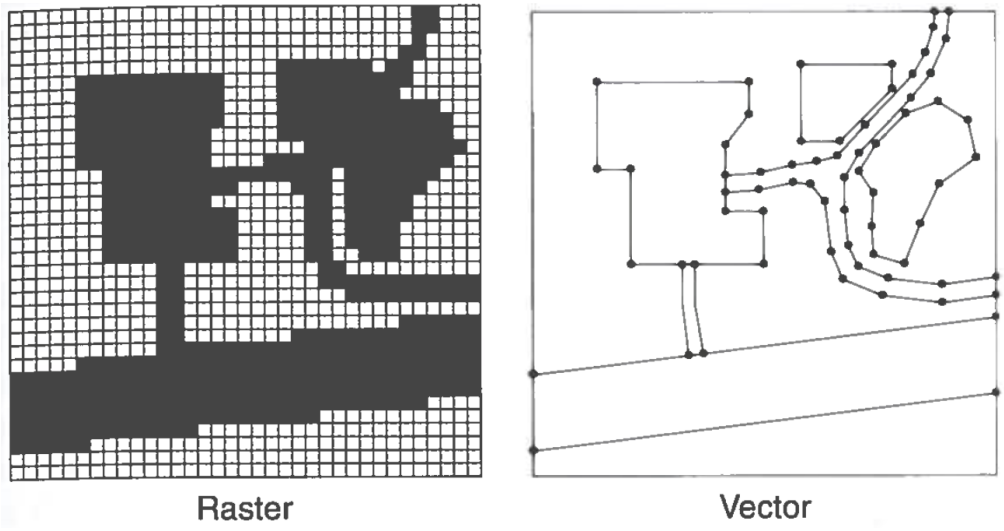

Figure 3.1: Raster and vector data [18]

There are multiple reasons for storing data in vector format: The geographic accuracy is higher since it is not dependent on grid size. It allows for efficient encoding of topology, an important aspect when doing analysis that utilizes topologic relations, such as proximity and network analysis. Vector data allows for storage of attributes in the data, giving us another dimension of information. The storage size is smaller.

There are multiple different techniques for vectorization. The most known are:

- Hough Transform based methods
- Thinning based methods
- Contour based methods
- Run-graph based methods
- Mesh pattern based methods
- Sparse-pixel based methods

All these have different properties and it is important to choose the one that is best for the specific problem.

Chapter 4

Image segmentation with Deep Learning

In this chapter, we will look at the problem of image segmentation and the state of the art regarding segmentation and object detection using Deep Learning. We will look at both semantic and instance segmentation.

Semantic segmentation of images is one of the key problems in the field of computer vision. It is about making dense predictions inferring labels at the pixel level, assigning a class to each pixel with its enclosing object [2]. Taking it a step further, we get to instance segmentation, where we want to associate the classes with a physical instance of an object.

Both semantic and instance segmentation can be seen as giving us an understanding of an image at a higher level. This fine-grained control of an image greatly helps with scene understanding which is becoming more and more relevant with the increasing number of applications, such as self-driving cars and augmented reality.

We can see an example in Figure 4.1 where we see the difference between the two approaches. In the middle photo, all the chairs have the same classification, as chairs. In the right photo, we see that the chairs now are classified as chairs, but with a different class for each of them. We can see that instance segmentation is the combination of both object detection and semantic segmentation.

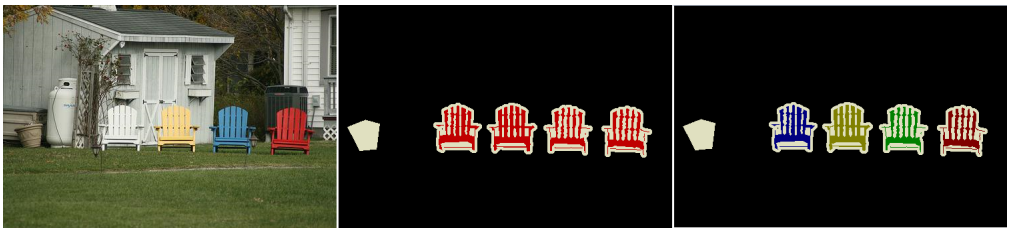

Figure 4.1: Left: input image. Middle: Semantic segmentation. Right: Instance segmentation. [7]

4.1 Neural networks

To get a deeper understanding of how neural networks perform segmentation of images, we need to take a look at the fundations behind them and how they operate.

