



Masterarbeit im Studiengang Computer Science and Media

Mega-fast or just super-fast? Performance
differences of mainstream JavaScript frameworks
for web applications

vorgelegt von

Andreas Nicklaus
Matrikelnummer 44835

an der Hochschule der Medien Stuttgart

am 25.09.2024

zur Erlangung des akademischen Grades eines Master of Science

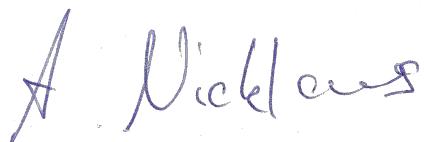
Erst-Prüfer: Prof. Dr. Fridtjof Toenniessen
Zweit-Prüfer: Stephan Soller

Ehrenwörtliche Erklärung

Hiermit versichere ich, Andreas Nicklaus, ehrenwörtlich, dass ich die vorliegende Masterarbeit mit dem Titel: „Mega-fast or just super-fast? Performance differences of mainstream JavaScript frameworks for web applications“ selbstständig und ohne fremde Hilfe verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe. Die Stellen der Arbeit, die dem Wortlaut oder dem Sinn nach anderen Werken entnommen wurden, sind in jedem Fall unter Angabe der Quelle kenntlich gemacht. Die Arbeit ist noch nicht veröffentlicht oder in anderer Form als Prüfungsleistung vorgelegt worden.

Ich habe die Bedeutung der ehrenwörtlichen Versicherung und die prüfungsrechtlichen Folgen (§26 Abs. 2 Bachelor-SPO (6 Semester), § 24 Abs. 2 Bachelor-SPO (7 Semester), §23 Abs. 2 Master-SPO (3 Semester) bzw. §19 Abs. 2 Master-SPO (4 Semester und berufsbegleitend) der HdM) einer unrichtigen oder unvollständigen ehrenwörtlichen Versicherung zur Kenntnis genommen.

Eislingen, den 17. September 2024

A handwritten signature in blue ink, appearing to read "A. Nicklaus".

Andreas Nicklaus

Zusammenfassung

Ein wesentlicher erster Schritt in jedem modernen Webanwendungsprojekt ist die Auswahl eines geeigneten Webentwicklungs-Frameworks. Oft werden schwerwiegende Entscheidungen aufgrund von Gefühlen getroffen, anstatt die Leistung des Frameworks im Vergleich zu den Projektanforderungen und -ressourcen richtig zu bewerten.

In dieser Arbeit wird eine Modell-Webanwendung untersucht, die mit sieben Mainstream-JavaScript-Webentwicklungs-Frameworks identisch erstellt wurde: Angular, Astro, Next.js, Nuxt, React, Svelte und Vue.js.

Leistungsmessungen werden mit den Tools Lighthouse und Playwright durchgeführt, um Stärken und Schwächen der Frameworks zu ermitteln. Dazu werden unter anderem die klassischen Seitenladezeiten sowie die Lade- und Aktualisierungszeiten von JavaScript-Komponenten ermittelt. Zusätzlich werden zwei neue geeignete abgeleitete Metriken evaluiert: die „Observed Visual Change Duration“ und eine „loadEventEnd“-Metrik.

Die Ergebnisse zeigen keinen eindeutigen allgemeinen Vorteil eines einzelnen Webentwicklungs-Frameworks. Die Aktualisierungszeiten der Komponenten weisen Nuxt als das schnellste Webentwicklungs-Framework aus. Next.js ist in diesem Zusammenhang das langsamste. In ähnlicher Weise scheint Google Chrome der schnellste Client-Browser zu sein. Desktop Safari ist der langsamste für die Aktualisierung des DOM nach Benutzereingaben.

Abstract

An essential initial step in every modern web application project is the selection of an appropriate web development framework. Often, detrimental decisions are made based on sentiment rather than a proper assessment of the framework's performance vs. the project requirements and resources.

This thesis presents a study of a model web application created identically with seven mainstream JavaScript web development frameworks: Angular, Astro, Next.js, Nuxt, React, Svelte and Vue.js.

Performance measurements are done with Lighthouse and Playwright tools to identify strengths and weaknesses of the frameworks. To this end, classic page load times and the load and update times of JavaScript components are retrieved among other data. Additionally, two new suitable derivative metrics are evaluated: the "Observed Visual Change Duration" and a "loadEventEnd" metric.

The results show no clear-cut general advantage of a single web development framework. Component update times indicate Nuxt as the fastest web development framework. Next.js is the slowest one in this context. Similarly, Google Chrome appears to be the fastest client browser. Desktop Safari is the slowest one for updating the DOM after user input

Disclaimer: This thesis has been written with the help of AI tools for translating sources and outlining parts of the written content. All content has been written or created by the author unless marked otherwise.

Contents

1	Introduction	4
2	Related Work	5
3	Setup of the application and test environment	6
3.1	Example Web Application	7
3.2	Choice of web frameworks	12
3.3	Hosting Environments	14
3.3.1	Vercel	15
3.3.2	Localhost	15
3.4	Performance Metrics	16
3.4.1	Page Load Times	16
3.4.2	Component Load Times	19
3.4.3	Component Update Times	20
3.5	Testing Tools	20
4	Implementation of the study	23
4.1	Component implementation	23
4.1.1	About Page	24
4.1.2	Create Page	26
4.1.3	MediaComponent	31
4.2	Configuration of testing tools	33
4.2.1	Lighthouse	34
4.2.2	Playwright	36
5	Evaluation	47
5.1	Page Load Times	47
5.2	Component Load Times	54
5.3	Component Update Times	59
6	Summary	63
7	Concluding remarks	66
A	Acknowledgements	68
B	Listings	68
C	List of Figures	72
D	Acronyms	73
E	References	74
F	List of Tables	77

1 Introduction

With the evolution of the world wide web, many changes have disrupted the way websites are created. From simple file servers run by few selected institutions, simple static web pages and dynamic services like blogs and forums to websites created with the help UI tools and web development frameworks, mainly written in JavaScript, development has changed drastically since its beginning.

Older web pages often lacked features that developers today work with as a matter of course. Yet their load and rendering most likely would be blazingly fast with today's technological advancements in networking, browser functionalities and user equipment. Modern websites though are often bigger in size, have a lot more features and are in many respects more complex. Due to the increased complexity, the mere volume of a website's data has increased, especially with more and more multimedia files. That in return has increased the demand for better performance on all components of the load and rendering process. This advancement has upped the technological sophistication for development tools as well. Today's modern web development frameworks support developers with tools to create sites and applications through terminal commands. They often increase the content-per-line-of-code quota through implicit page generation in contrast to the explicit writing of source code from earlier times. Many frameworks even feature configuration options for directly hosting the web page.

As the generation process changed from writing code manually to automatically, this implicit page generation undoubtedly increased speed through faster content generation and resulted in a greater development experience for some developers. Because developer experience varies between different frameworks and some approaches are more intuitive to respective developers, a current trend has evolved for developers to become experts in a single framework rather than many. This trend lead to a tribal conflict as to which framework is better than others with each tribe being convinced that their framework is the best. There is no apparent way to objectively determine a "best framework" in terms of developer experience because it is a subjective criterion. The performance of a framework as assessed by the developer can be similar or greatly different, depending on the frameworks and the interviewees.

When it comes to user experience and especially the perceived user experience however, there are plentiful collections of metrics and criteria to choose from so as to determine the performance of websites, not frameworks. The optimization of websites has become a goal during development because it has a real effect on both the ranking of web pages in search engines and the user behaviour. Both effects create business interests and financial incentives to invest resources into performance optimization (Li et al., 2010; Zhou et al., 2013). The lack of research on the topic suggests either a consensus for a negligible effect of the development framework on the website's performance or a lack of knowledge of the effect. Measurements on the effect of the development framework are a major convoluted task simply because the performance of a specific website can be dependent on many other factors such as the user's device, browser, networking hardware or server-side hardware. The number of possible combinations of factors and their reliability makes it difficult

to measure a single performance run with a reliable result. Every single result is only a small part of a large number of possible performances the same application could achieve with different parameters. It is therefore conceivable that a “perfect combination” of hard- and software exists for each framework or in general, but it is currently not possible to find such a combination because the necessary data is missing.

Many modern web tracking services provide data about the user, the user’s devices, current page load times and so on. This data is helpful in determining current poor performances and therefore possible starting points for optimization efforts. But it has very little information about recommended actions or recommended choice of frameworks for a redesign of a web application. Relying on marketing material for choice of frameworks is equally questionable because most modern frameworks claim to be fast, easy to use and performance efficient. This suggests that each would be a great choice for developers.

In order to find a suitable framework for an application, a set of metrics needs to be at least outlined for comparison. Many former studies suggest metrics to be relevant for the user experience or Search Engine Optimization. Content metrics such as word count or presence of meta tags might be important for some performance measurements, but might also have no effect on the user experience. In contrast, rendering metrics such as page load time or page weight might be ascribed to the framework used during development.

The performance of a framework towards the user can very rarely be compared because there are no publicly available comparisons between exact replicas of web applications built with different frameworks. Therefore, a comparative study between the same website built with different frameworks is needed to get as close as possible to an exact website replica. With this data, an informed choice might be made for other projects.

The goals of this thesis are to propose a set of metrics that allow comparing mainstream JavaScript frameworks for web applications, to provide a comparative study between selected frameworks and to create a tool to compare the rendering performance of a page as a whole and of dynamic components within a page.

