



Documentation

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1 The Problem

1.1 Introduction

Most of us know and love the famous online game *GeoGuessr*. You are dropped in the middle of nowhere in *Google Street View* and tasked with determining the location as closely as possible. “Am I on the North or South Pole?”, “Is this the African or South American jungle?” and “On which end of Russia am I?” are only some of the questions players are asking while playing the game. Fortunately, the problem we were tasked with is a little simpler (keyword: *a little*). Instead of playing GeoGuessr on a global scale, we play it only within Croatia. However, we won’t be playing GeoGuessr, rather, we will do our best to create a model which will determinate the location. *Photomath*, the sponsor of this competition, provided a **train set** of Google Street View images taken on Croatian roads along with their coordinates. The images come in quadruplets forming a non-continuous 360° view of the location, where each image was taken in a cardinal direction (north, south, west, east) from the perspective of the Street View car. Alongside the images themselves, we also received their locations in the form of latitude and longitude pairs for each set of four images. An example of the four images is displayed in Figure 1.



Figure 1: Example: location latitude: 45.131946, longitude: 14.002129

1.2 The Task

As we previously stated, our task is to predict the coordinates of the images, specifically, the coordinates of the images from the **test set** which we will receive in the last week of the competition (kept of course in the most secret government bunkers, shut away from our prying eyes). It’s important to note that we will not receive the true coordinates for images in the test set. After we provide predicted coordinates for each location from the test set, the total error is measured using the **great-circle distance** between the predicted and true coordinates. The great-circle distance measures the distance between two points over a curved surface, e.g. the distance between two cities on the Earth’s curved surface, and it uses the **haversine formula** to calculate this (fortunately for you, we won’t go into detail about this). Total error is calculated as the mean of all great-circle distances between the true and predicted coordinates for all locations. It’s also possible to explain the error in the following way: the further a bird needs to fly from the predicted coordinates to the true coordinates, the larger the error. The total error will be used to determine how successful one method is compared to others.

2 Solution

2.1 Computer vision

The type of data we were provided with are images (aside from latitude and longitude of the location). When trying to solve a problem which includes images as the main source of data, the method for the solution will most likely come from the area of **computer vision**. Computer vision is an area of research that has arguably seen the most growth from the advent of deep learning, being right up there with meaningless buzzwords. Over the past decade, it grew from a niche research area to one of the most widely applicable fields within machine learning. Today in computer vision, we use neural networks to analyze a large number of images, extract some potentially useful information from them, and use that information to classify those images into predefined classes or predict a target variable. It can be used in almost anything, from detecting traffic signs for self-driving cars to distinguishing fake works of art from real ones. The problem we were tasked with solving in this competition falls neatly into this category. Indeed, we will methods and knowledge from the computer vision to solve the problem.

On paper, our problem sounds fairly simple and is not unlike many other computer vision tasks. However, we are faced with the following problem: a country can look very similar over large swathes of land. Turns out, the grass is green and the sky is blue wherever you are in the world. For example, if we were randomly placed somewhere in the area of **Slavonia** and were told to say where we are located exactly, it might feel impossible to predict our exact (or even approximate) location (the unending flatness

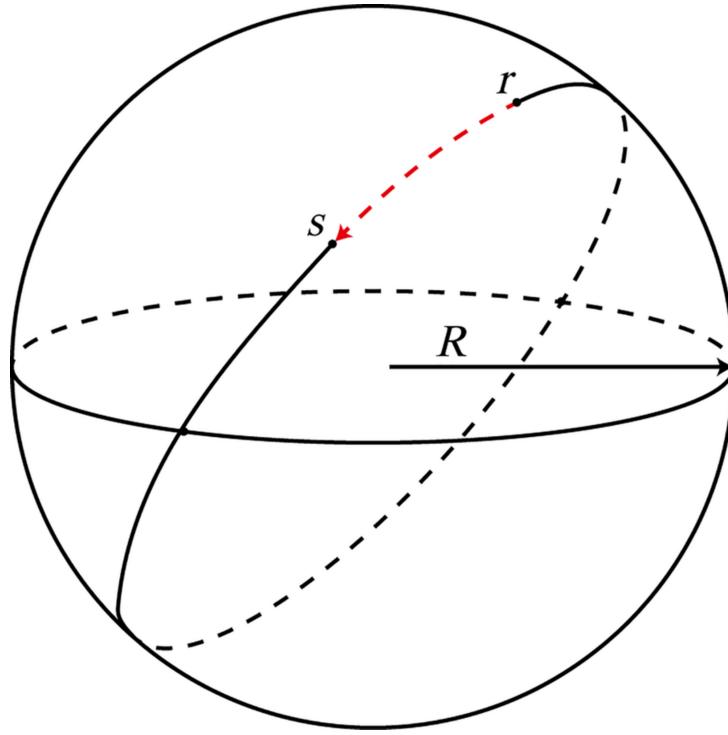


Figure 2: An image of a sphere where the dotted red line represents the great-circle distance between two points on the sphere's surface. Notice that the great-circle circle distance is larger than a **direct straight line (Euclidean distance)** through the sphere.

of Slavonia might give the model a clue though). Unless we've already seen the landscape or we notice some obvious features of the location, such as a town sign or a famous landmark, there is little chance for us to correctly predict our whereabouts. There is a silver lining to this though. Croatia, although small, is very geologically and culturally diverse (thank you centuries of non-independence). Due to this, mountains, houses, forests and even fields can look different depending on the region of the country, giving precedence to the idea that the model could learn to spot these differences. That being said, it is nonetheless a difficult problem to solve and requires clever feature engineering and a careful neural network setup in order to work, which we will talk about in the coming chapters.

2.1.1 Convolutional Neural Networks

What makes computer vision distinct from other fields of deep learning is its usage of **convolutional neural networks**. The main assumption convolutional neural networks (CNN) is that our data (images) has composite structure. The fancy term means that the data has a structure in which larger parts are created from smaller parts. For example, the Google Street view image might contain a house, a road, a car and a tree. A house contains front doors, windows, facade and chimney. The front door contains a knob, a small glass window and a sign. The composite structure assumption for convolutional neural networks (CNN) is important because of how they work: convolutional neural networks (CNN) is made up of multiple layers and each layer is in charge of learning large, medium or small features (simplified) of the image:

1. the first layer would learn how to recognize low level features - basic geometric shapes like angled lines and contours
2. the second layer would learn how to recognize medium level features - doors, windows, facade and chimney
3. the third layer would learn how to recognize high level features - a house, a road, a car, a tree

Before continuing with CNNs, let's first ask ourselves the following question:

Why should we use convolutional neural networks for the computer vision problems? Why can't we turn the 2-dimensional data structures (an image) into a vector with n features and feed it to already existing models like linear regression or SVM?

We *can* do this, but we *shouldn't*. In the past, computer vision problems were solved by this approach. However this method has some serious issues

1. it isn't robust to slight differences in images that appear very similar (to us humans)
2. models that were trained on images that were turned into vectors with n features need **a lot images** compared to convolutional neural networks to predict the location for unseen images

The concept of predicting the values (locations) of unseen data (images that model didn't yet see) is called **model generalization**.