Neural networks are a computational model that shares som properties with the animal brain in which simple units called neurons are working in parallel with no centralized control unit [8]. The primary means to long-term information storage is in the weights between the units and updating them is the primary way the network learns new information.

A network is defined by the number of neurons, number of layers and the connections between the layers. One of the easiest architectures to understand is the feed-forward multilayer architecture viewed in Figure 4.2. It is a neural network with an input layer, one or more hidden layers and an output layer. The input layers feeds input, in the form of vectors, to the rest of the network. The number of neurons at the input layer often reflects the size of the input vector.

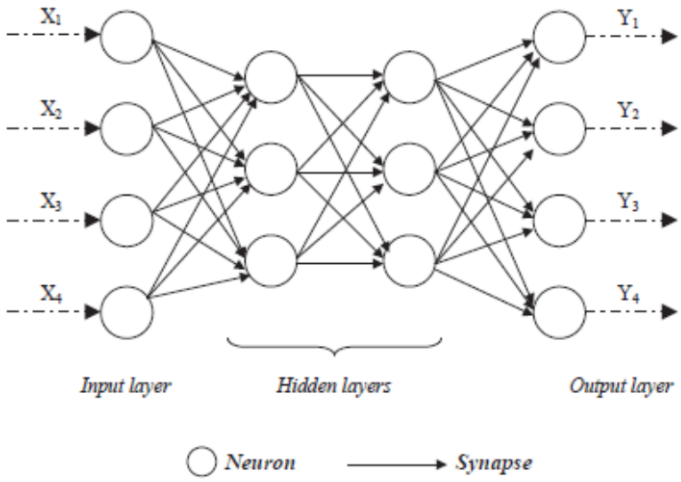

Figure 4.2: Structure of a multilayer feed forward network. [19]

4.1.1 Artificial neurons

Each layer consist of one or more artificial neurons, also called nodes. An artificial neuron is a mathematical representation of a biological neuron and consist of inputs with weights and bias, a transfer function and an activation function. The weights are what scales, either amplifying or decreasing, the input to the node. The bias is a constant scalar value per layer that is added to ensure that at least some of the nodes in the layer are activated, that is, forwarding a non-zero value to the next layer. The transfer function takes the weighted sum of the input variables and transfers it to the activation function. The activation functions are scalar-to-scalar functions that defines the output of the node based in the inputs, weights and bias. A model of an artificial neuron compared to a real one, can be seen in Figure 4.3.

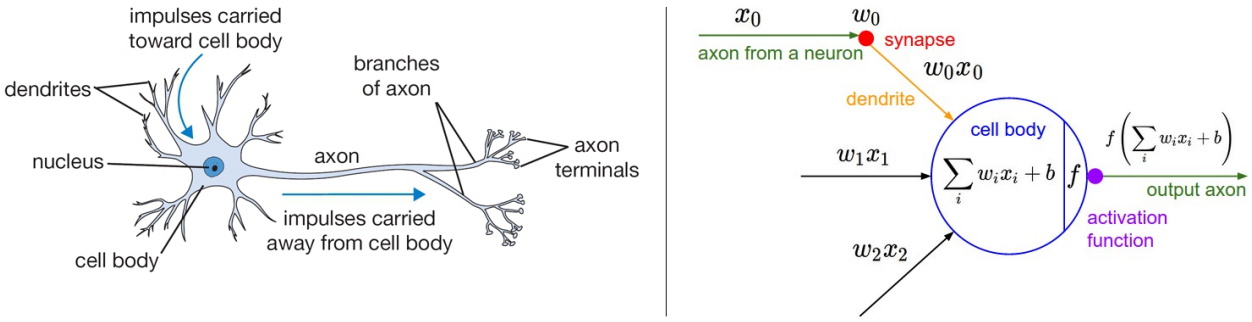

Figure 4.3: Structure of a real neuron compared with an artificial one. [4]

Activation functions

The use of activation functions in the hidden layers add the ability for the network to learn non-linear functions. We will now take a look at some of the usefull activations functions that are used today.