2 Related Work

Methods, measurements and metrics for the performance of web applications have been used and interpreted in many past works. Domènech et al. (2006) propose a list of metrics used for prefetching resources as well as considerations for comparing results and interpreting measurements from a user’s perspective. The considerations for the selection of metrics heavily inspire the selection of metrics in this work. In addition, they list differences in the underlying base system, the tested workload and key metrics as problems for comparisons between pages and test suites and recommend using latency per page as a key performance metric from the user’s point of view. Crook et al. (2009) and Li et al. (2010) describe relevant non-technical considerations for performance indicators from a user’s and stakeholder’s perspective. The effect of user-focused measurements of web page speed is clearly

important to a site's effectiveness for objective goals, such as customer lifetime value and user retention (Li et al., 2010; Crook et al., 2009; Zhou et al., 2013). Also, variants and ambiguities cannot be definitively ruled out as the main source of both bad and good results of performance tests.

Most previous studies focus on network components and measurements for the evaluation of performance (Krishnamurthy and Wills, 2000; Grigorik, 2013; Sundaresan et al., 2013). However, these works also take network speeds with a grain of salt because delays such as propagation, transmission, processing and queueing of requests as well as factors like number of requests, network speed and latency heavily influence the results. Recommended best practices for testing networks from these papers include using multiple clients and server sites. Additional to these factors, caching is one of the most important strategies for network performance (Pourghassemi et al., 2019; Sundaresan et al., 2013).

Pourghassemi et al. (2019) separate the page load time into network activities and computation activities by splitting contributions to the load time between rendering jobs. They also point out the fluctuation of measurements due to the choice of browsers, especially the negative effect of mobile browsers towards load time. The network activities are described by Li et al. (2010), Grigorik (2013) and Sundaresan et al. (2013). In contrast, Zhou et al. (2013) point out that the content of a page has a much larger effect on the page load time than the client or network conditions.

Work on client optimization efforts include the effect of page load time on the user, selection strategies for tested pages and factors for the customers' perception of response time. According to Li et al. (2010), a delay of 100 ms results in a sales loss of 1 % and 500 ms delay lead to up to 20 % sales loss. A delay of one second, decreases the customer satisfaction by 16 % (Zhou et al., 2013). The customers' expectation in most cases are availability and response time and their perception is based on many factors (Menasce, 2002). The choice of tested pages is a difficult one because no usage data is available at build time and sitemaps only give hints about the pages' content and pages that are important to the site's effectiveness (Aqeel et al., 2020).

Lastly, Subraya (2006) gives guidelines to designing a web performance testing tool and points out attributes of good benchmark. Tests are based on stakeholders' expectations for load times and web pages are classified based on the complexity and interactivity of their content. This classification strategy is also applied in this work. Results show that the page load time is pivotal for the bail out percentage of users.

3 Setup of the application and test environment

Whereas the following chapters cover the implementation of testing and evaluation of results, this section introduces the conceptual design of the comparative study. The goals of and requirements for the example application, the differences and choices for the hosting environments for testing and the tools for testing as well as selected metrics are described here.

3.1 Example Web Application

The example application for the study is designed to be a benchmark application for testing. The following goals were considered during the design process:

1. **Page types:** With the goal of covering most kinds of web pages, three types were identified based on the time of data loading. These types differ in timing at which the DOM content is loaded or updated. The definition of a finished load or update for this work is that the linking of resources does constitute a finished load or update of the web page regardless of the load time of said resource on the condition that any linked resource does not update the DOM in any way. If a resource does mutate the DOM, then the load or update is considered not finished.
 - (a) Static pages are web pages which do not change their content after the initial response from the web server. The initial HTML document already is the only resource that is necessary to create a complete DOM. If inline scripts update the DOM, they are considered external resources.
 - (b) Delayed pages do not have a complete DOM after loading and parsing the initial HTML document. Some data or content is loaded and inserted (or removed) into the DOM after the initial render. The time of these updates can be any time after the initial render, but the execution of code or start of request for the resource that is responsible for the update has to be directly or indirectly triggered by the content of the initial DOM or HTML document.
 - (c) Dynamic pages can be updated or update themselves by events that are not triggered by the content of the initial DOM or HTML document. These events can either be triggered by user interaction or other events such as websocket messages. The time of such changes is by their nature not predictable. Dynamic pages are either static or delayed with additional opportunities for updates.

This list is created with the knowledge that frameworks or other technologies such as caching may move a web page from one type to another.

2. **Modern Development Practices:** The example application should contain modern development practices that do project onto the DOM. Practices that have no effect on either the projection of data or user interactions, such as coding styles or project management, are considered to have no effect on the performance of the page.
 - (a) Components: All pages of the app have to consist of components that encapsulate reproducible HTML snippets and may project data onto the DOM.
 - (b) List iteration: Because iterating long lists may decrease performance noticeably, some components or pages should implement list iteration.

- (c) String interpolation: Although it is not considered a performance issue before testing, string interpolation is prevalent in all modern frameworks known to the author.
- (d) Services: Separation of functions in services is a wide spread practice to reduce code duplicates and easy refactoring. In this case, services also allow to intentionally implement delays for testing purposes.

3. **CSS:** Even though the usage of CSS can in no way be considered a modern practice, it is still used on effectively every web page. Additionally, stylesheets are considered render-blocking resources that impact performance negatively (MDN Mozilla, 2024b; Google, 2019a). For this purpose, CSS shall be included in all pages and components.

4. **Rendering time:** In addition to the page type depending on the time of data load, the time of composing the DOM is dependent on the content availability. For this thesis, three different types are considered:

- (a) Client-side Rendering (CSR): The initial request gets a response with a mostly empty HTML document (“skeleton”) except linked CSS and JS resources which after loading, parsing and executing update the DOM.
- (b) Server-side Rendering (SSR): Updates that happen after receiving the skeleton through JS code execution on CSR happen before the initial request is responded to on the web server. The initial HTML document is filled and no longer a skeleton with SSR. Therefore, it has greater byte size. Server-side Rendering requires an “active” front-end server rather than only a file server to execute code.
- (c) Prerendering: Rendering happens during build time of the application. This increases the build time and the byte size of the initial HTML document, but only a file server is needed for hosting.

5. **Multimedia:** Most of network load and therefore network delay is caused by multimedia files. Although compression has gotten better over time, the byte size taken up by multimedia files of a web page has gotten larger over the last years (Meenan et al., 2024). Therefore, size optimization of image and video files is considered a major part of performance optimization and a great potential for a performance increase by the used framework.

Based on these considerations, the application “NotInstagram” was designed as a comparable example application. It is heavily inspired by the Android app Instagram and a partial reproduction of its app design (Instagram from Meta, 2024). “NotInstagram” consists of four pages (see figure 1). 1a shows the design of the Feed page. It is the start page of the app and contains 4 parts: the header, the profile list, the post list and a footer. Each item of the Feed page is to be implemented as its own component or components. The plus icon in the header links to the Create page, the footer links to the About page and every instance of a profile picture and profile name links to a Profile page. The latter contains profile information including a profile picture, name, user handle / ID, profile creation time, caption

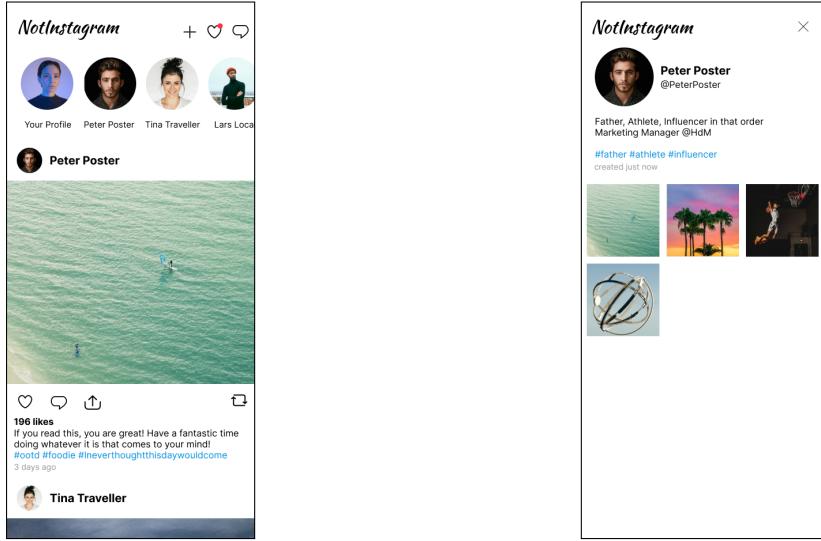
and a grid of all the user's posts (see figure 1b). The profile component encapsulates all HTML elements of that page except the header containing the app logo and X icon, which both link back to the Feed page. Both the Feed page and the Profile page are generally expected to classify as delayed pages, because the content of profile and posts lists can only be loaded after the page load.

The Create page (see figure 1c) has three parts. The header contains the app's logo and an X icon linking to the feed. A form with three input elements and a `<button>` element allows for the input of a multimedia source (image or video) and a text caption. The multimedia source can either be a URL or a selection from a list of preuploaded files. The post caption is a pure text input. The lower part of the page is the post preview, in which some predefined information such as user profile and the user inputs are combined. As such, the Profile page is a static page until the user uses the creation form, at which point it has to be considered a dynamic page. The About page (see figure 1d) is designed to statically display information about the application. It is a static page because no content is loaded after a delay and no user inputs are possible.

