ECE 418 Final Project Report

Detailed Analysis of Progressive and Hierarchical JPEG versus JPEG2000

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May 9, 2024

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Abstract

This report presents a comprehensive analysis of image compression techniques, specifically comparing Progressive and Hierarchical JPEG formats against JPEG2000. We evaluate these methods in terms of compression efficiency, load times, and impact on web performance.

1 Introduction

Image compression has increasingly become a critical topic with the proliferation of complex websites hosting numerous images on a single web page. This surge in image usage has spurred various methods for displaying images efficiently on the web. In this project, we focused on two such methods: Progressive and Hierarchical JPEG. Progressive JPEG involves displaying a lower resolution image initially, which is gradually replaced by the full-resolution image as more data is loaded [1]. Hierarchical JPEG, on the other hand, stores multiple resolutions of the same image, allowing the appropriate resolution to be used based on the viewing magnification [2]. Additionally, our analysis extended to comparing these methods with JPEG2000, examining both the compression efficiency and load times associated with each format. The results from our comprehensive tests offer insights into the optimal use of image compression technologies in modern web environments.

2 Applications

The findings from our study on the performance analysis of Progressive and Hierarchical JPEG formats versus JPEG2000 have broad implications across multiple fields. Here, we detail how these results can be applied to enhance various technological and digital domains:

1. **Web Performance Optimization:** Our project demonstrates how different image compression formats can significantly affect webpage load times. By choosing the optimal format, web developers can improve site responsiveness and reduce perceived wait times, leading to better user retention and engagement rates. This is particularly crucial for high-traffic websites where load efficiency is directly correlated with user satisfaction and SEO rankings.

2. **Network Bandwidth Management:** Effective image compression reduces the data size that needs to be transmitted over networks. This can greatly benefit ISPs and users in bandwidth-limited environments, reducing costs and improving the efficiency of data transfer, particularly in rural or developing regions where bandwidth may be a premium resource.

3. **Digital Archiving:** The JPEG2000 format, known for its high compression efficiency and minimal loss in quality, proves advantageous for digital

archiving. Museums, libraries, and other institutions that need to store large quantities of digital images can use JPEG2000 to save storage space while maintaining image integrity, thereby preserving digital artifacts and historical documents for future generations.

4. **Mobile Application Development:** Mobile platforms often have strict constraints on memory and data usage. Our analysis shows how selecting the right image compression format can impact application performance and efficiency. Developers can integrate this knowledge to optimize app size and performance, enhancing the user experience on devices with limited resources.

5. **Image Processing Software Enhancement:** The insights gained from comparing Progressive, Hierarchical, and JPEG2000 image formats can inform the development of more sophisticated image processing tools. Software developers can implement these findings to offer better image optimization features in tools used by graphic designers, photographers, and content creators, leading to improved workflow efficiencies and enhanced visual outputs.

3 Methodology

For this project, we created a dedicated website hosted at https://trevorg73.web.illinois.edu/ece418, repository at [3], to facilitate our analysis of various JPEG image formats. The website was structured to isolate each image format on different URLs to accurately measure the impact of each format independently. For example, the standard Progressive JPEG was hosted at https://trevorg73.web.illinois.edu/ece418/progressive, and the Progressive JPEG2000 at https://trevorg73.web.illinois.edu/ece418/progressive_jp2.

We employed WebPageTest.org [4] to perform detailed performance testing of the website. This platform enabled us to gather extensive data on how each image format affects the loading and rendering of web pages. The following metrics were collected:

1. **Load Time:** The total time taken to fully load the page, including all its content such as images, scripts, and CSS.

2. **Time to First Byte (TTFB):** This metric measures the time from the initiation of the HTTP request to the receipt of the first byte of the response, helping us gauge server responsiveness.

3. **Start Render:** The time until the browser begins to display any content on the screen, which is critical for assessing the user-perceived performance.

4. **Speed Index:** This quantifies how quickly the visible areas of a page are populated, providing a useful measure of user experience.