Sigmoid The sigmoid activation function has a characteristic "S"-shaped curve and can take variables of near infinite range and convert them to values between 0 and 1. It is good at reducing outliers and extreme values in the dataset. Expressed mathematical as:

$$a = \sigma(x) = \frac{1}{1 + \exp(-x)} \tag{4.1}$$

Tanh A trigonometric hyperbolic function. Tanh can normalize input to the range of -1 to 1 and can therefore deal with negative numbers better than the Sigmoid. Expressed mathemati-

cally as:

$$a = \sigma(x) = \tanh(x) \tag{4.2}$$

Rectified Linear Rectified Linear only activates a node if it is above some threshold. When the input raises above the threshold it has a linear relation to Equation 4.3. Nodes that use the rectifier are called Rectified Linear Unit or ReLU.

$$a = \sigma(x) = \max(0, x) \tag{4.3}$$

ReLUs are the state-of-the-art because of their proven usefulness in many situations and their ability to train better in practice than sigmoids. ReLU does not have the so-called problem of vanishing gradients either. Vanishing gradients is a problem that occurs when using gradient-based methods (EXPLAINED LATER) for learning, where large changes in the value of parameters from the early layers, does not have a big effect on the output, making the network lose its ability to learn. The reason for this happening is that some activation functions, such as sigmoids or tanh, forces the input space into small regions.

While removing the problem of vanishing gradients, ReLU introduces another one and that is the problem of "dying ReLU" [4]. This is a problem that occurs when a large gradient passes through the neuron causing the weight update to be so large that it causes the neuron to never activate again, that means that the gradient passing through the neuron will be forever zero.

4.1.2 Training

There are different forms of learning such as supervised, where we show the network what the correct answer is. Unsupervised, where the network itself decides how to label the data and reinforcement learning, where the network does not get to know the answer but learns by reward or punishment. We will only focus on supervised learning in this paper as this is the type of learning we use when doing image segmentation.

In supervised learning, the network learns by training on a set of inputs and desired outputs. As inputs are passed through the network and outputs are generated, it learns by adjusting weights and biases causing some neurons to become smaller and some to become larger. The larger a neuron's weight is, the more it affects the network and vice versa.

By adjusting the weights and biases, the network reduces the errors, also called loss. The loss is defined by some loss function that quantifies the correctness of the output from the network

in regards to the ground truth. By using a loss function we reclass the learning problem as an optimization problem, where we try to minimize the loss.

The most common algorithm for the weight adjustment in neural networks is called *backpropagation*.

Backpropagation Learning

When the output from a neural network produces a large loss, we need to update the weights accordingly. A problem with multilayer neural networks, however, is that there are many weights connecting an input with an output, so it becomes difficult knowing what weights that affect the output. We need a clever way of finding what specific weight that contributes to the output. This is the problem backpropagation tries to solve. A high level understanding of backpropagation is that we use the chain rule to iteratively calculate the gradients for each layer. The steps of the algorithm is as follows:

1. Initialize network with random weights
2. Loop trough the training examples
3. Compute the network output for the current training example
4. Compute the loss with the loss function.
5. Compute the weight update for the output layer with the weight update rule:

$$W_{j,i} \leftarrow W_{j,i} + \alpha \times \alpha_j \times \Delta_i$$

   Where

$$\Delta_i = Err_i \times g'(input\_sum_i)$$

   and g' is the derivative of the activation function
6. Loop trough all the layers in the network all the way to the input layer and:
7. Compute the error at each layer with the propagation rule:

$$\Delta_j \leftarrow g'(input\_sum_i) \sum_i W_{j,i} \Delta_i$$

8. Update the weights leading in to the hidden layer with the update rule:

$$W_{k,j} \leftarrow W_{k,j} + \alpha \times \alpha_k \times \Delta_j$$

The term α is the learning rate, and belongs to the family of what we call *Hyperparameters* in machine larning.