With these pages all page types are covered for testing. The About page and Create page are static, whereas the Feed page and Profile page are partly static (header and footer), but mostly delayed. The Create page is the only page with dynamic content.

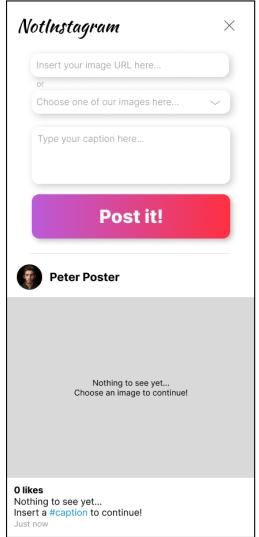
The data fetching and loading is designed to be implemented as services. For NotInstagram, two different services are needed. The PostService is a service for all components to query posts. The method `getAll()` returns a list of all posts by all users and `getByUserHandle(handle)` returns the same list filtered by those posted by a user with the handle equal to the function parameter. ProfileService is a service to query user profiles. It has the same two methods which return all user profiles and only one user profile respectively. Services are designed asynchronous, but the data is not queried from a server external to the browser, but hard coded. This design decision is based on the premise that delay can be coded into or out of asynchronous functions to mimic network delay for testing purposes if necessary.

Figure 2 describes the usage of components and services within page views. It displays the four pages of NotInstagram, the two services and 15 components. Seven of those components are icon components. Those components serve as wrappers for SVGs to ensure their correct scale and style. `XIcon` poses an exception to the design as it is a wrapper for a `PlusIcon` component rotated by 45°. The colored arrows show the usage of one of the services. Both the Feed page and the Profile Page use the services to load data. For the Feed page, both `PostService.getAll()` and `ProfileServices.getAll()` are needed to pass the data to `PostList` and `ProfileList`. Notably, each `Post` component accesses the ProfileService again, to get the profile image and name for its headline, even if the information is available in a parent or grandparent component. Figure 3 displays the connections between post and profile object instances. The member `userhandle` of a post references the member `handle` of a user profile. The Profile page needs access to the services in order to get the information of the requested profile and a list of posts from the `getByUserHandle` methods to pass into the `Profile` component. `LogoHeader`, `NotInstagramLogo` and `InfoBlock` are not data-presenting components, but rather

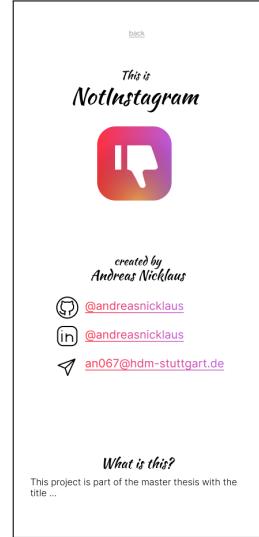


(a) Feed page (/)

(b) Profile page (/user/@PeterPoster)



(c) Create page (/create)



(d) About page (/about)

Figure 1: Screenshots of the NotInstagram application's pages (path in parentheses)

styling components. Their only function is styling text or projecting HTML elements with CSS information.

In contrast, the **MediaComponent** is designed as a way to allow both internal and external images and video sources. It is used by **ProfileList**, **Post** and **Profile** to display posts and profile images. Its main goal is to decide - based on the passed source string - how to project the multimedia file onto the DOM. The component accepts source strings for images and videos, differentiated by the string's ending and therefore the file's extension. If it is a local image, namely an image that was available for optimization at build time, the best available form of optimized `` tag should be used. For external image links starting with "http://" or "https://" a

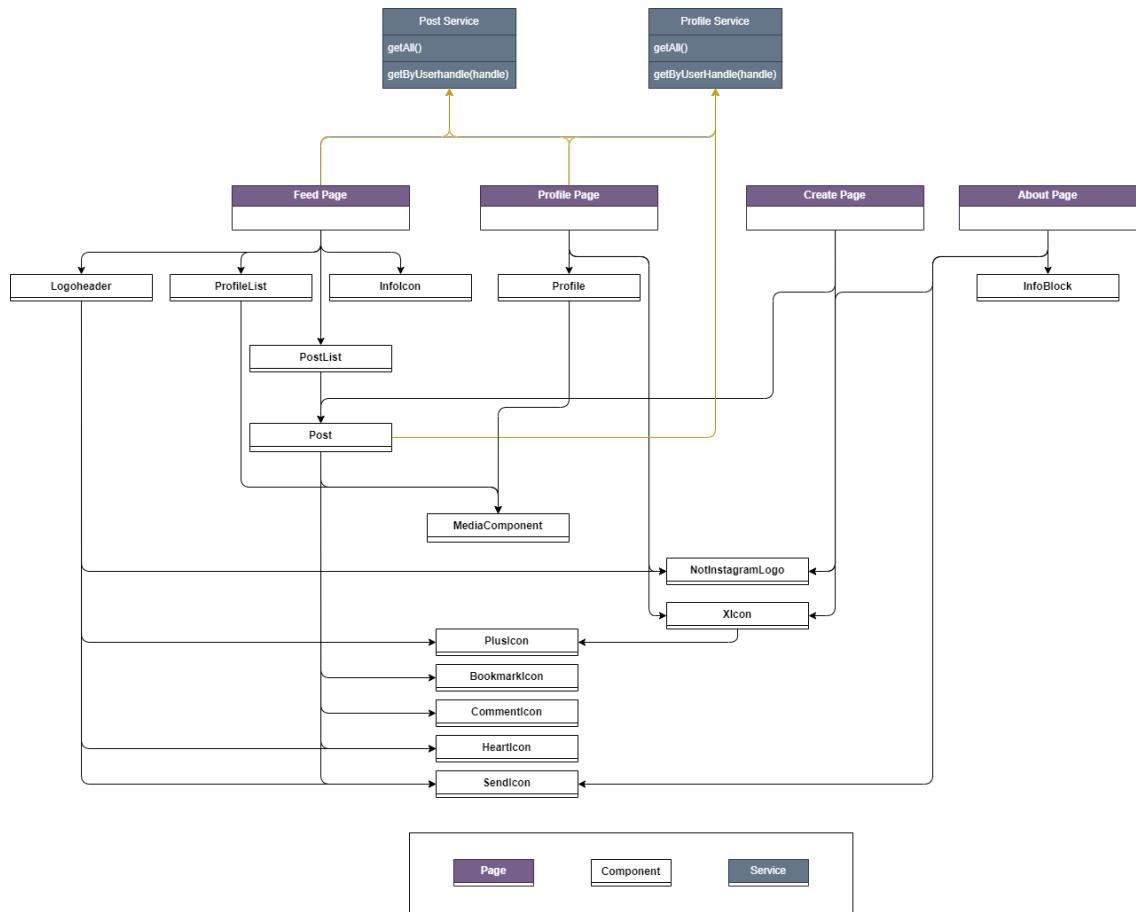


Figure 2: Pages, components and services of the NotInstagram application

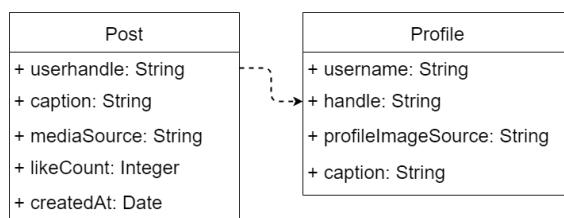


Figure 3: Classes used by the NotInstagram services

less optimized or unoptimized `` tag shall be inserted into the DOM. For videos, any source string is to be projected onto a `<source>` tag with identical `<video>` wrapper.

The application refers to local images, which can possibly be optimized, and external images, which cannot be optimized. The reason for this is the assumption for this project that optimizing multimedia files uploaded by a user and referencing them in a manner suitable for this application is not suitable for this study. Rather, the better alternative for serving the use case of the application would be a dedicated server for encoding, decoding and generally optimizing multimedia files. Since this solution would be independent from the front-end framework's performance and it would outgrow the scope of this work, a distinction is only made between static images, called local images here, and external images with full URLs.

3.2 Choice of web frameworks

The choice of tested frameworks for this study is the choice for which frameworks the application will be implemented in and tested. The requirements for this selection are twofold. The application has to be implementable as designed above with the framework without the use of any other non-native tool to the framework or any tool that was not officially intended to be used in combination by the developers of the primary framework. Additionally, the application must be implementable in JavaScript. This requirement includes TypeScript frameworks because it is possible to use JavaScript in TypeScript applications (Bierman et al., 2014). Ease of use and developer experience should explicitly not influence the selection process because it is not part of the performance of the resulting website.