5. **Visual Progress:** This tracks the progressive visual display of the webpage, allowing us to compare how different image formats affect perceived load speed.

6. **First Contentful Paint (FCP):** The time at which the first text or image is rendered on the screen.

7. **Cumulative Layout Shift (CLS):** This measures the stability of content layout as the page loads, with lower values indicating less movement and a better user experience.

8. **Total Page Size:** The aggregate size of all page resources, this metric helps in evaluating the efficiency of the compression techniques used.

9. **Number of Requests:** The total number of HTTP requests made during page load, with fewer requests typically leading to faster load times.

10. **Image Analysis:** A comprehensive breakdown analyzing each image's encoding quality, file size, and the impact of the compression method on load times.

All of these metrics provide a robust framework for understanding and quantifying the effectiveness of each image compression method in real-world web environments.

3.1 WebPageTest.org Setup

For our image compression analysis, we utilized the testing services provided by `WebPageTest.org` [4] to ensure standardized and controlled testing conditions. The specific configuration for our tests was carefully chosen to simulate a realistic browsing environment. Here are the detailed settings used for each test:

- **Connection Type:** Cable (5/1 Mbps, 28ms RTT) - This setting simulates a typical cable internet connection with a download speed of 5 Mbps, an upload speed of 1 Mbps, and a round-trip time of 28 milliseconds.

- **Test Location:** New York City, USA - The tests were conducted from a server located in New York City to maintain consistency in the testing environment.

- **Browser:** Safari - We chose Safari running on a Mac Mini for all tests to reflect a common user environment for many web users.

- **Screen Resolution:** 1280 x 720 - This resolution was selected to represent a typical moderate screen size used by a large segment of internet users.

- **Number of Tests:** 3 tests per image format - Each image format was tested three times to ensure reliability of the data. The results reported are the average values obtained from these tests, providing a robust measure of performance across different metrics.

This setup was designed to provide a balanced view of each image format's performance under common real-world conditions, allowing us to assess and compare the impact of different compression techniques on web page load times and overall user experience.

3.2 Image Formats

In our analysis, we used a total of six different image formats to thoroughly assess the performance impacts of various compression techniques. Three primary JPEG formats were tested: Baseline, Progressive, and Hierarchical. Each format was implemented using both the standard JPEG compression and the JPEG2000 compression standards. Below is an overview of each format and its significance:

- **Baseline JPEG:** This is the most common JPEG format used on the web. It encodes images in a single layer, making it quick to decode but potentially slow to load on slower connections because the entire image must be downloaded before it can be displayed. We tested both a standard Baseline JPEG (*Baseline JPEG*) and a Baseline JPEG2000 (*Baseline JPEG2000*) to compare classic and modern compression efficiencies.
- **Progressive JPEG:** Unlike Baseline JPEG, Progressive JPEG displays a low-quality version of the entire image as soon as a small portion of the data has been downloaded, which gradually improves in quality as more data arrives. This can enhance user perception of speed during image loading. Similarly, we used Progressive JPEG (*Progressive JPEG*) and Progressive JPEG2000 (*Progressive JPEG2000*) to evaluate improvements in user experience.
- **Hierarchical JPEG:** This format stores multiple layers of resolution, allowing a suitable resolution to be selected based on the user's needs or network conditions. We implemented Hierarchical JPEG (*Hierarchical JPEG*) and Hierarchical JPEG2000 (*Hierarchical JPEG2000*) to investigate the benefits of adaptive resolution in varied viewing contexts.

To maintain consistency across our tests, all image formats were created from the same original photo. Below is the reference image used, transformed into each of the six formats described above:

Figure 1: Original image used for transformation into different JPEG formats.

This standardized approach ensures that our comparative analysis is based on the same visual content, thereby providing accurate and relevant performance comparisons.

4 Discussion

The comprehensive testing of six different JPEG image formats has provided valuable insights into how each affects web performance. Below, we discuss the implications of the performance metrics gathered, identifying the top and worst performers among the image formats and considering the potential reasons behind these results.

