Vectorization and Compression of Animated Cartoon Videos

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Abstract

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1 Introduction

2 Background

This document makes no assumption of the reader's knowledge in computer graphics and its related fields, thus, this section will introduce the reader to some of the required knowledge needed for understanding this project. Firstly, we will introduce raster graphics, the current de facto standard for graphics data representation. We will then introduce its counterpart vector graphics, a different way to store graphics data that addresses some of the issues with raster graphics. We will then give a brief primer on image compression and some common methods of reducing the overall size of an image. Finally, we will explain how image graphics tie into video graphics and describe some of the few differences between the two.

2.1 Raster Graphics

Raster graphics is the current most popular way of representing and storing graphics data. This representation format stores the image data as a grid of pixels, a pixel (picture element) being the smallest element of the image containing the color information of the image at a particular point in the grid. Colors can be represented in many different formats but the most common is the three channel RGB (Red, Green, Blue) with RGBA (Red, Green, Blue, Alpha) gaining popularity. Each channel has a bit depth which details the number of possible colors that the channel can contain with 8 bits per channel being the current most common but higher values exist as well such as 10 and 12 bits per channel. So a pixel in RGB format is really just a 3-tuple (triple) of numbers for each color channel in that pixel. An image's resolution is the number of total pixels it contains, which is the image's width multiplied by its height, higher resolution images have more detail but are also more expensive to store as there is more data. While these concepts are seen as the current norm in computer graphics, they are more specific to raster graphics in particular.

Raster graphics are the most popular form of image and generally graphics representation as they are easy to understand and display. The main disadvantages of raster graphics concern image resolution and detail, namely that images will show pixelation artifacts when they are displayed at a higher resolution than their own where the image will start showing the raw pixels. To match the evolving increase in display resolutions, newer media uses higher resolutions in order to show optimally on these displays but at a cost. The first cost being that the new higher resolution images require more disk space to store as they are larger in size, but the less obvious cost is that it leaves the older lower resolution content behind. Any content made in low resolutions will forever live with that resolution and continue to scale more poorly as displays have higher resolutions. Therefore, while raster graphics are the current de facto standard for graphics representation, they are not without their major disadvantages, namely concerning the need for increased resolutions, meaning more disk space needed and old content becoming more and more outdated.

2.2 Vector Graphics

Another graphics representation format is vector graphics, which addresses some of the issues of raster graphics and is growing in popularity within some domains. Vector graphics uses a more declarative style of data storage, where instead of storing the data to be shown (such as pixels containing color information), vector graphics is based on instructions to a renderer about how to draw the image. These instructions are based on a set of standard geometric elements that are used in that vector graphics format or protocol. The most common and well known vector graphics format today is SVG, Scalable Vector Graphics, which is developed by the W3C since 1999, this is the format we will be using throughout this document when referencing vector graphics. An SVG file is nothing more than an XML-like text file with XML elements part of the SVG standard that describe to the renderer how to draw the image. The SVG specification defines many elements that can be used in an SVG file but the most important one in our case is the SVG `path` element. The `path` element can be used to draw a complex line by providing it with commands on where and how to draw, it is perhaps the single most powerful element within the SVG specification and is the only element that we will use in this project.

The greatest advantages of vector graphics that they address the main issues of raster graphics mentioned in the Raster Graphics section, that is to say that vector graphics are resolution independent and are (theoretically) infinitely scalable no matter the display. The scalability of vector graphics actually solves both issues at once because there is no longer a need for higher resolution media thus saving on disk space *and* keeping old media still usable because of infinite scalability. But such advantages don't come with some issues, and there's a reason vector graphics are not the current norm. Simply put, vector graphics are only good at displaying certain kinds of images and media because of the way they represent data, making it very difficult to accurately and efficiently store other kinds of images such as images of natural scenery or faces. This is because those kinds of images tend to have a large degree of color fluctuations and especially non-linear, complex color fluctuations. This is a particular weakness of vector graphics and one that has limited its adoption and growth because compared to raster graphics in this regard, vector graphics are significantly inferior. As a result, vector graphics are seen as mostly domain and use-case specific and not general purpose, they are excellent for logos and icons specifically because of their scalable nature but are inferior when used for photographs because of the complex color fluctuations of those images.

2.3 Image Compression

One of the most important subjects within computer graphics is image compression, that is reducing the file size of an image. Image compression concepts are fundamentally identical to those of classical file compression but to ensure the reader is up to date, we go over some of these briefly in addition to one novel concept somewhat specific to image compression. Compression really comes in two major

forms, both relating to the data loss that happens after the compression process is completed, lossy compression and lossless compression. Lossy compression removes data during the process of compression to make the most of the reductions, usually this is redundant or unnecessary data depending on the context or domain. For example audio compression algorithms will typically remove frequencies beyond the human hearing range, removing unnecessary data. In the graphics world this is what is known as *visually lossless compression* which means visually, to the human eye, no data was lost, although technically the algorithm is lossy and data was actually lost. Because of its lossy nature, lossy compression is a one way process that will have irreversible data loss such that attempting to compress again using lossless compression will not regain the lost data. Lossless compression on the other hand, aims to reduce file sizes without any loss of data, a more difficult task to achieve with often worse compression ratios than lossy compression algorithms. The compression ratio of a compression algorithm is the ratio of the uncompressed size to the compressed size but space savings is also popular as it is more indicative of the effects of compression.