Because research revealed in early stages of the study that many frameworks fulfill those requirements, the long list of candidates had to be sorted. The deciding factor for this selection was usage, awareness of and positive sentiment towards tools among developers because the evaluation of mainstream and general-purpose frameworks appear more valuable than lesser known or specialised tools. A ranking of the most-used JavaScript front-end frameworks of 2023 (Devographics, 2024)

	CSR	SSR	Previous Experience
Angular	yes	no	yes
Astro	yes	yes	yes
Next.js	no	yes	no
Nuxt	yes (generate)	yes (build)	no
React	yes	no	yes
Svelte	yes	no	no
Vue.js	yes	no	yes

Table 1: List of selected frameworks. Items with both Client-side Rendering (CSR) and Server-side Rendering (SSR) render some pages or components upon request, but also require Client-side Rendering (CSR). Previous Experience refers to the author's experience in developing web applications with the framework.

lists the four frameworks with the most developers who have used it before: React (84 %), Vue.js (50 %), Angular (45 %) and Svelte (25 %). In addition, Astro was chosen for its especially high awareness among the category “other front-end tools” (30 %), as well as its usage (19 %) and interest (62 %) in the category “meta-frameworks”. From the last category of tools, two other frameworks were selected: Next.js and Nuxt. Both tools are highly-used frameworks and have the appearance and goal of improving on React and Vue.js, respectively. For this reason, they are interesting choices for this study. All selected frameworks fulfill the requirements. The application is implementable with all frameworks or intended addition of tools. Next.js and Nuxt require the usage of React or Vue.js tools and dynamic components cannot be written in pure Astro (Schott, 2024a). Astro intends the usage of other frameworks to implement so-called “Islands”. For those components, React was chosen for its top usage rate.

Other frameworks were also considered for selection. Solid and Qwik seemed fitting candidates in this study because of high interest among developers without experience with the frameworks and apparent potential for fast performance of their end product. Additionally, from the ranking of most-used front-end frameworks Preact was at least considered with a usage percentage of 13 %. Ultimately, all three were not chosen because of negative sentiment or low usage among developers that do have experience with these frameworks. This concludes the framework selection for this study. Table 1 list the selection and categorizes them into groups with and without CSR and SSR. It also states whether the author of this thesis and developer for the application had any previous experience working with the framework. This information is important for the unintended performance optimizations and could later be used for interpretation of the frameworks performance measurements.

To summarize some comparisons between frameworks or groups of frameworks, the most appealing for the evaluation are the following:

1. **CSR - SSR:** Before testing, differences between CSR and prerendered pages are expected, but the metrics and amount of differences are probable subjects of interest. Because there is no perceivable difference between prerendered pages and server-side rendered pages from a client perspective, they are grouped together in this context.
2. **Angular - React - Vue.js:** Because these CSR frameworks have been competing for eight years at this point and they are still the most famous front-end frameworks (Devographics, 2024), the comparison of these frameworks is relevant for this study.
3. **Nuxt - Vue.js:** As a next generation of the Vue.js framework, the actual performance increase of Nuxt is interesting for developers.
4. **Next.js - React:** Same as above in relation to React.
5. **Vue-based - React-based:** Because a direct comparison of frameworks based on React and based on Vue.js is possible with multiple candidates, a difference in performance is an actual relevant factor for the choice between the two ecosystems.

6. **Svelte - Astro:** As the most recent popular frameworks in the selection of frameworks, Astro and Svelte have the potential to both outdo their contenders and outdo each other. This comparison is most interesting for fans of new tools and the development teams of the frameworks themselves.

3.3 Hosting Environments

After designing the application, the next step in the study process was to decide where the application is to be hosted for testing. Network delay is a great part of render delay and performance issues (Grigorik, 2013) because loading files in sequence will block rendering if parsing documents and executing code is dependent on network requests. The request delay is based on the speed of the web server, the network speed and the size of the generated file, request and response. Therefore the time needed for fulfilling network requests should be considered in the choice of hosting environment or service.

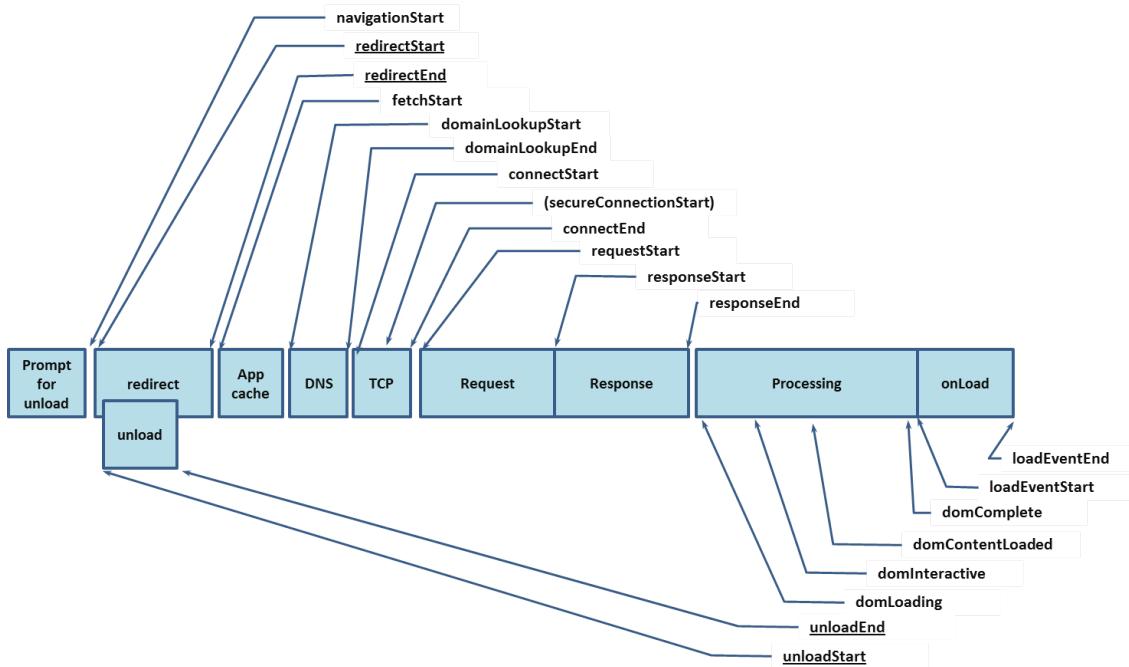


Figure 4: Timing attributes defined by the `PerformanceTiming` interface and the `PerformanceNavigation` interface (W3C, 2012)

Figure 4 illustrates how a slow network may delay the rendering process of a web page. The tests for this study shall cover real-world hosting using a publicly available service and local hosting to test the network delay and test the application without interference of network speeds. Additionally, tests can not be done only on local servers because tests shall include timings before `responseEnd`. Requirements for the distant hosting environment or service are threefold. The service shall have “active server capabilities”, meaning capabilities that exceed pure static files server functions for Server-side Rendering and similar functionalities. Furthermore, it is

required to be a widely used hosting service to ensure the real-world applicability of the study. Since this requirement is not clearly definable, it is considered a guideline. Lastly, to be applicable for small projects as well as established larger websites the service chosen for the study is required to support free usage and integration into a Continuous Integration and Continuous Delivery (CI/CD) pipeline because it is a widely used development practice. As such, the integration is important to require the least possible manual configuration for hosting the application because this study is not supposed to be about the configurability. Rather, the study shall focus on the "out of the box" performance of the frameworks. Continuing with that sentiment, the optimization and therefore configuration of the hosting environment is not part of this work. This is the methodology for answering the question: With which framework do developers get the best performance for their web applications without spending much or any time with optimization and configuration?

3.3.1 Vercel

Based on these considerations and personal experience with the service of the author previously to this project, Vercel was chosen for hosting the application. Vercel supports predefined configurations and automatic recognition of all frameworks chosen for this study. Also, Vercel projects integrate seamlessly into a CI/CD pipeline based on its integration with GitHub. A GitHub repository was created for each framework and connected to a Vercel project. During initialization of the Vercel projects and first preliminary tests, one problem with Vercel's free account quickly became apparent: The bandwidth limitation of 100GB per month and account was reached after two weeks of testing unoptimized and unfinished versions of the applications with large image and video files. Because no information was found on the effect of a reached limit, the account was deemed dead for the month. The solution to this problem was the creation a second free Vercel account and the plan to create another account every time the limit would be reached in the future, which it did not.

3.3.2 Localhost

Framework	Build Command	Host Command
Angular	<code>ng build</code>	<code>serve</code>
Astro	<code>astro build</code>	<code>astro preview</code>
Next.js	<code>next build</code>	<code>next start</code>
Nuxt	<code>nuxt build</code>	<code>nuxt preview</code>
	<code>nuxt generate</code>	<code>nuxt preview</code>
React	<code>react-scripts build</code>	<code>serve</code>
Svelte	<code>vite build</code>	<code>vite preview</code>
Vue.js	<code>vite build</code>	<code>serve</code>

Table 2: Build and host command for each used framework as used for testing the applications hosted locally

The second hosting solution for this study is hosting the application locally on the testing machine. The client device in question is a HP Envy x360 Convertible 15-eu0xxx with an AMD Ryzen 5 5500U processor and 16GB RAM. The operating system on the device is Windows 11 Home (Version 10.0.22631) during testing. This environment ensures minimal network load times and eliminates every other connected delay such as resolving domain names. If the framework supports a “preview” mode, it was used for hosting the application. Otherwise, the application would be build and hosted using the `serve` command or the active server would be started with `node <filename>`. If neither of the two options would be available, the “dev” mode of the application would be used and tested. Table 2 lists the used commands for building and starting the webserver per framework.

3.4 Performance Metrics

Slow load time and reactivity of a web page and its user interface decreases user retention and continuing user actions over time independently from the content (Li et al., 2010; Zhou et al., 2013). The “reaction time” is interpreted in three separate ways for this study: The page load time, meaning the time from navigation start to DOM mutation, the time from a state change, e.g. data query end, to DOM mutation, here called component load time, and the time between a user input to finished DOM mutation, called component update time for this study. Nearly most of these times can be combined from or described using navigation events (see figure 4). These timing categories are not exclusive, but measurements for these time categories do overlap (see table 3).