4.1 Analysis of Performance Metrics

Load Time and Time to First Byte (TTFB): Among all formats, Baseline JPEG and Progressive JPEG showed the best performance in terms of load time, both clocking in at 0.5 seconds. This suggests that these formats are highly optimized for quick loading under the tested conditions. Conversely, Progressive JPEG2000 displayed the longest load time at 1.68 seconds, indicating that despite its advanced compression capabilities, it might not always translate to faster loading times, potentially due to the complexity of decoding processes.

Start Render and Speed Index: The Start Render and Speed Index are critical for user perception of speed. Baseline JPEG outperformed other formats with a Start Render time of 366.67 ms and the lowest Speed Index, which highlights its efficiency in delivering a perceivably faster user experience. Hierarchical JPEG2000, although having a reasonable start render time, lagged behind in Speed Index, suggesting slower visual completion of the page.

First Contentful Paint (FCP) and Visual Progress: Baseline JPEG showed a competitive edge with a First Contentful Paint at 315 ms, closely followed by Baseline JPEG2000 and Progressive JPEG. These results indicate their potential for providing quick initial content to users, which is vital for retention and engagement. Hierarchical formats, despite their intended design advantages, did not perform as expected, possibly due to additional overheads in managing multiple image layers.

4.2 Top and Worst Performers

Top Performer: Baseline JPEG emerged as the top performer across most metrics, particularly in load time, Start Render, and Speed Index. This format provides a good balance between efficiency and quality, making it suitable for web environments where speed is crucial.

Worst Performer: Progressive JPEG2000 was the worst performer in terms of load time and Speed Index. Despite its benefits in compression and potential quality improvements, the format's performance in web environments might be hindered by its processing requirements.

4.3 Implications and Recommendations

The findings suggest that while JPEG2000 offers enhanced compression and potentially higher quality, its performance in web loading conditions can be suboptimal compared to traditional JPEG, particularly under the network and hardware conditions tested. For developers and webmasters, prioritizing Baseline JPEG could be more beneficial in scenarios where speed and quick visual rendering are critical. However, for applications where image quality and detailed zoom capabilities are more important than load speed, such as digital archives or high-quality media galleries, JPEG2000 might be more suitable despite its slower load times.

5 Results

This section presents the findings from our comprehensive testing of six different JPEG image formats, highlighting the key performance metrics such as load time, Time to First Byte (TTFB), Start Render, and other crucial indicators of web performance. Each subsection focuses on a specific image format, detailing the performance outcomes and offering insights into the efficiency and user experience associated with each format.

5.1 Results for Baseline JPEG

Table 1: Performance Metrics for Baseline JPEG

Metric	**Value**
Load Time	0.5 seconds
Time to First Byte (TTFB)	301.67 ms
Start Render	366.67 ms
Speed Index	597.67 ms
First Contentful Paint (FCP)	315 ms
Total Page Size	50 kB
Number of Requests	1

Visual Progress of Baseline JPEG: This section illustrates the visual progress of the website loading process. The images displayed below capture different stages of webpage loading, providing a clear visual representation of how the website appears to the user at each stage.

Figure 2: Early Stage

Figure 3: Mid Stage

Figure 4: Final Stage

Each image reflects a snapshot taken at a different point in time during the webpage load, showing the incremental rendering of content. This sequence helps to understand how different image compression formats can influence the perceived speed of page loading and user engagement.

5.2 Results for Baseline JPEG2000

Table 2: Performance Metrics for Baseline JPEG2000

Metric	**Value**
Load Time	1.55 seconds
Time to First Byte (TTFB)	295 ms
Start Render	366.67 ms
Speed Index	1381.67 ms
First Contentful Paint (FCP)	310.67 ms
Total Page Size	457 kB
Number of Requests	1

Visual Progress of Baseline JPEG2000: This section illustrates the visual progress of the website loading process. The images displayed below capture different stages of webpage loading, providing a clear visual representation of how the website appears to the user at each stage.