Image compression is used by all popular image formats to have more reasonable sizes. Lossy formats include JPEG and GIF which will show compression artifacts if encoded many times successively showing the data loss upon each compression pass, these formats are excellent for portability and transfer and indeed have been very popular on the web where bandwidth and data caps are noteworthy. Lossless formats include BMP and PNG which will always retain their data even after successive compresses, these formats however offer less compression compared to the lossy formats but are useful for those who need the highest quality with the guarantee of no data loss. These concepts are essentially identical to those found in classic file compression with the exception of *visually lossless compression* being a lossy compression method that aims to be "lossless to the human eye" which is preferred if lossy compression is the compression method of choice.

2.4 Vectorization

Converting graphics from raster to vector allows for one to make use of the benefits of vector graphics and is a used by people across multiple domains, this process is known as vectorization or raster-to-vector conversion. This process is often used by specialists when viewing image data captured in raster to be viewed by a vector graphics program that can then perform additional processing such as classification, labelling etc. This process is, by its nature, lossy, meaning the original data will be lost during the process because the process is transformative and even though a lossless process is theoretically possible, it would not be practical or efficient as it would not introduce any of the benefits of vector graphics and would instead just be converting pixels into pixels in vector graphics. Therefore, the process aims to be *Visually Lossless* aiming for highest accuracy while also trying to effectively and efficiently transform the data into suitable optimal vector graphics data. This will often mean trying to undo rasterization effects or artifacts in order to achieve a

better output that makes sense in a vector format such as for example, interpolating pixels in order to create smooth lines or doing some kind of color reduction, both of which change the original data in order for it to make more sense in the vector output.

In that vain, it is also important to note that the vectorization process will also be dependent on the input data provided with images that do not have vectorizable qualities resulting in poor vector results, either in terms of accuracy or file size or both. These kind of images are most often photographs or other kinds of images with a high degree of color fluctuations as mentioned in the Vector Graphics section. Whereas images with discrete color regions such as logos, icons and other "man-made graphics" often contain less of these qualities and will more likely do well in the vectorization process because the vectorization process does not work well on color fluctuations. In such cases raster graphics is always a better format as it will much more effectively store such data with high clarity and lower file sizes, as such, it is important for one to know where each format is more suitable as they each have their advantages and disadvantages. Knowing that however, when one does deduce that vector graphics is the more suitable format for their graphics, vectorization will allow those people to convert their graphics from raster to vector in a manner that is as effective as possible in order to obtain visually lossless transformation that will still be optimal as a vector graphics output.

2.5 Video Graphics

There is a reason we have only described image graphics specifically and not mention videos and that is because for the most part, the two are very interchangeable as videos are essentially a series of sequential images. The most obvious difference being twofold, videos are temporal, meaning they are concerned with time, and videos contain audio data in addition to the visual graphical data. For this project we will completely ignore the audio aspects of videos and remain only concerned with the visual properties of videos, ie the "moving pictures" part. While it is true that videos are essentially a series of images, raster images specifically, different formats and codecs will store the video data differently in order to optimize for quality, compression or both. One such codec, the popular MPEG and its derivatives, explicitly make use of video's temporal nature in order to find and eliminate redundant data to increase compression rate while minimizing quality loss. This essentially aims to group similar frames into a frameset and instead of storing all the frames, store only the difference between the frames which is especially effective when the frames are very similar to one another. These codecs also perform a wide variety of other smart operations to maximize compression rate while minimizing quality loss when doing so because of the main daunting issue with video, video is naturally very storage expensive. This issue continues to compound as display resolutions continue to increase and raster media keeps catching up to it showing the same issues mentioned with raster graphics in the Raster Graphics section. In addition to this, video media is ever-growing in popularity and ubiquity, especially

on the web, making the demand for high fidelity, low bandwidth consuming video higher than ever. Despite these smart compression focused codecs however, video graphics concepts are largely identical to those of image graphics with video being simply a series of sequential images that can be encoded in many different ways for optimal compression and quality.

2.6 Toolchain

This project uses a variety of popular tools and libraries to achieve its aims and objectives both efficiently and quickly, this section will briefly go over the most important tools used. This project uses Node.js as its runtime platform, Node.js is a cross-platform runtime environment that executes JavaScript code on a machine instead of the usual JavaScript runtime, the browser. The choice for Node.js was made paradoxically because of both a familiarity with the runtime and the JavaScript ecosystem as well as a strong desire to further enhance our knowledge and experience in both the platform and ecosystem. Node.js uses JavaScript as its runtime language, while JavaScript is a powerful and excellent language for rapid-prototyping, it is also a very error-prone language as it has no typing checks in place. TypeScript is a programming language that is a strict superset of JavaScript that adds typing features onto JavaScript and transpiles to performant, cross-platform compatible JavaScript by means of a TypeScript compiler. TypeScript was chosen as the programming language of choice for the project for its many benefits not limited to its added type safety.

Node.js also allows us to access the ever-growing JavaScript ecosystem which includes libraries and frameworks for both the front-end and back-end side of development, of which this project makes use of some notable tools such as Electron, GPU.js and OpenCV among others. Electron allows developers to write desktop applications using web technologies, it is essentially a Chromium browser with two processes, a front-end process called the "renderer" which is similar to a Chromium web page that displays HTML, and a back-end process called the main process which is a Node.js process. Electron combines Node.js and Chromium to allow a developer to write a native desktop application using the same technologies used on the web, this has its own advantages and disadvantages but in our case, it means we can quickly develop a GUI desktop application that can access our Node.js code without resorting to web servers and other more complicated means. GPU.js is a JavaScript library that allows developers to run code on the host machine's GPU making use of the GPGPU (General-Purpose computing on Graphics Processing Units) paradigm to allow for very large performance improvements and speedups for computationally expensive mathematical operations. In summary, the project uses the Node.js runtime for its large ecosystem, the TypeScript programming language for its added type safety benefits, Electron to easily display a GUI and GPU.js to run code on the GPU for additional performance when needed.