Naturally, other metrics than the navigation timings were also considered. From the list of measurements in Lighthouse reports (see chapter 3.5), sublists with relevant metrics were created to properly represent the time measurements of the described render sections and DOM mutation events. These reports cover the initial load of a page and visual content presentation after initial load. None of the Lighthouse metrics cover the time of DOM mutations after user input events. Therefore, yet additional measurements have to be considered to describe the performance of mutations. To this end, some self-written code is injected through Playwright (see chapter 3.5) to measure the time of updates to the DOM. The following sections describe which measurements are needed for each render section in detail.

3.4.1 Page Load Times

In the context of this study, the first contact point for a user to a web page is considered to be the first page load or initial page load. Within the initial load, the user’s main expectations and goals are assumed to be finding a page with the wanted information or input rather than finding the information itself. As a result, the aim of the client’s browser and render engine for this first time frame, called “page load” here, is to both parse HTML and project the content of the page onto the DOM. In order to focus on this time frame, these metrics describe the application’s performance.

- **Total Byte Weight (TBW):** The total size of files or response body directly

Page	Component	
Load Time	Load Time	Update Time
TBW	OLVC	
TTFB	OFVC	
TTI		
TBT		
LoadEventEnd		
DomContentLoaded	DOM Mutation Times	
LVC		
LCP		

Table 3: Assignment of metrics to the metric categories

increases either the App Cache time between `fetchStart` and `domLoading` or `domContentLoaded` if the resource can be cached in the client, or the response time between `responseStart` and `responseEnd` otherwise.

- **Time To First Byte (TTFB):** The time between `navigationStart` and `responseStart`. Most of the network delay can be described by the TTFB. Often inaccurately paraphrased as “ping”.
- **Time To Interactive (TTI):** The time until the page can be interactive is described by the DOM’s loading state. It is defined through navigation events as the time between `navigationStart` and `domInteractive`. Notably, the timing of `domInteractive` is not reliable because a DOM may become interactive, but the browser may not be interactive yet. Additionally, resources may still be loading. For example, a DOM from a HTML skeleton may be “interactive” after a few milliseconds, but no content may be rendered for the user to see, because CSR code is still loading (Web Hypertext Application Technology Working Group, 2024).
- **DomContentLoaded:** Similar to TTI, DomContentLoaded measures the time between `navigationStart` and `domContentLoaded`. At this point in time, “all subresources apart from async script elements have loaded” (Web Hypertext Application Technology Working Group, 2024). A large difference between TTFB and DomContentLoaded indicates a great size or at least long load time of subresources.
- **LoadEventEnd:** Total time spent immediately after initial load of a page until the DOM’s `onload` event is finished. This is the time from `navigationStart` to `loadEventEnd`. The time represents both the capability of the used framework to optimize the usage of a client’s and network’s resources on initial load and the prioritization of JavaScript execution by splitting not immediately needed code into async scripts. Therefore, it is a combined indicator for the code performance and general optimization.

- **Total Blocking Time (TBT):** The TBT is the total time spent by a browser with parsing and optionally resources that block the rendering process from finishing. This includes stylesheets and scripts without the `async` or `defer` tag. The metric directly represents the time before the browser can fulfill the user's goal on initial load.
- **Observed Last Visual Change (OLVC):** This is the time from `navigationStart` until the last visual change above the fold, meaning within the viewport of the user. Metrics with the “observed” are not throttled by the test tool.
- **Largest Contentful Paint (LCP):** The LCP is the time between navigation to the page and the time of rendering for the visually largest text or image element in the user's viewport (Google, 2020). Optimization of this metric requires an understanding of the page's content and element size within the viewport.

From this list of relevant metrics, some expectations can be formulated before measuring them.

1. TBT is most likely longer with CSR frameworks because the code execution filling the HTML skeleton takes some time that is not necessary in clients with SSR and Prerendered pages. On delayed pages this difference is expected to be very slight or nonexistent.
2. The LCP probably will not differ across frameworks, but naturally across pages. In contrast, if a framework does create a faster result for its LCP, it is expected to be a SSR or Prerendering framework because of its expected shorter TBT.
3. CSR frameworks differ from SSR and Prerendering frameworks by Total Byte Weight similar to Largest Contentful Paint. Although the HTML document is much slimmer with CSR, the JS files are expected to be equally larger than server-side rendered and prerendered pages. It is probably nearly equal in sum because the byte size of the page is likely mostly made up from multimedia files such as images and videos.
4. The selected frameworks should be inversely separable into groups by the Time To First Byte. Most likely CSR and Prerendering frameworks will be faster for this metric because the web server can serve as a static fileserver and does not have to execute any additional code.
5. Because CSR pages consist of only nearly empty HTML skeletons and links to JS and CSS files, the TTI is expected to be much faster for CSR pages.
6. The timing of the `loadEventEnd` is not clearly predictable before testing. The only expectation is that newer frameworks perform better in this metric simply because they are newer and are expected to make optimizations that go into a faster parsing and rendering of a web page.

3.4.2 Component Load Times

As a second category of relevant metrics, measurements for the separation of the app into components are grouped together. This category is designed to reflect the performance of the JavaScript that was generated by the framework. This stands in contrast to how much content can be rendered by the time of `responseEnd`. To this end, only measurements after `responseEnd` can be taken into consideration. Each mutation from the initial DOM has to be interpreted as an update to a component. The following metrics are part of this category.

- **LoadEventEnd**: as explained in section 3.4.1
- **Total Blocking Time (TBT)**: as explained in section 3.4.1
- **Time To Interactive (TTI)**: as explained in section 3.4.1
- **Observed First Visual Change (OFVC)**: The time of the first visual update from a blank canvas. It is an indicator for the start of visual rendering and a signal to a user that the page is working or loading. For pages with interactive elements, this metric is less important than the TTI.
- **Observed Last Visual Change (OLVC)**: The time of the last visual update to a web page. The metric is the most promising for this study as it indicates the end of the perceivable rendering process and therefore perceptible load speed.
- **Mutation Times**: Time from initialization of the app with a predetermined HTML element such as `<main>` to a DOM mutation. See section 3.4.3 for more info on this.

Based on the intention for the usage of these metrics, comparing or optimizing JavaScript frameworks, the following expectations were presented before tests.

1. Prerendered and SSR pages are expected to show an earlier FVC because the execution of any code for delayed components can start earlier. This expectation comes from the added code of CSR applications to add static elements to the DOM through JS.
2. CSR applications probably finish their LVC slightly earlier than other applications. The assumption for this prediction is that every application starts long tasks only after the HTML was parsed which takes longer for SSR or prerendered pages. As a result of these two expectations the observations of a `MutationObserver` most likely have a lower maximum and are less spread out for SSR and prerendered pages, but start later than CSR pages.
3. As described above, the TBT is expected to be slightly later for CSR than for SSR or prerendered applications.
4. CSR apps should have a slower TTI.

With these metrics, identifying bloated applications and components is the goal. JavaScript that is loaded, parsed and executed that increases the initial load time of a page should be indicated through these tests. Such unnecessary or render-blocking scripts are pointed out through TBT and little difference between FVC and LVC. For example, a script can be considered unnecessary for initial load if it is executed before rendering and only defines functions, initializes objects that are not yet needed, or creates a blocking dependency chain, e.g. through importing another script.

3.4.3 Component Update Times

For the third category of relevant metrics, DOM mutation stemming from events triggered by the user are grouped together. These events influence the user experience on the condition that they lead to DOM mutations. Only two kinds of measurements can be made to gain insight into the update speed.

- **User Input Times:** The time of a user input. The kind of user input is not restricted to `onInput` or `onChange` events, but rather any event triggered by the user.
- **Mutation Times:** Time of a mutation from user input within a predetermined HTML element such as `<main>` to another DOM mutation. A `MutationObserver` is initialized and all mutations are recorded. Designated mutations to the DOM are added child elements, removed child elements and attribute updates (added, edited and removed).

For these metrics no expectations could be formulated before testing because the speed of a mutation is purely based on the implementation of the framework itself. These implementations are not openly accessible without knowledge of the frameworks' source code. Still, some prediction can be made independently from a specific framework. Apps that represent their state in the DOM, e.g. an "edited" state for a user input or an updated value attribute of an `<input>` element, will most likely have ...

1. more entries in the recorded DOM mutations and ...
2. a later last entry in the recorded DOM mutations.

Also, the implementations of the app show differences here as additional elements, such as `<div>` elements as wrappers for each component can influence the time and number of updated elements in either direction, dependent on the use case.