Hyperparameters

The hyperparameters are what we tune to make the network train faster and better. The selection of these parameters are done to ensure that our network does not *overfit* or *underfit* the data. We say that our model is overfitted if it fits our training data too well but does not generalize enough over the entire dataset. We say our model is underfitted if it generalizes too much and is not able to fit the training set. The terms are illustrated in Figure 4.4. In the left image we see that the model does a bad job at approximating the function, it is underfitted. In the middle image we see that the model approximates the function well. In the right image we see that the model fits the training samples very good, but does a bad job at approximating the function, the model is overfitted.

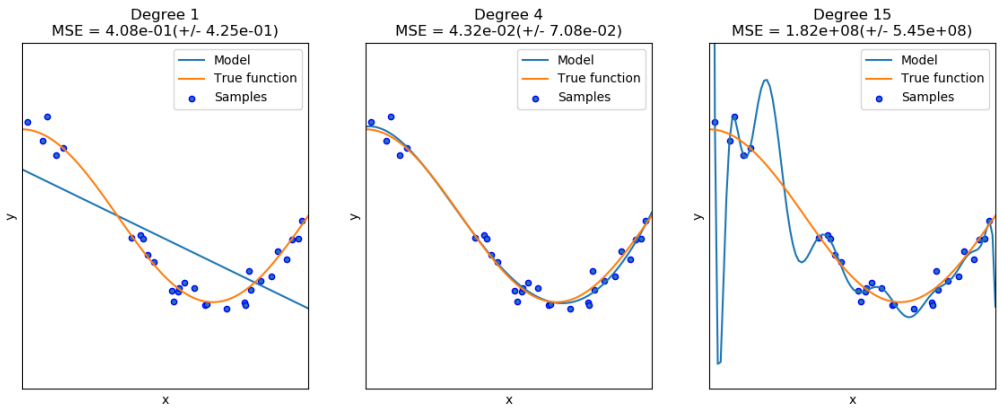

Figure 4.4: Left: Underfitted model. Middle: Appropriate fit. Rigth: Overfitted model.

The learning rate affects the amount we adjust the parameters during training. A large learning rate will make our parameters take large steps, thus saving time, but can cause us to overshoot the minimum of our loss function causing us to never find a minimum. A small learning rate causes us to take smaller steps and should help us reach the minimum, but can take a very long time to do so.

Another important hyperparameter is *regularization*. Overfitting often occurs when some weights have become very large and regularization is about reducing the effects of the large weights in the network. The perhaps most common form of regularization is L2 and is often implemented as the term $\frac{1}{2}\lambda w^2$ that we add to the weights [4]. Another regularization, introduced in [15] is *dropout*. Dropout works by randomly dropping some of the neurons during training causing it to train on a "thinned" version of the net. Dropout has shown major improvements over other regularization tehniques [15].

4.2 Convolutional neural networks

Fully connected multilayer neural networks take inputs as a one-dimensional vector. When using an image as input, these vectors become very large. The reason for this is that we represent each pixel in the image as one value in the vector. If we are working with color images represented with 3 channels of RGB information, each of these also needs to be mapped. For a single 200x200 image this means $200 \times 200 \times 3 = 120000$ connections in only the first layer. This illustrates how bad the fully connected neural networks scale.

Convolutional neural networks, or CNNs, tackle the scaling problem by assuming inputs as images and model them as three-dimensional objects with image width, image height and color channels as the dimensions. At a high level, the architecture consist of an input layer, convolutional layers, pooling layers and fully-connected layers [8].