3 Related Work

3.1 Current Research

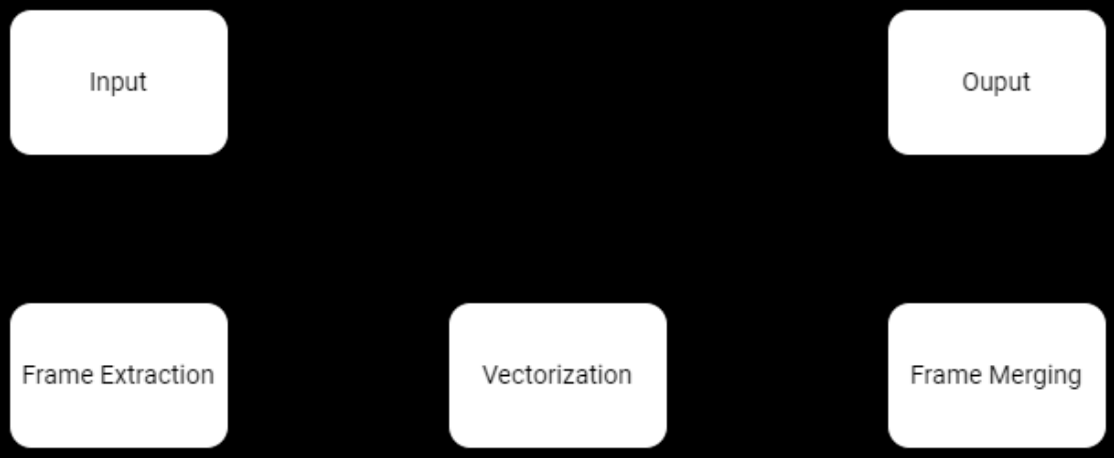
3.2 Current Applications

3.3 Existing Limitations

4 Implementation

The following section will go into high level detail describing the implementation details of the project. While this section may seem rather long, it is in fact made dense to ensure conciseness while keeping all the necessary details explained. This is because the project explores many different ideas and implementations to try to achieve its goals as will be evident by the multiple vectorization methods used. Firstly, we introduce the high level process pipeline of the project from input to output. Then, we explore in depth some of the many methods of vectorization used in the project. Finally, we describe the limitations and drawbacks that were found during the implementation.

4.1 Pipeline



The above image shows the high level process pipeline of the project from input to output with each phase of the pipeline further detailed in its own section below. Firstly, we explain the expected input video and its ideal characteristics that will result in a higher accuracy output. Then, we establish the expected and desired output and detail its expected and ideal characteristics before further discussing any of the processing. Then, the first phase of the processing begins, the frame extraction, where the frames of the video are extracted to be used further down the pipeline. Next, the main phase of the processing, the vectorization of a single frame, we describe and detail the multiple methods and approaches that were used in order to gain the highest level of accuracy and compression rate on each frame. Finally, the final stage of the processing, frame merging combines the vectorized frames back into a playable video form with additional computation executed to add favorable traits such as further reduced file sizes.

4.1.1 Input

Firstly, it is important to understand the input that the process will be expecting and detail what makes an ideal input file that will produce the best results. The minimum requirement is that the input file be any video, but more specifically, this project aims to work on animated cartoons, so while any video will technically work, for the purpose of this project, a video of an animated cartoon is expected. However, not all animated cartoons are equal, in fact there is a great deal of variation between cartoons in terms of art style, animation method, and many other artistic effects that can heavily influence the output of the process. Thus, we must define the "ideal" input file, or more precisely, the input file that will produce the best results because the process was designed with those files in mind for reasons to do with the limitations of vectorization. The ideal input video is one that is most friendly towards vectorization, meaning it has the most vectorizable qualities and characteristics with as few incompatibilities as possible, these were mentioned in depth in the Existing Limitations section but will be briefly repeated within this new context.

Since vectorization is heavily dependent on the color variation of the original raster image, an ideal input image would be one with discrete color regions made up of a single color, with no noise, gradients, shadows, lighting or any other effects, essentially an image made of a set of color blocks that are very discrete from one another. In addition to this, it is important to note that we are dealing with moving pictures and it is also ideal to have as little noise as possible *between* frames, this can be an artifact of compression or rasterization but can also be seen as an artistic style choice as shown in Cartoon Network's *Ed, Edd n Eddy*. Obviously very few real world media satisfies these conditions, but a surprising number of cartoon videos can come very close to this description, with very few complications such as shadows and light gradients that are usually in the background or are less important elements of the image. An example of a real world cartoon that has these ideal qualities is Nickelodeon's *The Fairly OddParents* which uses discrete color regions, very few (if any) gradients and no complex shadows or lighting. On the other extreme end cartoons with heavy use of photographs or heavy noise are the least ideal as well as any 3D cartoons, ie those that make use of 3D effects such as shadows, lighting and many complex gradients. Examples include Hanna Barbera cartoons prominent from the 1960s to the 1980s such as *Top Cat* and *The Flinstones* and modern 3D animations such as Pixar Animation Studios' *Toy Story* and *The Incredibles*. In summary, the minimum required input is simply any video but the expectation is that it will be an animated cartoon video and the ideal input being an animated cartoon video that has highly vectorizable qualities.