3.5 Testing Tools

In order to test for these metrics, a set of multiple testing tools is needed. These testing tools are required to cover the measurements described above and the tools have to work with similar configuration for all selected frameworks. Test reports

have to be generated in a machine-readable format in order to evaluate the results and create aggregate metrics from them. This is a requirement because it is known from previous work that performance values in the web development context have a considerable variance. To this end, two different tools for automating tests were chosen:

1. **Lighthouse CLI:** The Lighthouse CLI makes it possible to automate the generation of Lighthouse reports. Tests for these reports combine measurements with weights in categories and reduce them to a single score, as well as five main category scores. These categories are performance, accessibility, best practices, Search Engine Optimization (SEO) and Progressive Web App (PWA). Additionally, Lighthouse reports contain recommendations for optimizing metrics and increasing the scores. It is a popular tool for measuring the initial page loads, page content and meta information for a website. Changes after the initial page load are not possible to test with the Lighthouse CLI. Reports are by default generated as HTML files, but the tool was configured to generate both HTML and JSON reports for this study. Since Lighthouse is designed to test live websites in production, the tool does not integrate starting a local development server. Testing with Lighthouse therefore needs to be manually joined with building and hosting the application locally while tests are running.
2. **Playwright:** Playwright features front-end testing tools for web applications in development. It mainly supports checking page content, but also supports the execution of injected JavaScript and full control over the browser. This also means that the control over the user inputs enables the measurement of timings connected to user behaviour such as clicking links and buttons, hover the mouse over elements or using `<input>` elements. Such options are needed to evaluate the timings of interactive elements. The development-focused design also bears the advantage of its initialization being included in some framework's initialization options. Both Svelte and Vue.js support installing and initializing configuration for Playwright in their own initialization (see chapter 4 for more on this). Similar to Lighthouse, reports can be created as HTML and JSON files. For this study, only JSON reports were used for the results, but HTML reports were used for debugging tests.

Although all requirements can be fulfilled with these tools, multiple problems were found with them. Because Lighthouse reports include data that is influenced by all actors and constraints regarding the web page, many factors contribute to the variability of its results. Google (2019b) lists possible sources for performance variability. The relevant sublist of factors for this study contains for local tests client resource contention, client hardware variability and browser nondeterminism. Client hardware variability is mitigated through the usage of the same client device for all tests (see section 3.3.2). Client resource contention could not be fully mitigated. Attempts to keep a lid on client resources were killing the most hardware intensive background tasks and services on the test machine before starting tests. Browser nondeterminism was taken into account and adopted as a test dimension because

the target group of an application should be factor for the choice of framework, especially for purely desktop or mobile applications. To this end, tests were executed with the most commonly used browsers wherever possible. For Lighthouse tests, such an option was not found. Instead, all tests were explicitly executed on Google Chrome for desktop. A Lighthouse report was not generated on other browsers.

For tests on a distant server, other factors contribute to the fluctuation of Lighthouse test results in addition. Local network variability, tier-1 network variability and web server variability have to be considered for the tests. The first two could not be mitigated. The internet connection speed at the test location was 100 Mbit/s to simulate common modern consumer internet connections in Germany (Gerpott, 2018). Web server variability could not be mitigated as well. For this reason, a hosting service was explicitly chosen for all tests to minimize the variability across frameworks (see section 3.3).

For mitigation of all factors of variability, Lighthouse tests were executed 20 times to gain an average of all measurements. The repetitions were configured with the same browser context and web server for local tests for each run. The reason for this decision is that fluctuations based on the first requests within the client or the server should be mitigated with this method.

Two additional problems with Playwright were found before the start of the test phase. The time of injection for JS scripts could not be properly determined. This fluctuation could not be mitigated. Also, reading data from the window context after the fact proved to be difficult because the context closes after the test ends and the report only contains the explicitly tested values. Objects such as the needed navigation timings are no longer available after the fact. The solution to this problem was to attach all necessary information as a file to the report so it is readable after the context is closed.

Lighthouse	Playwright
Total Byte Weight (TBW)	domContentLoaded
Time To First Byte (TTFB)	loadEventEnd
Time To Interactive (TTI)	User Input Times
Total Blocking Time (TBT)	Mutation Times
Largest Contentful Paint (LCP)	
First Visual Change (FVC)	
Observed First Visual Change (OFVC)	
Observed Last Visual Change (OLVC)	

Table 4: Assignment of metrics to the test tools

With all tools and workarounds in place, the data needed for the study could be collected. Lighthouse covers TBW, TTFB, TTI, TBT, LCP, FVC, OFVC and OLVC, whereas Playwright covers all navigation and HTML event times, namely DomContentLoaded, LoadEventEnd, user input times and mutation times (see table 4).

4 Implementation of the study

This chapter contains details of the implementation and the strategies for the creation of the project as well as for the separation of projects for each framework. The goal is to define taken steps to ensure reproducibility and traceability of implementation choices and, as a result, interpretability of the results in the following chapters.

The implementation for each framework was started using the official “get started” guide on the framework’s website (Google LLC, 2024; Schott, 2024b; Vercel, Inc., 2024; Chopin et al., 2024; Meta Platforms, Inc., 2024; Svelte, 2024; You, Evan, 2024). Each website provides a command which creates a project directory and project files. The initialization options for the creation process were chosen with the following rules.

1. The project is to be created as empty as possible to ensure the focus on the framework “as is” rather than how it can be configured. No demo project is chosen if an option with fewer preconfigured files is available.
2. No testing tools are to be preconfigured except Playwright. If Playwright is not an option, then no testing tool should be chosen.
3. Otherwise the default options (recommended or first) should be chosen. If “none” is an option, it should be selected.

After the initialization under these rules, the four web pages of the respective apps, their components and the routing between the pages were configured. After creation of the Vue.js and React app, each component’s template, code and style information was copied from either their Vue.js or React counterparts and adapted to the framework in order to speed up the creation process. Then, optimization efforts such as configuring image components (see section 4.1) and adaptation to the hosting environment were performed.

Additionally, project directories were separated into GitHub repositories. The separation is a requirement for hosting with Vercel because a maximum of three Vercel projects can be hosted from the same repository. This study exceeds this limit. This limiting condition entails that all testing configuration could not be centralized, but had to be duplicated across repositories. The setup of the testing environment has been the last step of the project creation (see section 4.2).

4.1 Component implementation

While most of the design decisions for the components of the application have been made during the design of the application itself, the design choices relating to the implementation of said components are open to adaptation to the framework. The goals for this implementation period are few:

1. The implementation for each framework should be as similar to the others as possible, meaning the HTML elements should be the same.

2. The implementation should follow the design language of the framework. Therefore no principles should translate from one implementation to another if they do not fit to the framework's design principles.
3. The implementation has to follow the component design as described in section 3.1. If the design of the example application cannot be followed, changes are to be as minimal as possible.

This section describes selected components and code snippets where they are either interesting for the performance, unforeseen choices or where they differ notably between frameworks. The author of this study has had the most experience with Vue.js prior to this project. For this reason, code snippets in Vue.js have the most presentability and code snippets in this paper are shown in Vue.js wherever possible. The components described in this section are the About as a opportunity for fast load times, the Create page as an example for dynamic pages and components and the MediaComponent for its implementation differences between frameworks.

4.1.1 About Page

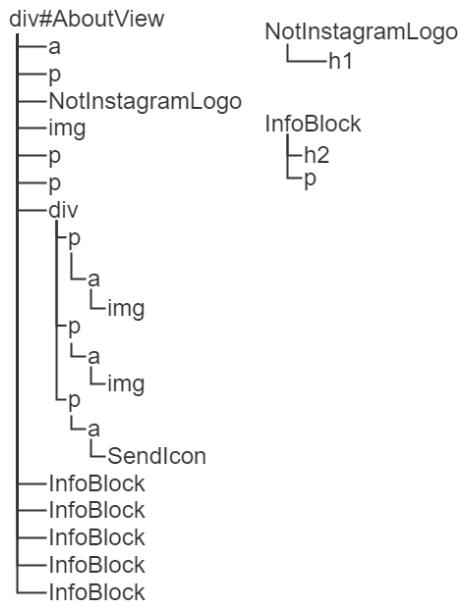


Figure 5: Graphical subdivision of the About page into components

The About page is an interesting case because, as described in section 3.1, it is the only static page of the application. Its components and HTML children are therefore also static. Figure 5 shows a graphical overview of the page's contents from a DOM perspective. Because of its static nature, it is also the only page that can be fully prerendered. Notably, the lower part of the page consists of multiple subcomponents `<InfoBlock>` with a title passed as a prop and a paragraph passed in a slot as a HTML child for the component. Functionally, its only purpose is styling and its only effect on the DOM is the addition of a `<h2>` and a `<p>` element.