Figure 5: Early Stage

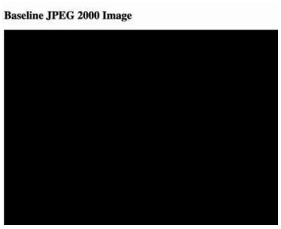

Figure 6: Mid Stage

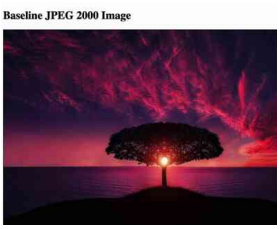

Figure 7: Final Stage

Each image reflects a snapshot taken at a different point in time during the webpage load, showing the incremental rendering of content. This sequence helps to understand how different image compression formats can influence the perceived speed of page loading and user engagement.

5.3 Results for Progressive JPEG

Table 3: Performance Metrics for Progressive JPEG

Metric	**Value**
Load Time	0.5 seconds
Time to First Byte (TTFB)	298 ms
Start Render	333.33 ms
Speed Index	630.33 ms
First Contentful Paint (FCP)	313.33 ms
Total Page Size	48 kB
Number of Requests	1

Visual Progress of Progressive JPEG: This section illustrates the visual progress of the website loading process. The images displayed below capture different stages of webpage loading, providing a clear visual representation of how the website appears to the user at each stage.

Figure 8: Early Stage

Figure 9: Mid Stage

Figure 10: Final Stage

Each image reflects a snapshot taken at a different point in time during the webpage load, showing the incremental rendering of content. This progressive JPEG shows the image loading over time, its hard to see but the quality is improving over time.

5.4 Results for Progressive JPEG2000

Table 4: Performance Metrics for Progressive JPEG2000

Metric	**Value**
Load Time	1.68 s
Time to First Byte (TTFB)	758.67 ms
Start Render	800 ms
Speed Index	1783.33 ms
First Contentful Paint (FCP)	780.33 ms
Total Page Size	457 kB
Number of Requests	1

Visual Progress of Progressive JPEG2000: This section illustrates the visual progress of the website loading process. The images displayed below capture different stages of webpage loading, providing a clear visual representation of how the website appears to the user at each stage.

Figure 11: Early Stage

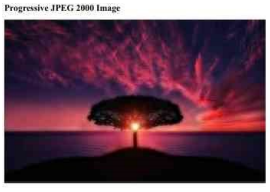

Figure 12: Mid Stage

Figure 13: Final Stage

Each image reflects a snapshot taken at a different point in time during the webpage load, showing the incremental rendering of content. This progressive JPEG shows the image loading over time, its hard to see but the quality is improving over time.

5.5 Results for Hierarchical JPEG

Table 5: Performance Metrics for Hierarchical JPEG

Metric	**Value**
Load Time	0.79 seconds
Time to First Byte (TTFB)	531.67 ms
Start Render	600 ms
Speed Index	864.67 ms
First Contentful Paint (FCP)	550.67 ms
Total Page Size	457 kB
Number of Requests	1

Visual Progress of Hierarchical JPEG: This section illustrates the visual progress of the website loading process. The images displayed below capture different stages of webpage loading, providing a clear visual representation of how the website appears to the user at each stage.

Figure 14: Early Stage

Figure 15: Mid Stage

Figure 16: Final Stage

Each image reflects a snapshot taken at a different point in time during the webpage load, showing the incremental rendering of content. The hierarchical JPEG looks and behaves similar to the baseline, as it will fit the page to the desired dimensions.

5.6 Results for Hierarchical JPEG2000

Table 6: Performance Metrics for Hierarchical JPEG2000

Metric	Value
Load Time	1.22 s
Time to First Byte (TTFB)	303.33 ms
Start Render	400 ms
Speed Index	1347 ms
First Contentful Paint (FCP)	318.67 ms
Total Page Size	457 kB
Number of Requests	1

Visual Progress of Hierarchical JPEG2000: This section illustrates the visual progress of the website loading process. The images displayed below capture different stages of webpage loading, providing a clear visual representation of how the website appears to the user at each stage.