It can also be described as model's ability to adapt properly to new, previously unseen data, drawn from the same distribution (in our case the distribution are Google Street view images in Croatia) as the one used to create the mode. The key takeaway is that convolutional neural networks generalize better than SVM for images.

Each layer in CNN uses 2D *filters* to capture image features. A filter is a 2D matrix where each element has it's own learnable weights. This filter slides across images to detect patterns. You can think of it like a magnifying glass that slides across the image. Ideally, each filter (magnifying glass) in a CNN layer would specialize in learning different image features. The top level magnifying glasses would learn how to recognize high level features (a house, a road, a car, a tree) while the low level ones would learn to recognize simple lines. By stacking multiple layers of these filters, each layer can learn a higher order of abstraction of the image data. For instance, the first layer might only learn to recognize simple lines. The second layer might combine these lines into shapes, while the third layer could finally combine these shapes into something recognizable, like a car. Such an architecture mimics how the human brain actually recognizes objects, that is to say, by combining smaller elements we see into larger ones. After we have stacked enough convolutional layers for recognizing objects, we finish off the network by feeding all the results into a fully connected layer for classification or regression and train it with any generic loss function.

A large advantage of CNNs compared to other network architectures is their interpretability. The filter weights can be visualized to depict what each filter detects in an image, while network weights depict how the filters are combined. This can help us in understanding how the network learns from images. (IMG: insert filter image)

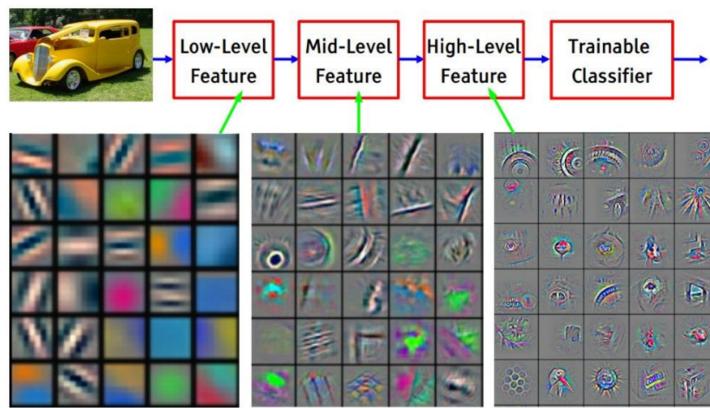


Figure 3: Example: feature maps of the CNN trained on car images

2.2 Data and Feature Engineering

The dataset we received contains directory with images and a `data.csv` file. Images should be self explanatory (apologies to the blind) but we will explore the `data.csv` further. The `data.csv` looks something like this:

uuid	latitude	longitude
69387a76-b6f6-4a76-9d82-59367e14cb12	45.55222786237915	18.53839695354916
83fd0354-8781-4325-9139-653ba0ce718f	45.11632629078026	14.82181715265881
5e2f692d-a2e6-45b1-b18b-3cec90b31b64	45.42498633931014	18.76785331863612
b3447ea2-8ea2-4c4e-b2a8-8611c8253995	46.15450138396207	17.0570928956176

It's quite simple. `uuid` represents the directory name which contains four images at the location `latitude longitude`.

In this chapter, we describe how transformed this `data.csv` to a new csv which we will call **statically enriched csv**

uuid	lat	lon	poly_idx	center_lng	center_lat	crs_y	crs_x	crs_center_x	crs_center_y
69387a76-b6f6-4a76-9d82-59367e14cb12	45.55	18.53	45.0	18.74	45.64	5531731	159131	5542646	175076
83fd0354-8781-4325-9139-653ba0ce718f	45.11	14.82	25.0	14.74	45.14	5482666-		5486160	-137869
5e2f692d-a2e6-45b1-b18b-3cec90b31b64	45.42	18.76	45.0	18.74	45.64	5518068	177432	5542646	175076

uuid	lat	lon	poly_idx	center_lng	center_lat	crs_y	crs_x	crs_center_x	crs_center_y
b3447ea2-8ea2-4c4e-b2a8-8611c8253995	46.15	17.05	50.0	17.21	46.11	5596833	43038	5592979	55064

One more thing that would be interesting is to visually inspect the distribution of the locations. Understanding the distribution of the data gives us the insight into things we might not be aware of.

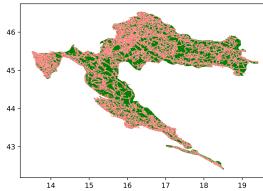


Figure 4: Distribution of the dataset. It's visible that the mountainous part of Croatia contains the least amount of locations in the dataset.

2.3 Data Representation

Because Croatia is a small country (though not as small as Slovenia) and its coordinates have a range of no more than a few degrees in both latitude and longitude, we needed to normalize them. But, before doing that, there was another transformation we needed to perform. The thing is, we can't use the haversine distance function during the training phase of the model due to its slowness (it contains a lot of trigonometric operations that don't cooperate nicely with GPU-s). But we also can't use regular coordinates even after transforming them because the Earth's surface is curved (even though some would want you to believe otherwise) and generic loss functions don't take this into account. Coordinates that are expressed as a latitude and longitude pair live in the [ESPG:4326](#) latitude/longitude coordinate system that's based on the Earth's center of mass. Notice that coordinates in the ESPG:4326 system are coordinates that we *do not want*. Before we continue, let's forget those four digits by calling the ESPG:4326 space a **global space**. The issue with **coord space** is that the straight path distance (a.k.a "digging a tunnel" a.k.a the Euclidean distance) between coordinates isn't scaled well. For example, straight path distance locations (lat: 10, lng: 0) and (lat: 20, lng: 0) isn't the same as the distance from location (lat: 20, lng: 0) to (lat: 30, lng: 0). **What we want are new and simple x and y coordinates in 2D Euclidean space in which we can use straight path distance without remorse!** Multiple ideas were tested to solve this, including cosine transforming the coordinates, as well as projecting them into Cartesian coordinate system. Finally, we ended up using a much more elegant solution with fewer steps: the **coordinate reference system (CRS) projection**. Here's how it works. It transforms every coordinate on Earth's curved surface into a different coordinate on a flat surface (2D Euclidean space) using a projection. Essentially, the projection transforms the latitude and longitude pair to x and y pair. Wonderful thing about x and y is that they are expressed in meters and the error of the Croatia's projection is minimal (no more than about 1m). Maybe most importantly, a generic [mean square error](#) loss function is directly applicable to these coordinates, or at least, the standardized version of them. The exact name of the new space is called [ESPG:3766](#) which we will call **Croatia CRS space**, tailor made for projecting Croatia's latitude and longitude coordinates into x and y coordinates which live in 2D Euclidean space.