The other imported subcomponents `<NotInstagramLogo>` and `<SendIcon>` are also wrappers for a `<h1>` and a `` element, respectively. Listing 1 demonstrates the static nature of the page view and the hard-coded addition of all text and multimedia in the template.

```

1  <!-- AboutView.vue -->
2  <template>
3    <div id="AboutView">
4      <RouterLink id="top-backlink" class="backlink" :to="{ name:
5        'Feed' }"> back </RouterLink>
6
7      <p class="cursive">This is</p>
8      <NotInstagramLogo />
9      
11
12      <p class="cursive">created by</p>
13      <p class="cursive big">Andreas Nicklaus</p>
14      <div id="socials">
15        <p>
16          <a href="https://github.com/andreasnicklaus"
17            target="_blank">
18            
20            @andreasnicklaus
21          </a>
22        </p>
23        <p>
24          <a href="https://www.linkedin.com/in/andreasnicklaus/"
25            target="_blank">
26            
28            @andreasnicklaus
29          </a>
30        </p>
31        <p>
32          <a href="mailto:an067@hdm-stuttgart.de">
33            <SendIcon/> an067@hdm-stuttgart.de
34          </a>
35        </p>
36      </div>
37
38      <InfoBlock title="What is this?">
39        This project is part of the master thesis by ...
40      </InfoBlock>
41      <InfoBlock title="Placeholder 1"><!-- ... --></InfoBlock>
42      <InfoBlock title="Placeholder 2"><!-- ... --></InfoBlock>
43      <InfoBlock title="Placeholder 3"><!-- ... --></InfoBlock>
44      <InfoBlock title="Placeholder 4"><!-- ... --></InfoBlock>
45      <InfoBlock title="Placeholder 5"><!-- ... --></InfoBlock>
46
47      <RouterLink id="bottom-backlink" class="backlink" :to="{ name:
48        'Feed' }"> back </RouterLink>

```

```

42      </div>
43  </template>

```

Listing 1: About page in Vue.js (as displayed in figure 5)

4.1.2 Create Page

The Create page poses an opposite to the About page. In contrast to a static page with non-changing content, the purpose of the Create page is to preview a new post. Its purpose is to update after user input. Listing 2 and 3 show the implementation of the Create page in Vue.js. The data of the component has four dynamic parts: The options and the choice for the selection of the post image in a `<select>` element, the caption of the new post and the media URL for the `<input>` element. The last data point for the component is the user handle, which is static for the preview in this example application. The computed property `mediaSource` (see listing 3, line 40) represents the logical choice between the media selection and source URL for the multimedia file in the previewed post. This template contains a static `<header>`, the `<form>` with dynamic attributes and a `Post` component. This subcomponent has to be dynamic and reactive to its props as they are changing throughout the process of post creation.

```

1  <!-- CreateView.vue -->
2  <template>
3    <header>
4      <RouterLink :to="{ name: 'Feed' }" > <NotInstagramLogo/>
5        </RouterLink>
6        <RouterLink :to="{ name: 'Feed' }" > <XIIcon/> </RouterLink>
7    </header>
8
9    <form id="newPostForm" action="" method="post">
10      <input type="url" name="mediaUrl" id="mediaUrl"
11        placeholder="Insert your media URL here..." 
12        v-model="mediaUrl" />
13      <p>or</p>
14      <select name="preloaded-image" id="preloaded-image"
15        v-model="mediaChoice">
16        <option value="">Choose one of our media files
17          here...</option>
18        <option v-for="media in preloadedMedia" :key="media"
19          :value="media">
20          <span>{{ media }}</span>
21        </option>
22      </select>
23      <textarea name="caption" id="caption" cols="30" rows="3"
24        placeholder="Type your caption here" v-model="caption"/>
25      <button type="submit" :disabled="!(caption && mediaSource)">
26        Post it! </button>
27    </form>
28
29    <hr />
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
559
560
561
562
563
564
565
566
567
568
569
569
570
571
572
573
574
575
576
577
578
579
579
580
581
582
583
584
585
586
587
587
588
589
589
590
591
592
593
594
595
596
597
597
598
599
599
600
601
602
603
604
604
605
606
606
607
607
608
608
609
609
610
610
611
611
612
612
613
613
614
614
615
615
616
616
617
617
618
618
619
619
620
620
621
621
622
622
623
623
624
624
625
625
626
626
627
627
628
628
629
629
630
630
631
631
632
632
633
633
634
634
635
635
636
636
637
637
638
638
639
639
640
640
641
641
642
642
643
643
644
644
645
645
646
646
647
647
648
648
649
649
650
650
651
651
652
652
653
653
654
654
655
655
656
656
657
657
658
658
659
659
660
660
661
661
662
662
663
663
664
664
665
665
666
666
667
667
668
668
669
669
670
670
671
671
672
672
673
673
674
674
675
675
676
676
677
677
678
678
679
679
680
680
681
681
682
682
683
683
684
684
685
685
686
686
687
687
688
688
689
689
690
690
691
691
692
692
693
693
694
694
695
695
696
696
697
697
698
698
699
699
700
700
701
701
702
702
703
703
704
704
705
705
706
706
707
707
708
708
709
709
710
710
711
711
712
712
713
713
714
714
715
715
716
716
717
717
718
718
719
719
720
720
721
721
722
722
723
723
724
724
725
725
726
726
727
727
728
728
729
729
730
730
731
731
732
732
733
733
734
734
735
735
736
736
737
737
738
738
739
739
740
740
741
741
742
742
743
743
744
744
745
745
746
746
747
747
748
748
749
749
750
750
751
751
752
752
753
753
754
754
755
755
756
756
757
757
758
758
759
759
760
760
761
761
762
762
763
763
764
764
765
765
766
766
767
767
768
768
769
769
770
770
771
771
772
772
773
773
774
774
775
775
776
776
777
777
778
778
779
779
780
780
781
781
782
782
783
783
784
784
785
785
786
786
787
787
788
788
789
789
790
790
791
791
792
792
793
793
794
794
795
795
796
796
797
797
798
798
799
799
800
800
801
801
802
802
803
803
804
804
805
805
806
806
807
807
808
808
809
809
810
810
811
811
812
812
813
813
814
814
815
815
816
816
817
817
818
818
819
819
820
820
821
821
822
822
823
823
824
824
825
825
826
826
827
827
828
828
829
829
830
830
831
831
832
832
833
833
834
834
835
835
836
836
837
837
838
838
839
839
840
840
841
841
842
842
843
843
844
844
845
845
846
846
847
847
848
848
849
849
850
850
851
851
852
852
853
853
854
854
855
855
856
856
857
857
858
858
859
859
860
860
861
861
862
862
863
863
864
864
865
865
866
866
867
867
868
868
869
869
870
870
871
871
872
872
873
873
874
874
875
875
876
876
877
877
878
878
879
879
880
880
881
881
882
882
883
883
884
884
885
885
886
886
887
887
888
888
889
889
890
890
891
891
892
892
893
893
894
894
895
895
896
896
897
897
898
898
899
899
900
900
901
901
902
902
903
903
904
904
905
905
906
906
907
907
908
908
909
909
910
910
911
911
912
912
913
913
914
914
915
915
916
916
917
917
918
918
919
919
920
920
921
921
922
922
923
923
924
924
925
925
926
926
927
927
928
928
929
929
930
930
931
931
932
932
933
933
934
934
935
935
936
936
937
937
938
938
939
939
940
940
941
941
942
942
943
943
944
944
945
945
946
946
947
947
948
948
949
949
950
950
951
951
952
952
953
953
954
954
955
955
956
956
957
957
958
958
959
959
960
960
961
961
962
962
963
963
964
964
965
965
966
966
967
967
968
968
969
969
970
970
971
971
972
972
973
973
974
974
975
975
976
976
977
977
978
978
979
979
980
980
981
981
982
982
983
983
984
984
985
985
986
986
987
987
988
988
989
989
990
990
991
991
992
992
993
993
994
994
995
995
996
996
997
997
998
998
999
999
1000
1000
1001
1001
1002
1002
1003
1003
1004
1004
1005
1005
1006
1006
1007
1007
1008
1008
1009
1009
1010
1010
1011
1011
1012
1012
1013
1013
1014
1014
1015
1015
1016
1016
1017
1017
1018
1018
1019
1019
1020
1020
1021
1021
1022
1022
1023
1023
1024
1024
1025
1025
1026
1026
1027
1027
1028
1028
1029
1029
1030
1030
1031
1031
1032
1032
1033
1033
1034
1034
1035
1035
1036
1036
1037
1037
1038
1038
1039
1039
1040
1040
1041
1041
1042
1042
1043
1043
1044
1044
1045
1045
1046
1046
1047
1047
1048
1048
1049
1049
1050
1050
1051
1051
1052
1052
1053
1053
1054
1054
1055
1055
1056
1056
1057
1057
1058
1058
1059
1059
1060
1060
1061
1061
1062
1062
1063
1063
1064
1064
1065
1065
1066
1066
1067
1067
1068
1068
1069
1069
1070
1070
1071
1071
1072
1072
1073
1073
1074
1074
1075
1075
1076
1076
1077
1077
1078
1078
1079
1079
1080
1080
1081
1081
1082
1082
1083
1083
1084
1084
1085
1085
1086
1086
1087
1087
1088
1088
1089
1089
1090
1090
1091
1091
1092
1092
1093
1093
1094
1094
1095
1095
1096
1096
1097
1097
1098
1098
1099
1099
1100
1100
1101
1101
1102
1102
1103
1103
1104
1104
1105
1105
1106
1106
1107
1107
1108
1108
1109
1109
1110
1110
1111
1111
1112
1112
1113
1113
1114
1114
1115
1115
1116
1116
1117
1117
1118
1118
1119
1119
1120
1120
1121
1121
1122
1122
1123
1123
1124
1124
1125
1125
1126
1126
1127
1127
1128
1128
1129
1129
1130
1130
1131
1131
1132
1132
1133
1133
1134
1134
1135
1135
1136
1136
1137
1137
1138
1138
1139
1139
1140
1140
1141
1141
1142
1142
1143
1143
1144
1144
1145
1145
1146
1146
1147
1147
1148
1148
1149
1149
1150
1150
1151
1151
1152
1152
1153
1153
1154
1154
1155
1155
1156
1156
1157
1157
1158
1158
1159
1159
1160
1160
1161
1161
1162
1162
1163
1163
1164
1164
1165
1165
1166
1166
1167
1167
1168
1168
1169
1169
1170
1170
1171
1171
1172
1172
1173
1173
1174
1174
1175
1175
1176
1176
1177
1177
1178
1178
1179
1179
1180
1180
1181
1181
1182
1182
1183
1183
1184
1184
1185
1185
1186
1186
1187
1187
1188
1188
1189
1189
1190
1190
1191
1191
1192
1192
1193
1193
1194
1194
1195
1195
1196
1196
1197
1197
1198
1198
1199
1199
1200
1200
1201
1201
1202
1202
1203
1203
1204
1204
1205
1205
1206
1206
1207
1207
1208
1208
1209
1209
1210
1210
1211
1211
1212
1212
1213
1213
1214
1214
1215
1215
1216
1216
1217
1217
1218
1218
1219
1219
1220
1220
1221
1221
1222
1222
1223
1223
1224
1224
1225
1225
1226
1226
1227
1227
1228
1228
1229
1229
1230
1230
1231
1231
1232
1232
1233
1233
1234
1234
1235
1235
1236
1236
1237
1237
1238
1238
1239
1239
1240
1240
1241
1241
1242
1242
1243
1243
1244
1244
1245
1245
1246
1246
1247
1247
1248
1248
1249
1249
1250
1250
1251
1251
1252
1252
1253
1253
1254
1254
1255
1255
1256
1256
1257
1257
1258
1258
1259
1259
1260
1260
1261
1261
1262
1262
1263
1263
1264
1264
1265
1265
1266
1266
1267
1267
1268
1268
1269
1269
1270
1270
1271
1271
1272
1272
1273
1273
1274
1274
1275
1275
1276
1276
1277
1277
1278
1278
1279
1279
1280
1280
1281
1281
1282
1282
1283
1283
1284
1284
1285
1285
1286
1286
1287
1287
1288
1288
1289
1289
1290
1290
1291
1291
1292
1292
1293
1293
1294
1294
1295
1295
1296
1296
1297
1297
1298
1298
1299
1299
1300
1300
1301
1301
1302
1302
1303
1303
1304
1304
1305
1305
1306
1306
1307
1307
1308
1308
1309
1309
1310
1310
1311
1311
1312
1312
1313
1313
1314
1314
1315
1315
1316
1316
1317
1317
1318
1318
1319
1319
1320
1320
1321
1321
1322
1322
1323
1323
1324
1324
1325
1325
1326
1326
1327
1327
1328
1328
1329
1329
1330
1330
1331
1331
1332
1332
1333
1333
1334
1334
1335
1335
1336
1336
1337
1337
1338
1338
1339
1339
1340
1340
1341
1341
1342
1342
1343
1343
1344
1344
1345
1345
1346
1346
1347
1347
1348
1348
1349
1349
1350
1350
1351
1351
1352
1352
1353
1353
1354
1354
1355
1355
1356
1356
1357
1357
1358
1358
1359
1359
1360
1360
1361
1361
1362
1362
1363
1363
1364
1364
1365
1365
1366
1366
1367
1367
1368
1368
1369
1369
1370
1370
1371
1371
1372
1372
1373
1373
1374
1374
1375
1375
1376
1376
1377
1377
1378
1378
1379
1379
1380
1380
1381
1381
1382
1382
1383
1383
1384
1384
1385
1385
1386
1386
1387
1387
1388
1388
1389
1389
1390
1390
1391
1391
1392
1392
1393
1393
1394
1394
1395
1395
1396
1396
1397
1397
1398
1398
1399
1399
1400
1400
1401
1401
1402
1402
1403
1403
1404
1404
1405
1405
1406
1406
1407
1407
1408
1408
1409
1409
1410
1410
1411
1411
1412
1412
1413
1413
1414
1414
1415
1415
1416
1416
1417
1417
1418
1418
1419
1419
1420
1420
1421
1421
1422
1422
1423
1423
1424
1424
1425
1425
1426
1426
1427
1427
1428
1428
1429
1429
1430
1430
1431
1431
1432
1432
1433
1433
1434
1434
1435
1435
1436
1436
1437
1437
1438
1438
1439
1439
1440
1440
1441
1441
1442
1442
1443
1443
1444
1444
1445
1445
1446
1446
1447
1447
1448
1448
1449
1449
1450
1450
1451
1451
1452
1452
1453
1453
1454
1454
1455
1455
1456
1456
1457
1457
1458
1458
1459
1459
1460
1460
1461
1461
1462
1462
1463
1463
1464
1464
1465
1465
1466
1466
1467
1467
1468
1468
1469
1469
1470
1470
1471
1471
1472
1472
1473
1473
1474
1474
1475
1475
1476
1476
1477
1477
1478
1478
1479
1479
1480
1480
1481
1481
1482
1482
1483
1483
1484
1484
1485
1485
1486
1486
1487
1487
1488
```

```

23     <Post :userhandle="userhandle" :caption="caption" :likeCount="0"
24       :mediaSource="mediaSource" :hideActionIcons="true" />
25   </template>