4.1.2 Output

Before discussing any of the processing, it is important to first understand the expected output that the process will generate and detail the expected and ideal

characteristics of the output. In essence, the output is a playable video that uses vector graphics to store the same data as the input file but with the added benefits of vector graphics, namely improved scalability and reduced size. Ideally, the output will be visually indistinguishable from the original but with a smaller size essentially achieving so called *Visually Lossless Compression*. However, since the video is using vector graphics, it will be much more scalable in comparison and essentially void of the pixelation problem that plagues traditional raster graphics. The size difference should especially be evident when taking the upscaling ability into account since the new video can be effective at any resolution display whilst the original will show pixelation once it is displayed on high enough resolution displays. Thus, an input video in 480p could likely produce an output video of larger size, and an input video in 720p could likely produce an output of similar size to the original, but the new vector graphics videos will be scalable to any resolution such as 4K or higher where the originals will show major pixelation at those resolutions. One important thing to note is that the output will still be frame based, this means the video data is frames of images moving at some given framerate, as is the case with raster video formats. This is in contrast to what vector animations are often represented in (usually for UI animations) and that is using some form of interpolation making the playback framerate independent, that is not the case here as that would add much more complexity. This frame-based characteristic of the output is important because it means we can leverage existing theories and concepts from raster videos mainly with regard to compression as is made clearer in the Frame Merging section. This frame based vector graphics video output makes the process as simple as possible while still achieving the desired benefits of vector graphics into the original raster video, namely improved scalability and reduced size.

4.1.3 Frame Extraction

The frame extraction phase has a single purpose and that is to convert the input video into a some form of medium that can be vectorized, namely images. Since the input video will always be frame based, we can thus convert a video into a set of vectorizable units that accurately represent its data, frames. Each frame of the video will be represented in an image which we can then vectorize in the next step. To do this, we use the industry standard tool, FFmpeg to create a directory of PNG images for each frame of the video using the command:

```
ffmpeg -i input.mp4 outputDirectory/%d.png -y
```

This is so that the next step (vectorization) can be done on each frame can be independently and can more easily be parallelized, since the vectorization of a single frame does not depend on any other frames around it. While in theory one can skip this step and read each frame of the video performing the vectorization step in serial for each frame, it is much more efficient to split the workload first by first dividing the video into frames stored on disk and then perform the vectorization step, now with the additional benefit of being able to run the vectorization step on multiple frames at once.

4.1.4 Vectorization

The most important and most difficult step of the process is vectorization, which converts frames from raster graphics to SVG vector graphics. The expected behavior of this step is extremely simple, a raster graphics input image will be converted to a vector graphics output image ideally one with the highest possible accuracy and lowest size possible. While the expected behavior is extremely simple, the actual process is extremely difficult and complicated and there are many possible correct approaches to this problem that yield varying results. These processes are detailed more thoroughly in the Vectorization Methods subsection further below with their advantages and disadvantages. From a high level standpoint however, all the approaches aim to achieve the same result, that is to transform the data from one representation format (raster) to another representation format (vector). This inherently means that there will be some form of data loss with the goal being to achieve what is called *Visually Lossless Compression* while gaining the benefits of vector graphics such as scalability in addition to the aforementioned smaller size. To achieve this, we convert the input image into an SVG image made up only of one SVG element, the powerful `path` element. As mentioned earlier the `path` element allows us to declare a path of arbitrary shape by declaring the commands used to draw it. An image can be represented as a set of discrete connected color regions that together form the whole image, these can be done using the path element which can then be filled with a single color allowing us to create single-color regions of arbitrary shape. Across all tried approaches, this is the common method used to create a vector graphics image, with the only differences being in how these color regions are parsed and determined from the original raster image.

4.1.5 Frame Merging

The final processing step is frame merging, the step that will combine all frames (now in glorious vector graphics) back into some playable video form. This is the step where the most optimizations and improvements can be made with regards to file size. Since we are returning back to the realm of video, i.e. moving pictures, we can make use of the existing compression technology and theory that is used in raster based video to drastically reduce file size. This is true because the output is still frame based just as raster videos are, and thus the same theories can be applied, this would not be true if the video was not frame based such as using interpolation or some other advanced method. The main concept to be brought over from current raster video compression is compression through leveraging temporal redundancy in a video as mentioned in the Video Graphics section. In this case, we can join a series of similar frames into what we call a frameset which will have a root or anchor frame. Only the root frame will be completely stored, all successive frames in the frameset will only be stored as the delta between the root frame. This is currently the only concept that is taken from raster video to reduce size but as mentioned, since the video is still frame based, many of the same ideas can be directly ported into the vector graphics world for further size reduction. Many more compression

optimizations can be done during this step to further reduce the size of the final video, hence the importance of the frame merging step within the process pipeline.

4.2 Vectorization Methods

As previously mentioned, many different approaches and methods were used to tackle the vectorization step of the pipeline in order to achieve the best possible results, or sometimes even acceptable results in some cases as will be detailed below. Three main approaches were used to tackle the problem, a color quantization based approach and two connected component labelling based approaches, one using edges as components and the other using colors as components. One detail to note is that multiple approaches were not planned early on and were in fact researched and explored as the project developed and as results began to appear. This is noteworthy because each successive approach aimed to fix the issues with the previous one, only to introduce new issues of its own. We will explain all three approaches in depth in their own subsections below as well as give an introduction to the theory of connected component labelling as two of the three approaches are based on this.

4.2.1 Color Quantization Approach

The first approach is based on color quantization, or simply, reducing the total number of distinct colors in an image while still aiming for *Visually Lossless Compression*. This approach was chosen because it is the one used in the *ImageTracer.js* library that was used as an initial blueprint and foundation for the project's codebase. Color quantization can be implemented in a variety of different algorithms but essentially any 3-dimensional (or 4-dimensional if including alpha) clustering algorithm can work because it is in essence a classification problem. All algorithms have the same expected behavior though; given an image and a desired number of colors n, find the n-size set of colors that best represents this image. Each pixel in the image is then changed from its original color to the color in the reduced palette that is closest to its original color, and thus the image has been reduced since the image has only n distinct colors. Each distinct color can then be assigned a single SVG path element, this is like a layer because it need not necessarily be connected, thus we end up with an SVG image made up of n number of SVG path elements, each a single color.