Splendid! Now we simply need to find the maximum and minimum coordinates of the train dataset and use them to normalize the data into a 0 - 1 range. This is done to improve training stability and simplify the output. It is worth noting that we calculate these values only on the training part of the dataset, as using other parts of the dataset would essentially give the model access to their information, which wouldn't be fair at all (this term is called [Data Leakage](#)). Since our model will be predicting coordinates in the Croatia CRS space we need to re-project them back into to global space so we can properly calculate the great-circle distance. Degrees to radian transformation is one more transformation that will also be applied since functions like the haversine distance take radians as the input.

2.4 Classification Approach

The problem of predicting the coordinate given four Google Street view images can be approached from two different angles. Fearing encroaching on any originality, we will call them the **Classification approach** and the **Regression approach**.

In the Classification approach, we classify images into a fixed set of regions of Croatia in the form of a grid on the map (notice: we lose the information about the image's exact location here), while in the regression approach we try regressing the image coordinates to a continuous output from the model that will be restricted by the minimum and maximum possible coordinates (bounds of Croatia).

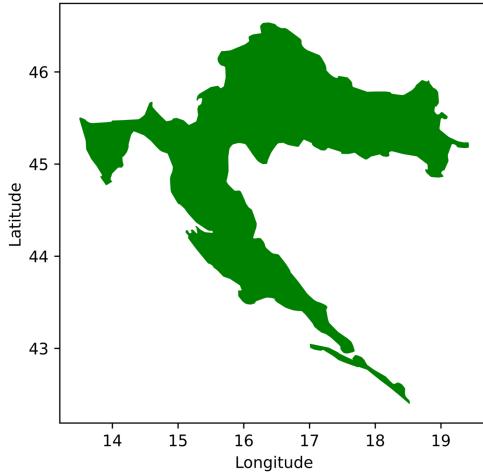


Figure 5: Croatia. We have lot of islands but images from islands are not included in the dataset

The set of regions of Croatia we mentioned above can be represented in the form of square regions on a map. Each region corresponds to a single class and each region also has a centroid that represents the coordinates assigned to the class. The idea is that, instead of predicting the *exact* coordinates of an image, the model classifies the images into regions from the previously described set of regions (you can also see them on the figure below). Notice that we don't predict coordinates for each set of four images, rather we predict the class (region). Model will classify four images into a single region. Later however, we do have to provide a concrete value for the latitude and longitude coordinates. How will we decide what's the final coordinate, given that our model classified an image to some region? We declare the predicted coordinates to be the **centroid of the predicted region**. Centroid of the region will be used to calculate our error in regards to that centroid. Notice that the image's true coordinates might be relatively distant from the centroid of the region into which the image was classified. This error shrinks as the number of specified regions (classes) grows.

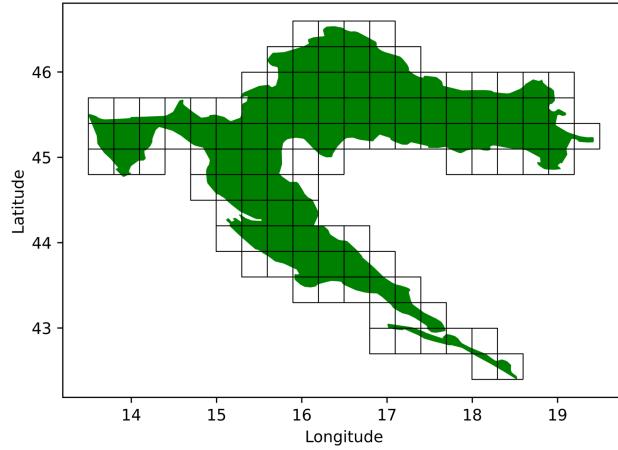


Figure 6: Croatia divided into region (square) regions. In this case, there are 115 regions that intersect with Croatia.

2.4.1 Class Creation

How is this grid-like set of regions created? First, we create a generic grid that is located fully inside the bounds of Croatia. It contains numerous regions (squares) which are adjacent to each other. Although we are working with a fixed number of regions, not every region is created equal. This is because, unfortunately, some of them aren't located in Croatian territory at all, as they don't really intersect Croatian territory. Therefore, they shouldn't be taken into consideration further on and are filtered out. After this is done, we proceed to the task of finding the centroids of these regions. Using the `geopandas` library, this problem can be reduced to a single simple Python property: `region.centroid`. Great! Now we have a set of classes for our model. But before we continue

the journey let us double-check what we did so far...

Figure 7: Examples of maps of Croatia divided into distinct regions that represent classes. Red dots represent the centroids of the regions, or otherwise, the point on land closest to the centroid if the centroid is at sea. The image on the right has a denser grid than the image on the left, meaning that it contains more classes.

2.4.2 Problems That Arise

Let us observe the following example. Even though the centroids of the regions were calculated correctly (they're in the center of the squares), some of them decided to go sailing and ended up in the middle of the sea. This doesn't make sense for our prediction, as we know for a fact that the dataset contains images only taken on land. This has to change. Therefore, we introduce *clipped centroids*. Clipped centroids are a modification of regular centroids that fix the previously stated issue by clipping the undesirable centroid to the closest possible point on land. By doing this, we reduce the error rate of the model by moving seaborne centroids closer to the image's true coordinates, which are on land.

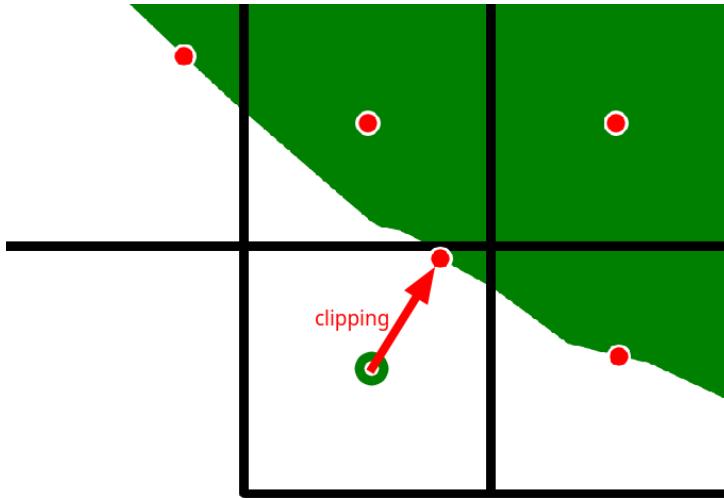


Figure 8: Clipped centroid (red dot). The true centroid isn't located at the center of the region so the centroid is relocated (clipped) to the nearest point on the land.

We have previously mentioned that it's possible to specify the number of classes we desire before creating the grid and thereby make it more or less dense. By choosing a dense grid, we can essentially simulate something akin to regression. This is because, as the number of classes increases and the size of each class decreases, more regions and centroid values are available as potential classes. A smaller class means that the theoretical maximum distance between a class' centroid and the true image coordinates is also smaller, and therefore has the potential of decreasing the total prediction error. Note that, at the end of the day, this is what matters, not the accuracy of our class predictions, because we calculate the final error by measuring the distance between an image's coordinates (here the class centroid) and its true coordinates. Even if we classify all images correctly, we will still have a potentially large average haversine distance because we never actually predict the true image coordinates, only the class centroids. If we take this to the extreme, which is an infinite number of classes, we can come quite close to regression, but there is a caveat. In classification models, each class needs a certain number of images to effectively train. If this number is too low, the model simply can't extract enough meaningful information from the images of a class to learn the features of that class.