4.2.1 Convolutional layers

The convolutional layers, or CONV layers, are the core building blocks of a CNN. The layers consist of a set of learnable filters also called kernels. Each of the filters are small in regards to width and height but are always the same size as the input in regards to depth. The filter is applied to the input by sliding, or *convolving*, the filter accross the width and height of the input. At each position, the dot product between the filter and the input is calculated. The output is a two dimensional map that is called *activation map*. This process is illustrated in Figure 4.5. For each of the filters in the CONV layer we get such a map and stack them in the depth direction, this in turn represents the output of the layer.

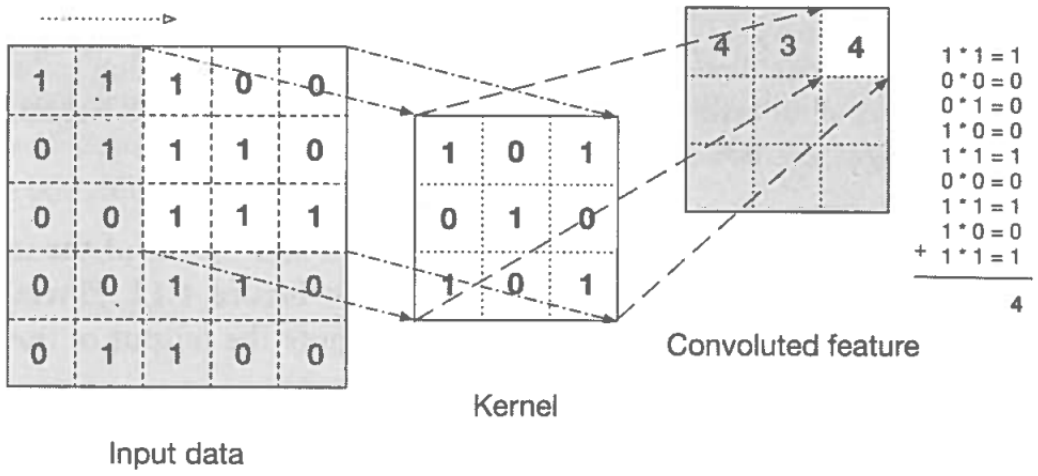

Figure 4.5: The convolution step.
Source: Patterson and Gibson[8]

The network will learn filters that causes the node to activate when certain visual features are seen, for instance an edge. Deeper into the network we will se filters that become more global in term of the input and recognizes nonlinear combinations of features. An example of what the filters look like in a deep CNN can bee seen in Figure 4.6 where we see filters learned in the first convolutional layer in an eight layer network [5].