Color quantization is an excellent way to reduce the size of an image drastically while making it visually similar to the original and it is usually an extremely fast and efficient process. Their are a few drawbacks though, the first being that it performs much worse when attempting to reduce images with gradients and noise and there will be a visually obvious loss of data, similar to the issues that affect vectorization. However, in our case, the larger issue is to do with the manually inputted number of colors that the algorithm requires. The number of colors that are given to a color quantization algorithm can drastically change all of accuracy, performance and file size all at the same time. A high number such as 1,000 colors will yield very high

accuracy for most images but will have much less size reductions and have significant performance impacts. Even ignoring performance, choosing the correct number of colors that will yield the highest compression rate while also being visually identical in quality is another major task in itself, especially when considering that not all frames or images have the same color space. The truth is, while color quantization is an excellent way to reduce file size and still achieve *Visually Lossless Compression*, it depends too heavily on the provided number of colors and computing this color deterministically is another major problem of its own.

4.2.2 Connected Component Labelling (CCL)

A more logical way to approach the problem is to approach it as a partitioning problem, meaning we want to partition the image into a set of discrete adjacent parts that altogether make up the whole image. This is because that is exactly how the end result SVG will be created, as a set of SVG path elements that together form the whole image as if they are parts of a partition. This way of thinking lends itself extremely well to Connected Component Labelling (CCL) which is exactly that, dividing the image into a partition of connected components that together form the whole image. Connected Component Labelling does not in itself describe any particular implementation and thus can be implemented in many different ways depending on the context and desired outcome. However, the basic idea is that a single pass is made across the image and each pixel is checked to see if it fits within its neighbors' components, if so it is added to that component, if not it is the first in a new component. A second pass may be made to merge any components that are adjacent but this can be done in a single pass by checking to merge components after the initial component assignment. The concept itself is relatively simple with the intricate details left to the implementation which can heavily affect the results depending on how it is implemented and approached. Two CCL based approaches were used to attempt to tackle the vectorization problem, each differing only in the means by which a "component" is defined, the first using edges as components and the second using pixel colors as components.

4.2.3 Edge Based CCL Approach

The first approach using CCL is based on defining a component as an edge of the image. Edges can be easily detected using any edge detection algorithm, for this we used OpenCV's Canny edge detection but the actual edge detection is not the important factor here. For higher accuracy and confidence, a large sample size of edge detection passes with different parameters was averaged to create a single averaged edges image. This image is a monochrome image in which, a pixel with value of 0 is never an edge in any pass and a pixel with a value of 255 is an edge in every pass, thus we need to use some thresholding to determine what defines an edge. Once that is determined however, the CCL algorithm can pass through the average edges image to find the connected edges that make up the image. The reasoning behind this is that in theory, this will return the edges of all the polygons that make

up the image and thus by filling them with their average color, we can recreate the image using color regions. However, this is much easier said than done, and indeed there are many edge cases that need to be noted, specifically the effect of a single pixel. A single missing pixel could mean a polygon is incomplete, a single extra pixel between two unrelated polygons could mean the polygon is incorrect, basically the algorithm is very sensitive to any discrepancies within the averaged image. This can be tackled using further processing and analysis to undo some of these effects, but this would be very complicated and time consuming. In the end however, the edge based CCL approach did not yield the expected results and was very disappointing, although theoretically it can be perfected with time, that was something that was very limited and valuable and thus a new approach was explored.

4.2.4 Color Based CCL Approach

The second approach using CCL is based on defining a component as a region of similar colors based on the pixel values. This approach is the most logical way to approach the problem solely based on the desired output, i.e., SVG path elements of a single color each representing a color region. Since each pixel contains its color information, we can cluster pixels that are adjacent and have colors that are within a given delta threshold, that is to say, they are close enough in color to be part of the same color region. In essence we are performing a kind of color quantization since there will be reduced colors at the end of the process but unlike classic color quantization mentioned in the Color Quantization Approach section, the desired number of colors is no longer an input, solving the issue with that approach. As with other CCL approaches, the image is looped on and each pixel is queried to check whether it is eligible to be part of any of the components of its preceding neighbors, if so it joins that component, if not it is assigned its own new component where it is the first element. The reasoning behind this approach is that in theory each color region in the original image will naturally form a cluster which can then be reduced to a single color that is an average of all the pixels in that region. Thus, the image is transformed from a grid of unrelated pixels to a partition of adjacent color regions each being a single color that altogether form the entire image.

While being fairly complex and computationally expensive, this approach yields shockingly positive results both in terms of size reduction and image accuracy with any data loss incurred being minor. However, upon further inspection, a huge issue became obvious; the total number of components that was created was surprisingly high, an image with at most perhaps a few thousand color regions results with tens of thousands of color regions. The distinct colors were still reduced so color quantization was successful but an efficient partitioning was not and upon further investigation and research, it was clear that the culprit was anti-aliasing. Anti-aliasing is an effect popular in raster graphics that is used to make edges less sharp by adding blurs between them, and in the case of two different color regions, pixels with colors *in between* those two colors. What ends up happening is that our algorithm cannot determine which region these *in between* pixels are because their colors are

not close enough to either region and so they are assigned their own region. This is shown when we analyze the number of components with less than 5 total pixels and the result is a whopping 97% of all regions have less than 5 pixels in total and upon investigating, it is clear that these are the pixels at the edges of color changes and thus the ones responsible for anti-aliasing.