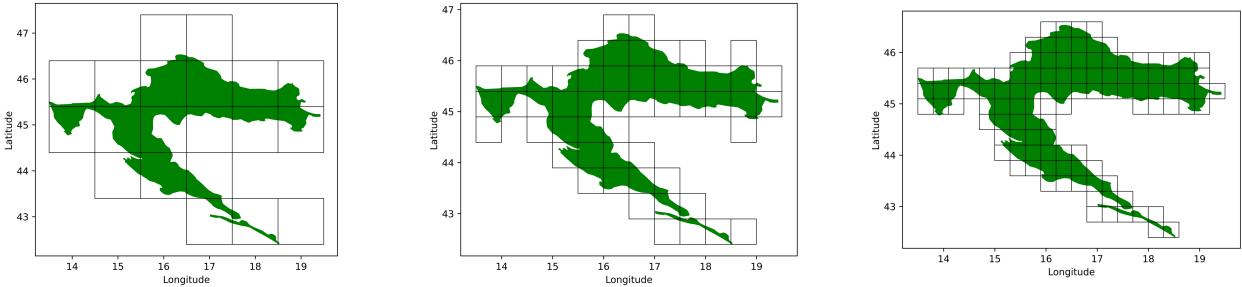


Figure 9: Grids for different number of regions (20, 55, 115).

Another problem arises because of Croatia's unique shape, only matched by that of Chile and The Gambia. For some regions, the intersection area with Croatia's territory is only a few tiny spots, meaning that the majority of the region's area ends up in a neighboring country. If this was anywhere before 1991., this wouldn't be a problem, but it isn't. The usage of clipped centroids we previously defined somewhat alleviates this issue, but another problem arises because there simply might not exist any images in the dataset that are located in that tiny area of the region, that is, within Croatia. And in fact, we did end up in such a situation. We solved this by discarding these regions and pretending like they didn't exist in the list of classes we could classify the images into. Fortunately, this doesn't happen too often as the dataset is fairly large and the image's locations are uniformly distributed.

In the late stage of the project, someone got a light bulb above his head. Why do we declare a centroid (clipped or not) as the final coordinate of the region? What if the region inside of the region is a mountainous terrain? However technologically advanced, Google's car would have issues climbing in some parts of [Lika](#). Naturally, more Google Street View images would come from a subpart of the region. To take this into account, we created **weighted centroids** for each region. Weighted centroid is calculated as a mean location of all images in a specific region. Note: only the images from the train set were used in this process (drip, drip, remember the data leakage!).

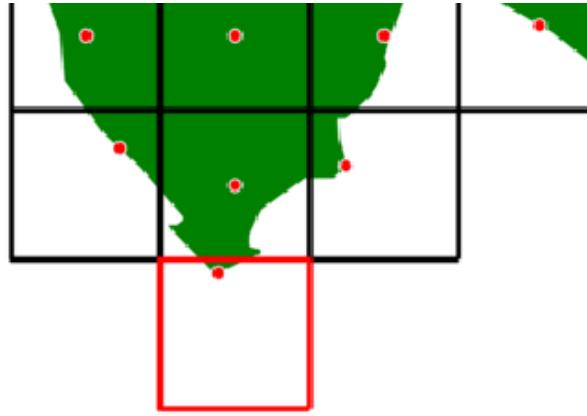


Figure 10: Image on the depicts a class which doesn't contain any images from the train set due to being mostly made up of sea. This class will be ignored during training and prediction.

2.4.3 Loss Function

Lastly, as with most classification approaches, we use **cross entropy loss** on the predicted and true classes. If you don't know what cross entropy loss is we won't bother to explain the details but will try to pass you the intuition behind it. Essentially, the dialog between the cross entropy loss and the model would look something like this:

Cross entropy loss to the model: "I will make sure that you classify the image in the true region!"

Model: "Okay, can I classify the image so that it belongs to all regions at once? Then I surely classified the image in the true region! At least on some level..."

Cross entropy: "No. Your classification can't be indecisive. I will punish your indecisiveness for the true region! But I don't care how indecisiveness you are about *other* regions."

Model: "So if the true region is region 0, you will punish me the same for these two predicted probabilities: [0.6, 0.3, 0.1], [0.6, 0.2, 0.2] ?

Cross entropy: "That's right. The only thing I care about is that the next time I see you, the number 0.6 rises as close to 1.0 as possible."

The true classes are represented with a one-hot encoded vector ([1, 0, 0]), while the predicted classes are represented with a vector of probabilities for the likelihood of each class ([0.6, 0.3, 0.1]). Now that we have probabilities for each class/region, how do we obtain the final coordinates? Firstly, we extract the centroid from all classes. Secondly, we multiply locations with corresponding probabilities. You can think of probabilities as weights in this context. Thirdly, we add everything up and end up with a **weighted arithmetic mean**. Notice that our final predicted image coordinate is not necessarily within our predicted class, but as our model becomes more sure in its predictions, so do these averaged coordinates come closer to the class. We have noticed that this averaging approach improves performance.

2.5 Regression Approach

This approach is a bit more obvious. Each set of images has its target coordinate, and we task our model with predicting these coordinates. Therefore, the size of the output of the model is not determined by the number of classes, but is simply 2, accounting for the latitude and longitude (or to be precise, the standardized versions of the x and y coordinates from the Croatia local space). We directly compare these output coordinates to the true image coordinates and calculate the distance (error) using the mean squared error. This distance (error) is almost exactly the same as the haversine between two coordinates in the global space. Unlike in the classification approach, the loss function we use for the model can also tell us an accurate state of our predictions, as we are not bound by an artificial limit like having classes. That being said, in practice, we noticed that this approach often performs worse than the classification approach and is also slower. It appears that the presence of classes does help the model in training somewhat. Regression approach might be perform better if we were patient enough to train the model for more than a few days.

2.5.1 Loss Function

For the loss function, we use mean squared error loss and we predict the coordinates directly. After we obtained predicted coordinates we re-project them back into global space and calculate the haversine distance for the purposes of logging and statistics. It is worth noting that these two approaches, classification and regression, can only be compared using the haversine distance metric, as their loss functions work in very different ways and output vastly different values. Therefore, they can't be compared during training, but only during validation and testing, because we calculate the haversine distance value only then.

2.6 Technology Stack

Before diving into the architecture of the solution, the technology stack we used will be described briefly.