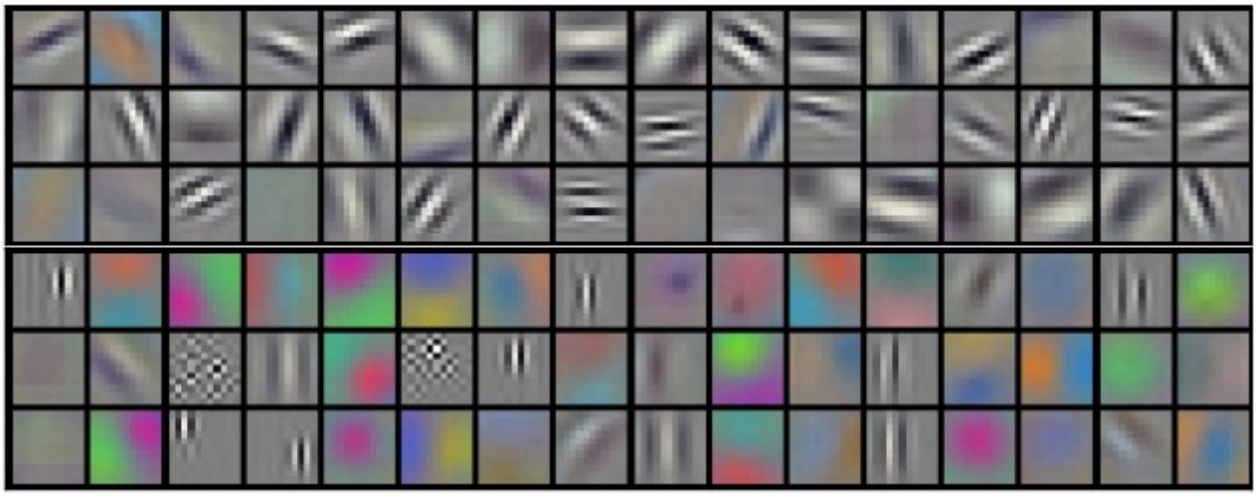

Figure 4.6: 96 learned filters in the first convolutional layer.
Source: Krizhevsky et al.[5]

If we imagine that we freeze the filter as it is convoluted accross the input, a single step and its

calculation, can be viewed as the output from a neuron. The activation map then represents a sheet of neurons with each of the neurons looking at a small part of the input, not knowing anything about the rest of the image. This feature is called *local connectivity* and is an important part of how the network keeps the number of parameters smaller then a regular neural network. All the neurons in the sheet also share parameters, since it is the same filter that did the calculation. This is the concept of *shared paramters* and is the other important part of how CNNs keep the number of paramters low.

4.2.2 Pooling layers

Another way to reduce the number of parameters in the network, is the use of pooling layers. Pooling layers essentially reduces the input size by downsampling the input with different pooling functions. The most common operation is *max pooling* with a 2x2 filter with a stride of 2 that reduces the size by two in the height and width dimension [4].

Chapter 5

Previous work - Image segmentation

In this chapter, we will look at some of the previous work done in the field of image segmentation with neural networks.

We will see that all of the networks presented are trained on real-world imagery and not images of maps. The reason for this being that the research is more mature in the field of real world/natural image segmentation but the same principles apply to segmentation of map images. We will also look at some of the approaches towards maps and geographical data later on in the paper.

During the last ten years, we have seen many important advances when it comes to the architecture of deep networks for image segmentation. AlexNet [5], VGGNet [14], GoogLeNet [16], ResNet [3], ReNet [17] and the very recent CapsNet [12] are all examples of such advances. In the next section, we will look at the main points from each of these networks.

5.1 Important architectures

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5.1.1 AlexNet

Achieving first place in the ImageNet Large Scale Visual Recognition Challenge (ILSVRC) [11] in 2012 with a top-5 test accuracy of 84.6% by a margin of 10% to the next competitor, AlexNet pioneered deep CNNs in image classification. The network consisted of a total of eight-layer,

five convolutional layers with max-pooling and three fully-connected layers. All the layers used ReLU as activation. To reduce overfitting they used dropout. Figure 5.1 shows the architecture of the network.

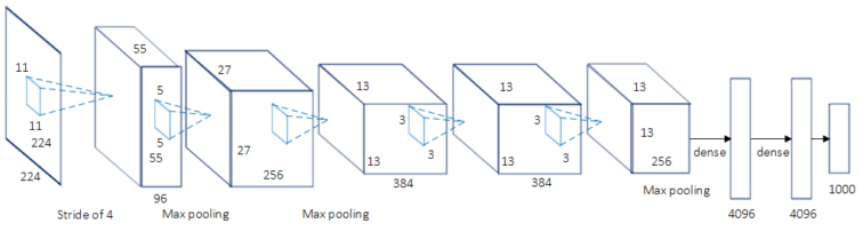

Figure 5.1: AlexNet architecture
Source: Krizhevsky et al.[5]

5.1.2 VGG

The Visual Geometry Group (VGG) model was introduced by the Visual Geometry Group at oxford university. In their paper, they propose multiple different architectural configurations with weight layers ranging from 13 - 16 layers deep. The most interesting is the model with 16 weight layers. It was submitted to ILSVRC 2013 and managed to get a top-5 test accuracy of 92.7%. In Figure 5.2 we can see that the architecture makes us of more layers with small receptive fields rather than a few layers with large receptive fields.