5 Software Engineering

This section will detail the software engineering aspects of the project's development, specifically the methodology used to develop, the risks of the project and the software testing techniques used in the project's development.

5.1 Methodology

The software methodology used for the development of this project is a very lean agile methodology aptly named, Lean-Agile. This methodology inherits heavily from modern agile methodologies following all the core principles and values but adds principles adapted from lean manufacturing, particularly emphasizing minimal waste and minimal prediction. While a more commonly known methodology such as Scrum could have been used, it seemed more appropriate to use a methodology that has extreme unpredictability built into it nature especially during the growth phase of the COVID-19 pandemic, which caused many unpredictable events. The pandemic's potentially adverse effects on the development of the project meant that it was critical to use a methodology that is extremely efficient and has little fixed planning with a very easy way of adapting to changes. This proved to be extremely beneficial, more so than expected because of the many major roadblocks that were faced during development which are further explained in detail in the Results section. The constant occurrence of very negative results, especially after a complex and time-consuming amount of work put in meant that plans had to change and adapt rapidly in accordance to this, which is common and expected in any research based project such as this one. As a result, while the Lean-Agile methodology is an unorthodox methodology choice, it was absolutely the correct one to use and has been the saving grace of the time management of this project since very few other methodologies could have allowed for the rapid adaptation and movement of this project.

5.2 Schedule

While the Lean-Agile methodology is not particularly well suited to long term predictions, it is still important to have a schedule in place in order to keep track of time and to have a general idea of how many tasks are left and how much time is available to complete them, even if the predictions of time may be incorrect. This is why a Gantt Chart was used to plot a schedule containing the general phases of the project's development against the time allocated to work on the project.

Gantt Chart

- Frame Managing (video to frames and frames to video)
    - Video to frames (ffmpeg)
    - Read frame image data
    - Write frame image data (SVG and PNG)
    - Combine frames to a playable video
- Vectorization
    - Core programming (ImageTracerJS)
    - Edge detection
    - Connected Component Labelling
    - Path/Polygon parsing
- Writing
    - Latex setup and learning
    - User evaluations
    - Resource compiling
    - Core writing

5.3 Risks

Naturally, a project of this scale that is very experimental in nature has many multi-faceted risks associated with it that can severely impact the development of the project if not correctly mitigated. As such, it is important to detect these risks as early as possible and have detailed and usable mitigation strategies to counter such risks and avoid their possibly devastating effects.

Risks Chart

- Bad time management
- Data Loss
- Hardware performance issues
- Tools too difficult
- Tools not cooperative
- Personal issues (stress, burnout)
- Covid related crap
- Poor results
- Catastrophic fatal disaster ;)

5.4 Testing

Testing is an important part of software engineering, as it allows developers to ensure that the program behaves as expected even after changes to the code, this means that refactors or new implementations can easily be done since any breaking changes will fail the tests that previously passed. This makes developing new changes or code more reliable since there is a pillar of trust knowing that if the tests pass, then the software is behaving correctly, assuming of course the tests are well written and defined. In order to ensure that the application is behaving in the expected way, the project needed some kind of testing facilitation. A variety of classic testing methodologies and philosophies were used in this project namely, unit testing, integration testing and acceptance testing.

5.4.1 Unit Testing

The first testing methodology used was none other than the classic and simple unit testing. In our case we used a variety of classic automated unit tests, in-code `assert` statements and regular logging messages each serving different purposes. Firstly, the typical automated unit tests were used at the end of a computation to ensure that the output image was as expected, using whatever possible methods to do this. One of the ways was to test the output image's properties such as resolution, bit depth, size, distinct colors, among others. Secondly, in-code `assert` statements were used before any requirement that was needed to be true before computation, usually with regards to expected inputs. While this is not a traditional testing method, it was used as such here as there are many times where the input is not guaranteed to meet the requirements and thus a graceful failure is the only option with detailed messages. Finally, regular logging messages were used throughout the processing. These were used less as hard tests and more as indicators of less critical correct or incorrect behavior and very often used to measure time passed for every phase or step as execution times became fairly long. These three techniques were all used to ensure that the application was tested from the lowest point possible and the developer is able to understand how the code is being run and when and why it may be failing.

5.4.2 Integration Testing

Since many phases and process had to interact with one another and pass data to each other, it was important to ensure that this was behaving correctly using integration testing. In this case, a process such as average edge detection for example would have a specific output that perhaps the next process, edge based CCL, may not be expecting or may not know how to behave with. In addition to the core concepts were used from unit testing such as using in-code `assert` statements and logging statements, additional code was added in order to ensure that the application would either use the same data formats, or have a trustworthy converter to convert the data. An excellent is example is OpenCV's `Mat` type representing a matrix which

was used during edge detection but the next steps would only know how to handle a built in type representing images. Thus, a converter was created to ensure that whenever the `Mat` type was used it was immediately converted to the internal type ensuring that the entire application would be uniform in what data types it would use and expect. Using integration testing using measures like these, we can ensure that the application can have components and processes interact with one another in the expected and correct behavior.

5.4.3 Acceptance Testing

Perhaps the most used and most important methodology used in this project was acceptance testing. In this case specifically this was done manually while developing in order to ensure results are visually as expected. This is because this is a graphics based project after all and the final judge as to whether the image is correct or not, is of course the human eye. A typical test case here was to run some computation on a frame, (have a coffee because it took a while) and check to see if the output image was something that was at least close to what was expected. This was how the majority of the main important validation was done since no automated test can ever tell if an image is acceptable. Indeed, there were many cases where the output image would have the expected properties such as resolution, color depth, size reduction etc and yet still be nothing more than noise because of some oversight or bug in the code. Thus, it is safe to say that while unit testing and integration testing were extremely important in this project, the true most important testing methodology used in this project was that which uses the the human eye and that being acceptance testing.