- `python3.8` - the main programming language used for the project, everyone and their mom uses it so no explanation needed here
- `git` - the quintessential version control system

Some of the Python packages we used:

- `PyTorch` - an open source deep learning framework based on the Torch library used for applications such as computer vision and natural language processing. Although it is primarily developed by Facebook's AI Research lab, we can assure you that it does not collect any data from your computer
- `PyTorch Lightning` - a PyTorch framework which allowed us to skip a lot of boilerplate code and organize PyTorch code in a sensible and efficient way
- `black` - code formatter, so we're all on the same page (pun intended)
- `aiohttp` - Asynchronous HTTP Client/Server for asyncio and Python. Used for sending/receiving asynchronous requests when calling Google's Street View API. Thank you for letting us download a ton of images.
- `Pandas` - the popular Python data analysis library. Used for loading, managing and decorating *.csv files
- `geopandas` - Pandas version used for geospatial data. Used to wrangle, manage and generate geospatial data
- `imageio` - write and read image files
- `isort` - sort python imports
- `matplotlib` - data visualization with Python
- `NumPy` - mathematical functions and management of multi-dimensional arrays. Does anything even run without this?
- `requests` - a HTTP library for Python. The goal of the project is to make HTTP requests simpler and more human-friendly

- `scikit-learn` - a free machine learning library for Python. It features various classification, regression and clustering algorithms
- `Shapely` - package for manipulation and analysis of planar geometric objects. It is based on the widely deployed GEOS (the engine of PostGIS) and JTS (from which GEOS is ported) libraries
- `tabulate` - easy and pretty Python tables
- `tensorboard` - library used for fetching and visualizing machine learning model training data in a browser
- `tqdm` - easy Python progress bars

2.7 Solution architecture - PyTorch Lightning

The core library used for this project is PyTorch Lightning (PL) which was started by [William Falcon](#). You should glance through its [introduction website](#) to get a sense of what PyTorch Lightning actually does. PyTorch Lightning (PL) doesn't introduce significant complexity to the *existing* PyTorch code, in fact, it organizes the *existing* PyTorch code in intuitive PyTorch Lightning modules. Example of organizing already existing PyTorch code can be seen [here](#). It's important the main component `LightningModule` is a `torch.nn.Module` but with added functionality. You don't need to know the details of this fact but it's useful to keep it in mind. PyTorch Lightning to note that .PyTorch Lightning library passively forced us to write clean code with smaller overhead (compared to raw PyTorch code) and allowed us to quickly add crucial functionalities like logging, model checkpoints, general prototyping, and more. Kudos to [PyTorch Lightning team](#) for creating, maintaining and improving this great library.

To get a sense of how PL organizes the code we will show a *simplified* version of our `pl.LightningModule` :

```
class LitModelClassification(pl.LightningModule):
    def __init__(self,
                 num_classes: int,
                 model_name: str,
                 pretrained: bool,
                 image_size: int,
                 ):
        super().__init__()

        self.image_size = image_size

        backbone = torch.hub.load(
            DEFAULT_TORCHVISION_VERSION, model_name, pretrained=pretrained
        )
        self.backbone = model_remove_fc(backbone)
        self.fc = nn.Linear(
            get_last_fc_in_channels(self.image_size, self.batch_size), num_classes
        )

        self.save_hyperparameters()

    def forward(self, image_list):
        out = self.backbone(image_list)
        out = self.fc(out)
        return out

    def training_step(self, batch, batch_idx):
        image_list, y, _image_list, y = batch
        y_pred = self(image_list)
        loss = F.cross_entropy(y_pred, y)
        acc = caculate_accuracy(y_pred, y)
        data_dict = {"loss": loss, "train/loss": loss, "train/acc": acc}
        return data_dict

    def validation_step(self, batch, batch_idx):
        image_list, y_true = batch
        y_pred = self(image_list)
        loss = F.cross_entropy(y_pred, y_true)
        acc = caculate_accuracy(y_pred, y_true)
```

```

data_dict = {"loss": loss, "val/loss": loss, "val/acc": acc}
return data_dict

def test_step(self, batch, batch_idx):
    image_list, y_true = batch
    y_pred = self(image_list)
    loss = F.cross_entropy(y_pred, y_true)
    acc = caculate_accuracy(y_pred, y_true)
    data_dict = {"loss": loss, "test/loss": loss, "test/acc": acc}
    return data_dict

def configure_optimizers(self):
    wait_n_epochs_before_reducing_learning_rate = 5
    reduce_learning_rate_by_factor_of = 0.1 # from 10 to 1, from 0.01 to 0.001...
    learning_rate = 1e-4

    optimizer = torch.optim.Adam(self.parameters(), lr=learning_rate)
    scheduler = torch.optim.lr_scheduler.ReduceLROnPlateau(
        optimizer,
        "min",
        factor=reduce_learning_rate_by_factor_of,
        patience=wait_n_epochs_before_reducing_learning_rate,
    )

    config_dict = {
        "optimizer": optimizer,
        "lr_scheduler": {
            "scheduler": scheduler,
            # How many epochs/steps should pass between calls to `scheduler.step()`?
            # 1: check if learning rate has to be updated after every epoch/step
            "frequency": 1,
            "interval": "epoch",
            # what metric to monitor?
            # Reduce learning rate when val loss isn't going down anymore
            "monitor": "val/loss_epoch",
        },
    }

    return config_dict

```

(optional) you can quickly glance over Key PyTorch Lightning (`pl`) modules:

1. `pl.LightningModule` - LightningModule organizes your PyTorch code into 6 sections:
 1. Computations (init)
 2. Train Loop (`training_step`)
 3. Validation Loop (`validation_step`)
 4. Test Loop (`test_step`)
 5. Prediction Loop (`predict_step`)
 - this is also where the actual **model** is created
2. `pl.DataModule` - datamodule is a shareable, reusable class that encapsulates all the steps needed to process data:
 1. Download / process the data (for example from a website or CSV file)
 2. Clean and (maybe) save to disk
 3. Load the data into `Dataset`
 4. Initialize transforms (rotate, resize, etc...) that will be sent to `Dataset`
 5. Wrap `Dataset` inside a `DataLoader`. `DataLoader` will be returned to the `Trainer`.
3. `pl.Trainer` - once you've organized your PyTorch code into a `pl.LightningModule`, the `pl.Trainer` automates everything else:
 1. Automatically enabling/disabling grads
 2. Running the training, validation and test dataloaders
 3. Calling the Callbacks (logging, model checkpoints, learning rate scheduling...) at the appropriate times

4. Putting batches and computations on the correct devices

2.7.1 GeoguesserDataset (`src/dataset_geoguesser.py`) - The Pawn

`GeoguesserDataset` is responsible for lazily fetching images and their coordinates during the training. We initialize `GeoguesserDataset` three times (train, validation and test set). Now, each of the three `GeoguesserDataset`s is responsible only for fetching the data from its corresponding appropriate set. For example, `GeoguesserDataset` with parameter `dataset_type = DatasetSplitType.TRAIN` will only return the images from the train set. The most important operation that the `GeoguesserDataset` module performs, aside from defining from which set images are fetched, is lazily fetching and **passing the location and four images** (one for each cardinal side) **to the `pl.Trainer`** during the training, validation and testing phase. Essentially, this module answers the question "**What data will start coming in batches once I start the training process ?**"

It's also worth mentioning that any image or coordinate transformation is generally done in this module. What does this mean? > Let's say we want to resize our original image, 640x640 pixels, to a size of 224x224 pixels. Model obviously requires more time to train on large images. Since this competition lasts a few months and not a few years (this would be interesting), we will resize our images to 224x224 pixels. Instead of resizing images on the disk we can do this in runtime (during the training). You might say "yes but it would be faster to resize them in advance so that the program doesn't waste precious resources". That's true, but computation required to resize the image is negligible compared to other actions that occur during the training phase. Okay, so we settled on resizing the images during the runtime. So who is responsible for resizing images during the training phase? That would be exactly `GeoguesserDataset`. Before returning the image and coordinate to the trainer (which sends it further to the model), the `GeoguesserDataset` will apply resize transformation for the image. In fact, any transformation can be specified before we create the `GeoguesserDataset` and that exact transformation will be applied before trainer gets the data. Examples of such image transformations, alongside resizing, include cropping, translation, noise injection, color space transformations, and **more**.