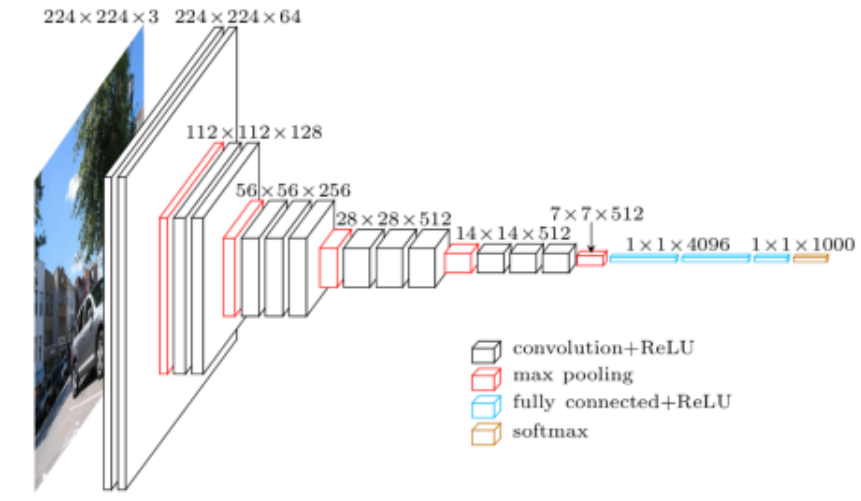

Figure 5.2: VGG 16 architecture
Source: https://blog.heuritech.com/2016/02/29/a-brief-report-of-the-heuritech-deep-learning-meetup-5/

5.1.3 GoogLeNet

This network won the 2014 ILSVRC challenge with a top-5 test accuracy of 93.3%. The network introduced a new architectural concept called the *inception* model (see Figure 5.3). The model is essentially a new mini-network with a pooling operation, large convolution layers, and smaller convolution layers. They proposed the use of small 1x1 convolution layers to reduce the complexity before the large convolution layers to keep the parameters and computational cost under control. This showed an increase in speed ranging from 3-10x faster than similar networks without the inception module.

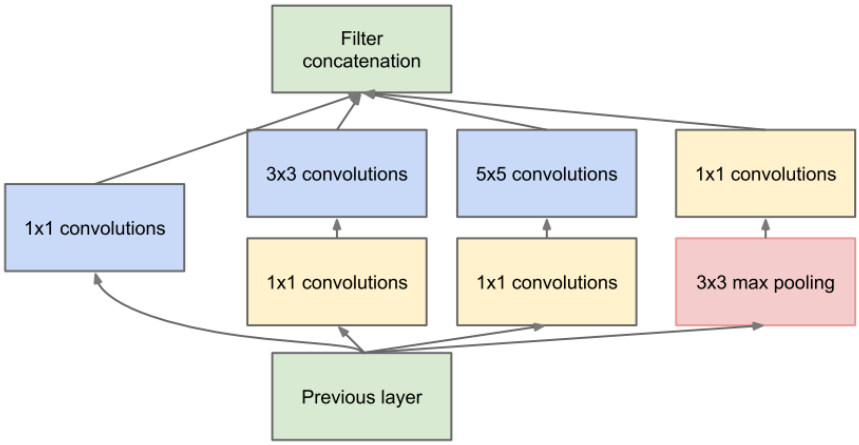

Figure 5.3: Inception module
Source: Szegedy et al.[16]

5.1.4 ResNet

ResNet won the 2015 ILSVRC, with a top-5 test accuracy of 96.4%. The network is known for its depth of 152 layers and a new kind of building block called residual block. The residual block contains two paths between the input and the output where one of the paths serve as a shortcut connection to the output (see Figure 5.4) essentially copying the input to the output layer. A big problem with very deep networks is that they are hard to optimize. When the depth of the network increases, the accuracy gets saturated. This is called *degradation* and is the problem that the residual blocks are addressing by forcing the network to learn on top of already available input.