6 Evaluation

In order to know when the program is behaving correctly and to evaluate how well it is performing its task, we need to define some evaluation methods and metrics. Essentially there really only exist two key traits to the process, how accurate is the process and how well is the compression. A possible third angle could be performance, but this was never a priority to begin with and this can be heavily optimized and improved later, not to mention that it will differ across machines and architectures. Thus we will only discuss and detail the two key evaluation properties, accuracy and compression.

6.1 Accuracy

The first property to evaluate is accuracy, or more accurately (pun intended), the lossy-ness that is incurred from the process. As mentioned earlier, since the vectorization process is transforming data from one form of representation to another, there will be data loss, especially if one intends to reduce size as we do. However, since we are aiming for *Visually Lossless Compression*, it is important to know how to measure this data lossy-ness accurately in a meaningful way. Below we detail the two methods of evaluating the accuracy of an image using quantitative methods and qualitative methods.

6.1.1 Quantitative Methods

The quantitative methods we can use to evaluate the accuracy of the process are fairly straightforward since really all that we need to do is compare the data of both images, the input and the output. As such, we can relatively easily loop over every pixel in the original image and compare the color of that pixel to the color that is visible at that coordinate within the output SVG image. While vector graphics do not use the concept of pixels, we can still go to a specific coordinate on the image and query the color visible their using our own means. It is important to note here that 100% may not only be impossible, but in fact is actually not ideal as we are not aiming for a truly lossless transformation. What we are aiming for is a *Visually Lossless* transformation, meaning any data loss should be invisible to the human eye. Therefore, while quantitative methods for accuracy are quick and easy, they do not accurately represent the true goal of this project, which was never aimed to be lossless.

6.1.2 Qualitative Methods

The qualitative methods of comparing accuracy are the most meaningful and important but at the same time, the most difficult to measure and make sense of. Really, the main judge of whether a compression algorithm is *Visually Lossless* is the human eye, but measuring perceived quality and difference has complications. However, despite being difficult to accurately measure, as after all, visual perception

differs amongst people and "quality" can be subjective, there are ways to measure this and make *some* informed conclusion based on the data. This of course can be done by using a sample set of different people with as diverse possible perception and notion of "quality" as possible. Despite being very difficult and expensive to gather such a sample set (especially in these times), a sample set of close friends and family of fairly diverse ages and backgrounds was gathered and used to measure perceived accuracy.

6.2 Compression

The other property to evaluate is compression rate, i.e., the size ratio of the new file's size to the original file's size. It is important to note that the project's aim with regard to compression in that the aim is to have smaller file sizes *and* scalability, that means there may be instances where file size may actually become larger, like when dealing with a low resolution input. However, that same output file can now be used on higher resolution displays with no issues, whereas the original cannot and any upscaled copies of the original will never be as small in size as our output, at least that is the aim. Thus, the upscaling factor needs to be taken into account when viewing the data in order to gain a fuller understanding of the whole picture. Below we detail the many different quantitative methods that can be used to evaluate the compression of the process.

6.2.1 Quantitative Methods

Compression can really only be quantitatively measured but it can be measured fairly easy and therefore, we can gather a large amount of data to gain a more concrete understanding of the compression rate of the process especially when considering upscaling.

7 Results

8 Challenges

As shown by the previous sections in this document, this project has been far from trivial, in fact it was much more difficult and challenging than initially anticipated despite already expecting a high level of difficulty. While the project has been overall a very mentally stimulating, rewarding and fulfilling project it is important to note some of the major challenges that were faced during the development. This serves the purpose to inform future readers and those interested in this project about some of the challenges faced and how to either overcome them early, or more likely, to expect and prepare for them. While some of these issues can be mitigated earlier with further planning and research, the most difficult and major challenges are those inherent to the vectorization process and conversion of raster graphics.

8.1 Toolchain

Arguably the most preventable and frustrating challenges faced were those that were a direct result of the toolchain used, especially when there exist other tools that do not have these problems. The most frustrating of these is the lack of maturity in the JavaScript ecosystem. This can be seen with the very minimal Node.js standard library which contains only the most necessary built in functionality and instead delegates anything else to libraries, frameworks and other open source contributors. While this does have benefits it also has major disadvantages especially coming from the vast ecosystems of the JVM and Android which both come with large fully featured but modular standard libraries that provide standard ways to perform common operations. This weakness is shown extensively whilst using any JavaScript collections such as Array, Set or Map, which provide only the most basic functionality leaving common operations like copying and adding an element to an index up to the user or to some external dependency. However, perhaps the best example for an argument of the JavaScript ecosystem's immaturity is the fact that JavaScript supports object oriented concepts, including classes and methods, but does not allow programmers to declare when two objects are equal or not. The Set collection contains only distinct elements by first checking if an element already exists before inserting it and ignores it if it already exists. JavaScript does not allow the programmer to determine how this equality is checked which is done using `===` by default, instead, if the programmer wants a Set of custom objects they have to implement this themselves or use an external library, further adding to dependency hell.