`GeoguesserDataset` inherits the `torch.utils.data.Dataset` class.

2.7.2 GeoguesserDataModule (`src/datamodule_geoguesser.py`) - The Bishop

The `GeoguesserDataModule` is mainly responsible for two things:

1. preprocessing that can't be done by `GeoguesserDataset`. This preprocessed data is sent to the `GeoguesserDataset`.
2. creating train, val and test `DataLoader`s, each for one `GeoguesserDataset`

We will first describe what kind of preprocessing actually happens here. `GeoguesserDataModule` will receive the CSV file which contains information about image's locations, regions in which they are placed. Then this CSV is enriched with new columns in advance, values which we would need to calculate during the training. For example, we create a new column `crs_x_minmax` which is the x coordinate in Croatia's local system scaled to [0, 1]. We mentioned how we exclude the regions that contain no image data. But how can we know this in advance? What if someone decides to add more images (like we did) in the sets and suddenly some region that was long forgotten becomes a viable option? This is why we create classes in `GeoguesserDataModule`, during the runtime. The weighted mean centroid of each region is also calculated here. We also perform some dataset statistics extraction, as well as data standardization for all CRS features. Finally, we split the data into the train, validation and test dataset and create the dataset instances that will be described in the next paragraph. We also do some sanity checking to make sure everything is in order before continuing. <todo: insert image of croatia, grid and each class and its number>

Great thing about this module is that it's dynamic in terms of defining the size of the dataset. Parameters that define the fraction each set (`train_frac`, `val_frac`, `test_frac`) or the dataset as a whole (`dataset_frac`) turned out to be quite useful during the prototyping phase of the problem solving. Although you almost always want to use all your available data (`dataset_frac = 1`) it's nice to have options too.

`GeoguesserDataset` inherits the `LightningDataModule` class.

2.7.3 LitModelClassification (`src/model_classification.py`) or LitModelRegression (`src/model_regression.py`) - The King

The convolutional neural network model that is going to perform the training is defined in the model module. The different models we defined here (classification and regression) all inherit the `LightningModule` class to make things as simple as possible. Each model fetches a pretrained network and changes its last layer to a layer more suitable for the model's task. We then define each model's `forward` function, which defines how our data is processed through all the layers of the model, as well as define and all of the training, validation and testing functions. Each function performs an iteration of training through its respective dataset and calculates error, and additionally in the case of validation and testing, the haversine distance function. We then log all the parameters of the model into a file for later fetching and usage.

2.7.3.1 Forward function - The King

<Todo: populate this>

2.7.4 Train Function - The Queen

Finally, we join everything together in the `train` function. Here, we parse the arguments passed to the model, define the data transformations, initiate the `GeoguesserDataModule` module, initiate the logger, create the specified model, define our optimization algorithm and how the learning rate behaves, and finally, train the model. Optionally, we can also visualize our results after training.

2.7.5 Optimizers and LR Schedulers (configure_optimizers) - The Rooks

Our solution is composed of four main modules, as well as numerous utility functions. Utility functions were mainly used for tasks that were separate from the training process itself, such as transforming data into a format appropriate for training, geospatial data manipulation, visualization, report saving and loading, etc. Even though we love our utility functions which are crucial to this project, they are generally responsible for lower level work which isn't the focus of this project. Here, we will promptly ignore them and explain only the higher level components of our solution, namely, the four main modules.

3 Model

3.1 Pretrained networks

Because deep learning progresses at such a breakneck pace, there are numerous approaches that are considered state-of-the-art at the moment, all using vastly different architectures. As readily available high performance models that were pretrained on large datasets are the norm and us being extremely lazy, we chose to use one of these models instead of creating our own from scratch. The pretrained model is usually trained on large dataset (e.g. [ImageNet](#)) which include many different types of images and classes.



Figure 11: Sample of images from the ImageNet dataset used for creating pretrained models.

[!h]

Although solving a problem, where the content of images come in many different shapes, seems extremely hard, the model that learns to generalize on these datasets can usually be *tuned* to solve some another problem (like predicting the location of images). This method of using the pretrained model to solve another problem is called *transferred learning*. The main advantages of fine-tuning when solving computer vision tasks are the following:

1. the pretrained model already learned to generalize on key features of images (general shapes). Our model doesn't have to learn this again
2. robustness to small dataset - although this isn't a problem in our case since we have a fairly large dataset, we appreciate that transferred learning allows for training the model on smaller datasets

3.2 ResNeXt

Originally, we chose the EfficientNet architecture due to it showing both good performance and having lower system requirements when compared to other approaches. However, for reason we didn't explore enough, we had worse results and

slower convergence compared to the model we settled for. After some experimenting, we ended up using a version of ResNet called ResNeXt instead, as it simply proved more effective. It can easily be loaded in PyTorch with the following expression `torch.hub.load("pytorch/vision", "resnext101_32x8d")`.

ResNeXt is a highly modular architecture that revolves around repeating powerful building blocks that aggregate sets of transformations. It first processes the images with a simple convolution layer. It then feeds this into a sequential layer composed of multiple bottleneck layers. A bottleneck layer has the function of reducing the data dimensionality, thereby forcing the network to learn the data representations instead of just memorizing them. Each bottleneck layer is again composed of multiple convolution layers for information extraction. After the sequential layer is done, the network is fed into another sequential layer. This process is repeated multiple times. Finally, after all the sequential layers have processed their outputs, the data is fed into a fully connected layer for classification or regression. Of course, all of the mentioned layers also use numerous normalization techniques, such as batch normalization. This process is visualized in the figure below. Due to this modularity of the layers, ResNeXt includes few hyperparameters that have to be tuned for the architecture to be effective. Aside from the described architecture, we had to do some modifications to the network ourselves in order to make them work with our dataset. There were two modifications we made.

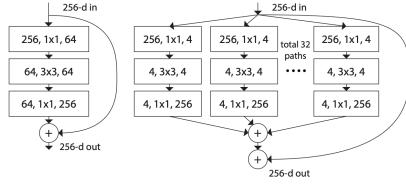


Figure 1. **Left:** A block of ResNet [14]. **Right:** A block of ResNeXt with cardinality = 32, with roughly the same complexity. A layer is shown as (# in channels, filter size, # out channels).