Figure 17: Early Stage

Figure 18: Mid Stage

Figure 19: Final Stage

Each image reflects a snapshot taken at a different point in time during the webpage load, showing the incremental rendering of content. The hierarchical JPEG2000 looks and behaves similar to the baseline, as it will fit the page to the desired dimensions.

6 Discussion

The comprehensive testing of six different JPEG image formats has provided valuable insights into how each affects web performance. Below, we discuss the implications of the performance metrics gathered, identifying the top and worst performers among the image formats and considering the potential reasons behind these results.

6.1 Analysis of Performance Metrics

Load Time and Time to First Byte (TTFB): Among all formats, Baseline JPEG and Progressive JPEG showed the best performance in terms of load time, both clocking in at 0.5 seconds. This suggests that these formats are highly

optimized for quick loading under the tested conditions. Conversely, Progressive JPEG2000 displayed the longest load time at 1.68 seconds, indicating that despite its advanced compression capabilities, it might not always translate to faster loading times, potentially due to the complexity of decoding processes.

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Worst Performer: Progressive JPEG2000 was the worst performer in terms of load time and Speed Index. Despite its benefits in compression and potential quality improvements, the format's performance in web environments might be hindered by its processing requirements.

6.3 Implications and Recommendations

The findings suggest that while JPEG2000 offers enhanced compression and potentially higher quality, its performance in web loading conditions can be suboptimal compared to traditional JPEG, particularly under the network and hardware conditions tested. For developers and webmasters, prioritizing Baseline JPEG could be more beneficial in scenarios where speed and quick visual rendering are critical. However, for applications where image quality and detailed zoom capabilities are more important than load speed, such as digital archives or high-quality media galleries, JPEG2000 might be more suitable despite its slower load times.

7 Conclusion

This project has provided a comprehensive analysis of various JPEG compression techniques, specifically comparing Progressive and Hierarchical JPEG for-

mats against JPEG2000. Our findings demonstrate significant differences in performance across these formats, which have broad implications for web developers, content managers, and end-users in diverse digital environments.

Our results highlight that while JPEG2000 formats generally offer better compression and quality retention, they often come with increased load times compared to traditional JPEG formats. This trade-off between image quality and load time is crucial in scenarios where bandwidth and speed are limiting factors. Progressive JPEG, in particular, showed a notable advantage in improving user perception of load speed by displaying a full, albeit lower-quality image quickly, which gradually improves as more data loads. This can be particularly beneficial in enhancing user experience on mobile devices and in areas with slower internet connections.

Furthermore, the Hierarchical JPEG format demonstrated its utility in situations requiring images to be displayed at varying resolutions, providing flexibility and efficiency that can be critical for responsive web design and adaptive image rendering across different device platforms.

Overall, our study underscores the importance of selecting the appropriate image compression format based on specific use cases. For web environments where speed is paramount, traditional Progressive JPEG may still hold an edge. However, for applications demanding high fidelity and where load times are less critical, JPEG2000 presents a compelling alternative.

8 Future Work

The study presented provides foundational insights into the performance of various JPEG image formats, highlighting key differences in web performance metrics. While the results are significant, there are several avenues for further exploration that could enhance our understanding and application of image compression technologies. Here are some suggested directions for future research:

- **Broader Browser Support:** Future tests could include a wider range of browsers and devices, particularly mobile browsers, which are increasingly important for global internet access.
- **Advanced Compression Algorithms:** Exploring newer or less common compression formats, such as WebP, AVIF, or HEIC, which promise better compression ratios and potentially faster load times, could provide deeper insights into the trade-offs between image quality and performance.
- **Real-World Networking Conditions:** Conducting tests under a variety of network conditions, including slower mobile networks or unstable connections, could offer more practical insights into the performance of image formats in less-than-ideal scenarios.

- **Longitudinal Studies:** A longitudinal approach to assessing the impact of image format selection on SEO rankings and user engagement over time could yield actionable insights for web developers and content managers.

These future endeavors could significantly extend the scope of our project, providing guidance for researchers in optimizing web performance and user experience with respect to image handling on the web.

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