Another issue from the toolchain used that was also completely unexpected and mostly taken for granted coming from the JVM world is the lack of true concurrency or multithreading in Node.js and JavaScript in general. Node.js is asynchronous meaning execution can jump between functions and wait until functions are complete by using the `Promise` API in addition to the `async` / `await` model. However, JavaScript does not allow multiple threads of execution at once and the only way to achieve this is by using multiple JavaScript instances, in the case of Node.js

multiple Node processes which adds a huge amount of complexity to the program. This meant that any possible optimizations that could be made would be much more difficult than expected and would take too long to develop. This is an issue because the application can make use of parallel execution and can heavily benefit from this but because of the issues with the toolchain, such benefits would be too costly to achieve. These are just some of the examples of when the toolchain used was actively discouraging and slowing down development and this is something that was a major challenge and annoyance during development as it was not expected and is out of our direct control.

8.2 Performance

Another major challenge was the performance of the program and trying to improve it in some way. Because of the desired accuracy and compression and the complexity and number of operations that are required to achieve these two key traits, the cost was performance since the program was just too complex. This was mostly expected at first, however what was not expected was the difficulty in optimizing and reducing the time it took to run the process on a single frame and any added code would only compound the problem. This meant that in order to test some new code worked a full loop had to be run first before further proceeding, this would take anywhere between 5 to 10 minutes to finish and as a result productivity was much lower than desirable. How to improve this was obvious since there were two clearly possible solutions to take, add multithreading as only one thread was running and the CPU was maxing at only 9% utilization, or use the GPU wherever possible as much of the code can theoretically be run on the GPU for insanely better results.

Adding multi-threading to the application was much more difficult than anticipated as the toolchain used simply did not allow for this to be an easy solution as mentioned in the above Toolchain section. However, more beneficially perhaps was to use the GPU wherever possible as the GPU is capable of having huge performance improvements if the code is written for it. Indeed, the GPU was used in some parts of the application leading to truly shocking results, what took 60-100 seconds now takes 4-6 seconds, however the difficulty and learning curve for correct and effective GPU programming is enormous. This really creates a very difficult decision to make because GPU optimizations are big cost big reward optimizations that can significantly increase productivity and in the long run provide us with more time to write and test code. In the end however, the time cost to rewrite code to run on the GPU was simply too high to risk and the potentially huge optimizations and performance improvements were not fully accomplished, thus, the program having very poor performance overall despite attempts to rectify this.

9 Reflection

After working on this project over the last few months, it is important to look back and reflect on the experience to see what was learned and what new experiences were made. Firstly, the unexpected difficulty of the project and the continuous roadblocks and negative results have been extremely humbling and have been excellent experiences in development struggle and hardship; struggle is an excellent teacher and this project was a huge struggle. The main thing learned is patience and a new desire and appreciation for experimentation, even if the results will not go according to plan and the time and effort spent was high, the experience of the challenge is by far the greatest reward. Secondly, and more concretely, the technical knowledge that was gained through this project within both the computer graphics field and also in the JavaScript ecosystem in general are extremely valuable. Computer graphics is a complex and daunting field full of intense knowledge and technicality and had it not been for this project so much knowledge and experience within the field would have never been gained.

Having said all this however, it is important to mention what would be done differently if starting from the beginning, something that future readers interested in this kind of project should take important note of. Perhaps the most important thing to change is the toolchain from Node.js to one that allows true multithreading but with the same vast ecosystem as JavaScript. The first toolchain that comes to mind is the JVM platform with its large thriving ecosystem, multiple languages to choose from (Java, Kotlin, Scala etc) and the addition of true multithreading, this is the ideal toolchain to use instead of a JavaScript based one. The other thing to note before starting over is to appreciate and comprehend the difficulty of this project and this problem. Vectorization is not an easy process and particularly so on complex media such as cartoons, even if they contain qualities that seem favorable towards vectorization. In knowing this beforehand one may face less frustrations and better expectations on what it means to achieve any decent results because while those results may not seem perfect, they are far more impressive than they seem. All in all however, the experience has been rewarding, fulfilling, mentally stimulating and a truly challenging adventure that is very much worth the time and effort to invest in simply for the experience and knowledge alone.

10 Future Work

Despite being given many months to work on this project, it would be dishonest to claim that it is close to being completed, as there are still many future endeavours and tasks that can be completed given more time. These tasks were left out as they were either lower priority or out of the scope of the project's initial aims and objectives and were thus cut for time saving.

10.1 Optimization

As discussed in depth in the preceding sections, one of the main issues with the project currently is the performance of the processing. This was never a high priority to begin with as it was clear early on that in order to aim for high accuracy and high compression, more instructions needed to be executed and thus more time was needed to execute them. However, given more time this is an angle that is important to investigate and tackle as the more complex the process becomes, the longer it takes to view any results, leading to significantly lower productivity. One of the main ways this can be achieved is by using the machine's hardware more efficiently especially by using more of the resources and making use of the many processing cores most modern machines possess today. As discussed earlier,

10.2 Future Research

Towards the end of the development cycle many new ideas began to make themselves apparent especially after the multiple consecutive failures to show major positive results. These ideas were noted and left aside in order to focus on the main goal of the project as they strayed slightly from the scope of the project and would have required more than the given time in order to truly explore correctly. However, given more time, these ideas should be further explored and tested as they can show further positive results and shed some light and insight onto the vectorization problem. The most important idea is the potential mixing of raster and vector graphics in a new graphics format in order to leverage the best of both formats and attempt to solve the issues of both. A potential algorithm would identify easily vectorizable areas of an image that would alter the data of the original image only less than a given maximum data loss threshold. These areas of the image would be vectorized and represented in vector graphics. Then, for the areas where vectorization fails to yield any positive results, usually because of noise, rasterization artifacts such as anti-aliasing or other non-vectorizable qualities such as gradients, the algorithm would keep those areas as raster pixel-based. As is made obvious by the simplistic high-level explanation, this idea is still not well thought out or researched, but given more time this is something that can be explored and researched in depth.

11 Conclusion