Figure 12: Single ResNext block

3.3 Modifications

Firstly, we removed the last layer of the network and replaced it with our own classification or regression layer in the form of a simple linear layer that had the appropriate output dimension for our problem. Secondly, because, as we mentioned before, every location contained four images, we modified our network to perform its forward operations for the four images in tandem and then concatenate the outputs before imputing them into the last layer. We did this after doing some research on what was the best way to compute the outputs of separate, but statistically linked images.

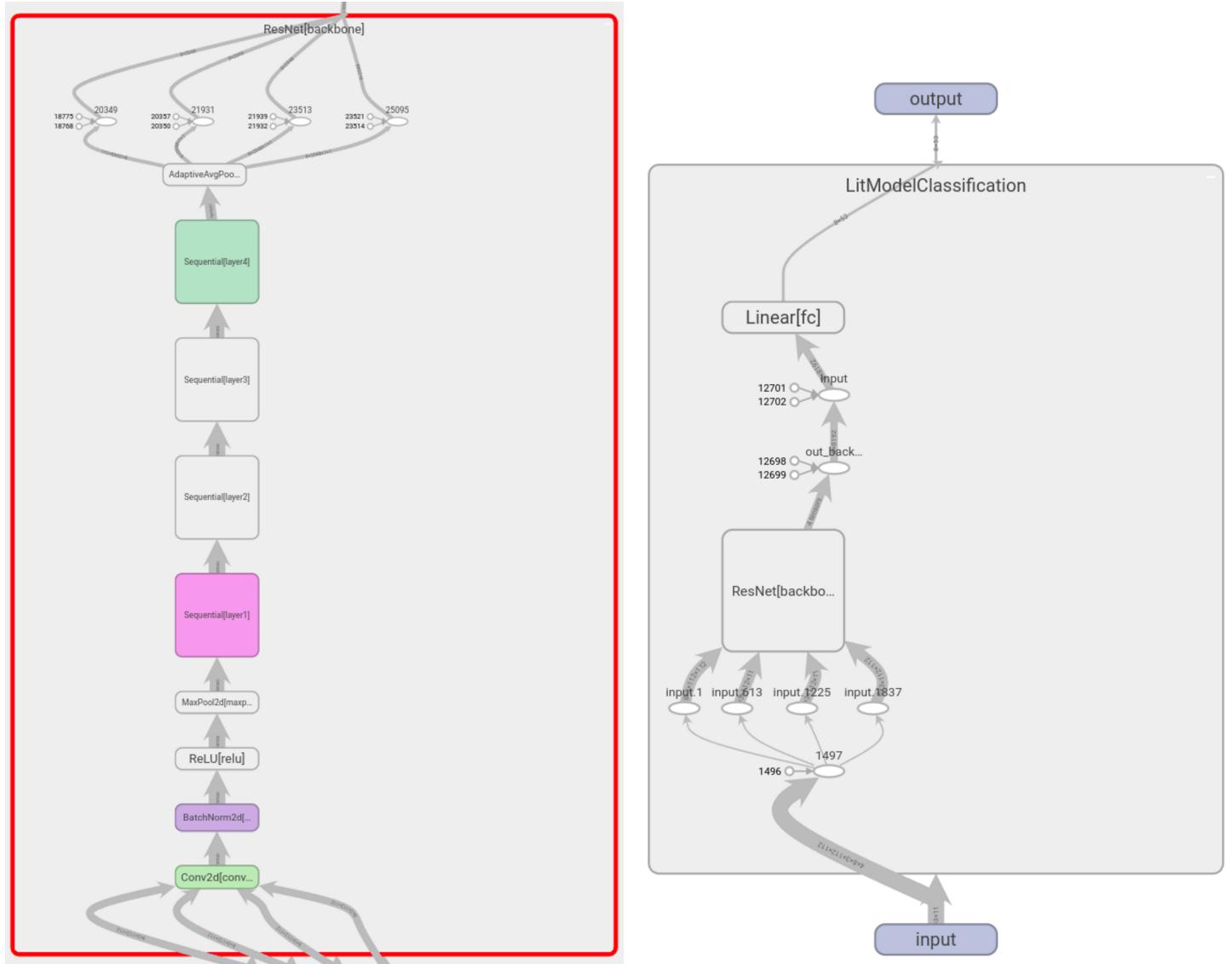


Figure 13: On the image on the left, we can see an overview of the model we used for training. Inputs are fed into the ResNeXt layer with four images being processed in parallel. The output is then fed into a linear layer which can either classify the results into distinct classes or predict coordinates directly as output. On the image on the right, a closeup of the ResNeXt backbone is shown. We can see that it is composed of an early convolution layer, followed by multiple sequential layers who all contain their own convolutions and transformations.

Name	Type	Params	In sizes	Out sizes
0	backbone	ResNet	86.7 M	[8, 2048]
1	backbone.conv1	Conv2d	9.4 K	[8, 64, 56, 56]
2	backbone.bn1	BatchNorm2d	128	[8, 64, 56, 56]
3	backbone.relu	ReLU	0	[8, 64, 56, 56]
4	backbone.maxpool	MaxPool2d	0	[8, 64, 28, 28]
5	backbone.layer1	Sequential	420 K	[8, 256, 28, 28]
6	backbone.layer1.0	Bottleneck	118 K	[8, 256, 28, 28]
7	backbone.layer1.1	Bottleneck	151 K	[8, 256, 28, 28]
8	backbone.layer1.2	Bottleneck	151 K	[8, 256, 28, 28]
9	backbone.layer2	Sequential	2.4 M	[8, 512, 14, 14]
10	backbone.layer2.0	Bottleneck	602 K	[8, 512, 14, 14]
11	backbone.layer2.1	Bottleneck	601 K	[8, 512, 14, 14]
12	backbone.layer2.2	Bottleneck	601 K	[8, 512, 14, 14]
13	backbone.layer2.3	Bottleneck	601 K	[8, 512, 14, 14]
14	backbone.layer3	Sequential	55.2 M	[8, 1024, 7, 7]
15	backbone.layer3.0	Bottleneck	2.4 M	[8, 1024, 7, 7]

Name	Type	Params	In sizes	Out sizes
16	backbone.layer3.1	Bottleneck	2.4 M	[8, 1024, 7, 7]
17	backbone.layer3.2	Bottleneck	2.4 M	[8, 1024, 7, 7]
...
37	backbone.layer3.22	Bottleneck	2.4 M	[8, 1024, 7, 7]
38	backbone.layer4	Sequential	28.7 M	[8, 1024, 7, 7]
39	backbone.layer4.0	Bottleneck	9.6 M	[8, 1024, 7, 7]
40	backbone.layer4.1	Bottleneck	9.6 M	[8, 2048, 4, 4]
41	backbone.layer4.2	Bottleneck	9.6 M	[8, 2048, 4, 4]
42	backbone.avgpool	AdaptiveAvgPool2d	0	[8, 2048, 4, 4]
43	backbone.fc	Identity	0	[8, 2048]
44	fc	Linear	434 K	[8, 8192]
				[8, 53]