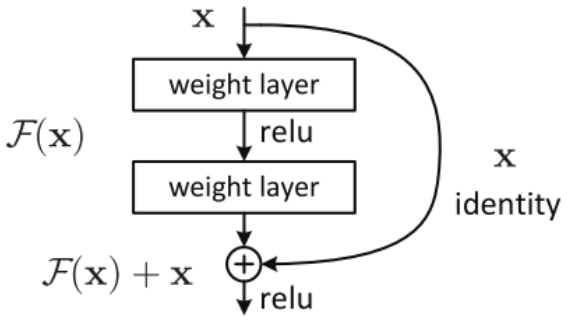

Figure 5.4: Residual block.
Source: He et al.[3]

5.1.5 CapsNet

Released November 2017, this is a very recent advancement in neural networks. It introduces a new type of neural network based on *capsules*.

BLABLABLA MORE ABOUT THIS

It addresses the issue that CNNs are not good at generalizing new viewpoints. They are good at generalizing to translation, but other affine transformations have shown to be difficult to learn.

It has not (yet) been tested in ILSVRC but has been run on the Modified Institute of Standards and Technology database (MNIST) that is a database of handwritten digits. The database has 60000 training images and 10000 test images.

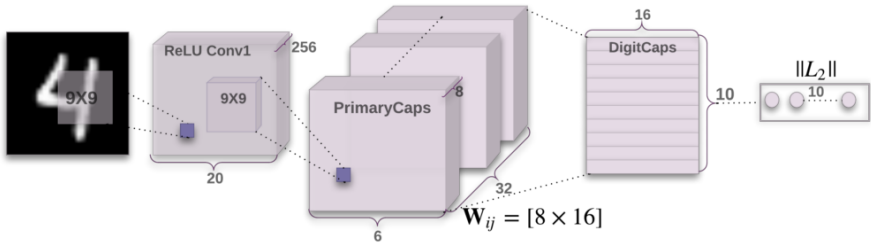

Figure 5.5: CapsNet with 3 layers.
Source: Sabour et al.[12]

5.2 Image segmentation

Many of the previous network architectures described in section 5.1 are predicting labels of what the images contain and not where and what part of the image the labels are to be found in. Image

segmentation is about assigning a class to each pixel with its enclosing object so we need output from the networks that are spatial maps instead of classification scores. In this section, we will review important networks that are specialized in image segmentation.

5.2.1 FCN

Fully Convolutional Network (FCN) by Long et al. [6] can be seen as a common forerunner for semantic segmentation with convolutional networks [2]. FCN adopted the contemporary deep classification nets AlexNet, VGG and GoogLeNet architectures we saw in section 5.1 to make dense predictions at the pixel level. It is important to note that they not only reused the architecture but used the pre-trained classification models as a starting point. The network replaced the fully-connected layers with convolutional ones, noting that the fully-connected layers could be seen as convolutional ones with kernels (filters) that cover the entire input region. This allowed segmentation maps to be generated from images of any size. Because of all the pooling operations in CNNs, a technique called *deconvolution* [20] was used to upsample the coarse output to dense pixels. Deconvolutional layers can learn interpolation functions the same way the network learns weights. Skip connections similar to the ones we saw in ResNet, are also included to give the deeper layers higher resolution feature maps.

5.2.2 SegNet

Dilated CONV Deeplab v1 and v2 Refinenet PSPnet Large kernel Matters Deeplab v3

Texton forest Random fort Patch FCN 2014 U-NET CRF postprocessing

EncoderDecoder

Chapter 6

Discussion

Chapter 7

Conclusion

Appendix A

Acronyms

FTA Fault tree analysis

MTTF Mean time to failure

RAMS Reliability, availability, maintainability, and safety

Appendix B

What to put in appendixes

This is an example of an Appendix. You can write an Appendix in the same way as a chapter, with sections, subsections, and so on. An appendix may include list of code (in case you are programming), more details about results that you have presented in the report (could be a more complete description of results, in case you decided to focus on the most important ones in the main report), supplementary information and descriptions you have found relating to the system you are analysing, such as drawings. You may discuss with your supervisor what are relevant information for appendixes.

B.1 Introduction

B.1.1 More Details

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