4 Training

4.1 Basics

Due to using pretrained models, we first performed what is called *fine-tuning*. During fine-tuning, we leave the weights of the early layers of a network unchanged and only train the weights of the last few layers. ResNeXt was pretrained on ImageNet, a large image dataset with a diverse assortment of objects. This gives the early layers of ResNeXt a collection of learned shapes and lines that are relatively similar to our own domain. In addition, our own dataset is much smaller than the number of ResNeXt parameters. If we were to train ResNeXt from scratch, we would quickly overfit. By using a model pretrained on a large generic dataset and then fine-tuning only the last layers, we preserve all the fine detail learned by all the early network layers and only overwrite the last layers where we essentially assemble these details into images. However, after performing fine-tuning for a sufficient number of epochs, we unlock other network layers so that they can be trained along with the last few layers. During this phase, by using a sufficiently small learning rate, we induce our dataset information into all the network layers without overwriting the previously trained model.

4.2 Dataset

As previously mentioned, the dataset is divided into two components. The first one is a collection of folders each containing four images taken in the same location. Each folder is named with a unique identifier. The second component is a CSV table where each row contains one of the previously mentioned folder IDs and the corresponding image's latitudes and longitudes expressed in degrees. We divided the data by hand into a training, validation and testing subfolder in a 80%/10%/10% split (for some models, it was 90%/5%/5%). This way, the data could be easily loaded during the training process from the appropriate folder depending on if we are in the training, validation or testing phase. Due to the datasets (and image's) large size, we were unable to load the whole dataset directly into memory (we only had a *measly* 12 GB of VRAM available on our GPU). We wanted to do this because it had the potential of greatly decreasing training times, but we were forced to figure out other methods of speeding up training, like using only parts of the dataset during experimentation and employing smarter learning rate schedulers.

Before the training process itself could begin, we needed to first process the data to make it more suitable for training. This entailed modifying the CSV file to include data such as class affiliation, class centroid information and the image's and centroids latitude and longitude information in CRS format. Aside from this, image information such as the minimum and maximum value of each channel had to be also stored for fetching during the training process, and later, inference.

For the competition, we were provided with a dataset of around 64 000 images (16 000 separate locations of four images each), but we added our own separately procured images from Google Street View numbering around 68 000. In other words, we doubled the available data for training. In common deep learning wisdom, having more training data is the best form of regularization, this being our main guideline for gathering additional images.

4.3 The Model Training Phase

4.3.1 Training

The algorithm was composed of 3 steps. In the first step, the algorithm goes through the training dataset in batches of a specified size (usually 8, more if memory constraints allowed). The training step had to be as quick and efficient as possible because time- and processing-wise, it entailed the vast majority of the learning phase. Due to this, the haversine distance of the true and predicted image coordinates wasn't calculated here. This not only let us skip the time consuming process of calculating the haversine distance itself, but also avoided the costly transformations of the data necessary for converting it to a format suitable for input into the haversine distance functions.

4.3.2 Validation

After we exhausted the training dataset (normally called an epoch), we validate our progress on the validation part of the dataset. This is done to prevent overfitting, which we will explain in more detail. As the model learns on the training dataset and if the model is of a sufficient size, i.e. it has more learnable parameters than there are images in the data, it will essentially memorize all the information in the training dataset by heart and learn how to predict it perfectly. However, because it has never seen the data in the validation dataset before, it will predict it correctly only if it has a good generalization capacity, that is to say, it can apply its knowledge on previously unseen data. Aside from this, the validation dataset allows us to finally calculate the haversine distance for the predictions, which is the most accurate (and only true) measure of our current progress, as well as the final performance of the model. It is worth noting that during the validation process, learning is disabled, as the model's trainable parameters are "frozen" here. Another thing to note is that the validation phase also functions as a "checkpoint" for our model. The best performing iterations of the model on the validation dataset are saved for later to be used on the testing and inference datasets.

4.3.3 Testing

Finally, after all the training epochs are over, meaning we went over both the training and validation dataset numerous times, we can test our model on the testing dataset. Just like the validation dataset, the test dataset has never been seen by our model before and is used as a final performance assessment. The best model found in the validation phase is used here. What makes the testing dataset special is that, during validation, we often change and test different values for hyperparameters. This is called hyperparameter tuning. During this process, some of the information from the validation dataset *leaks* into the model, because we are essentially training the hyperparameters on the validation dataset. Due to this, at the very end, another test is performed on a separate, never before seen test dataset to create a truly unbiased performance assessment of our model.

4.4 Hyperparameters

4.4.1 Image and Batch Size

We set the image size to either 224x224, 112x112 or 56x56 pixels, depending on the model. A smaller image size allows for larger batches and faster training, but potentially contains less information in the images due to resolution loss. Batch size itself has the purpose of regulating how fast and accurate our training is. You see, perfect backpropagation (an algorithm which we are sure you know very well and we won't explain for a millionth time) updates model weights only after going through all images in the entire training dataset. This usually results in the most accurate possible gradients for optimization, but has the downside of being very slow and often ending up in local optima. On the other end of the spectrum, training on only one image per batch is very fast and can easily escape local optima, but is also rather inaccurate and converges quite slowly due to imprecise gradients, especially in the later stages of training. The best of both worlds can be achieved by training on multiple images per batch, ideally as many as possible (actually, there is an upper limit to the number of batches one should use, but it is often infeasibly large). Memory and GPU limitations commonly don't allow for this, so we are forced to use the largest batch size we can (8, to be precise, for an image size of 112x112 pixels). Lowering the image resolution can give us more wiggle room in choosing batch sizes, but setting batch size too a too large value runs the risk of quickly filling up the GPU's memory and crashing the training process midway through.

4.4.2 Learning Rate

Aside from image size and batch size, another important parameter to be adjusted is learning rate. A learning rate with a large value can converge the model to a solution quickly, but lacks fine tuning capabilities necessary for that extra edge in performance during later phases of training. On the other hand, a small learning rate can make the training process very slow and can cause it to often end up in local minima (in other words, learning rate has the opposite behavior of batch size). Ideally, we should have a large learning rate in the early stages of training, while periodically reducing it as the training moves on. The application of momentum can also help in this. Momentum is a value that is proportionally added to the learning rate during training if it is going particularly well. An optimizing algorithm that includes all of the aforementioned mechanisms is [Adam](#). We chose it due to its good balance between precision and speed during training, as well as its built in momentum function.

4.5 Inference

Inference is performed after the entire training phase of our model is over. It is the process of testing our best performing model on never before seen images and can be described as the training phase in reverse: instead of seeing an image's coordinates and training our model on them, we now have to look only at the image itself and predict its coordinates. The true image coordinates are hidden from us and are compared against our answers without us overseeing any part of the process. This is how our model will finally be tested and compared against other models in the end to assess its final performance. More about how this is done can be found in our Technical Documentation (TM).