```

Listing 2: Create page in Vue.js (Template)

```

25 // CreateView.vue
26 export default {
27   name: "CreateView",
28   data() {
29     return {
30       preloadedMedia: [
31         "canyon.mp4", "abstract-circles.webp", ...
32       ],
33       userhandle: "@you",
34       caption: "",
35       mediaUrl: "",
36       mediaChoice: "",
37     };
38   },
39   computed: {
40     mediaSource() {
41       return this.mediaUrl || this.mediaChoice;
42     },
43   },
44 };

```

Listing 3: Create page in Vue.js (Script)

Listings 4 and 5 show the implementation of the Post component in Vue.js. It requires five props for the five data points of a post (see figure 3) and two additional props for the control over the design and loading behaviour of the post's image or video. Additionally, the `mounted` method loads the user data through the `ProfileService` (see listing 5, line 43). The template of the component uses `MediaComponent` twice, once for the profile picture and once for the post image or video. The attributes for the profile picture are mainly static because the user data is not edited through the create form. The attributes of the post multimedia are dynamic and editable except the class, width and height. Additionally, the projection of the post's caption onto the DOM is dynamic. Every time the caption changes, the string is split by whitespaces and each word is projected onto a `` element, so it can be styled as a hashtag if applicable. Afterwards, the list of `` elements is joined using whitespaces. The purpose of this projection method for the caption is only the styling of hashtags.

```

1  <!-- Post.vue -->
2  <template>
3    <div class="post">
4      <RouterLink v-if="user" :to="{ name: 'Profile', params: {
5        handle: userhandle } }" class="postUserInfo" >

```

```

5      <MediaComponent class="profileImage"
6          :src="user?.profileImageSource" alt="" width="44"
7          height="44" />
8      <span class="username">{{ user?.username }}</span>
9  </RouterLink>
10 <MediaComponent class="postMedia" :src="mediaSource"
11    :alt="caption" width="100%" height="100%"
12    :eagerLoading="eagerLoading" />
13 <div class="actionIconRow" v-if="!hideActionIcons">
14   <div class="leftActionIcons">
15     <HeartIcon />
16     <CommentIcon />
17     <SendIcon />
18   </div>
19   <BookmarkIcon />
20 </div>
21 <p class="likeCount">{{ likeCount }} likes</p>
22 <p class="caption">
23   <span v-for="(word, i) in caption.split(' ')" :key="i"
24     :style="word.startsWith('#') ? 'color: #0091E2' : ''">
25     {{ word }}{{ " " }}</span>
26   </p>
27   <p class="creationTime">{{ creationTimeToString }}</p>
28 </div>
29 </template>

```

Listing 4: Post in Vue.js (Template)

```

26 // Post.vue
27 import ProfileService from "@/services/ProfileService";
28
29 export default {
30   name: "Post",
31   props: {
32     userhandle: String,
33     caption: String,
34     mediaSource: String,
35     likeCount: Number,
36     createdAt: Date,
37     hideActionIcons: Boolean,
38     eagerLoading: { type: Boolean, default: false },
39   },
40   data() {
41     return { user: null };
42   },
43   mounted() {
44     ProfileService.getByHandle(this.userhandle).then((user) =>
45       (this.user = user));
46   },
47   computed: {
48     creationTimeToString() {
49       // ...
50     },
51   },
52 }

```

```
51 };
```

Listing 5: Post in Vue.js (Script)

Because the creation of such a dynamic component is an intended use case for Angular, Next.js, Nuxt, React, Svelte and Vue.js, their implementation is not unusual. Astro poses as an opposite to this. Because dynamic or reactive components are not implementable natively as Astro components, another framework has to be used in Astro Islands. For this reason, other components had to be invented in addition to the components as described in figure 2. `CreateForm` encapsulates the dynamic parts of the Create page. It is a React component with the form and post preview. Because Astro components cannot be used in Islands, every subcomponent used here had to be implemented with React as a duplicate to a native Astro component.

Listings 6, 7 and 8 show the implementation of this unique design in Astro. The Create component imports and inserts the React component `CreateForm` into HTML snippets for the page and marks it as a CSR component with `client:load` (see listing 7, line 18). From this component inwards, all HTML is generated on the client and purely as a React application. The `CreateForm` itself contains the form and Post subcomponent. Because of this structure, the components Post, MediaComponent, BookmarkIcon, CommentIcon, HeartIcon and SendIcon had to be implemented as Astro components and as React components. Figure 6 shows this updated component structure with Astro Islands.

```
1 // create.astro
2 export const prerender = false;
3 import HtmlWebpackPlugin from "../Layouts/HtmlLayout.astro";
4
5 import NotInstagramLogo from
6     "../components/NotInstagramLogo.astro";
7 import XIcon from "../components/icons/XIcon.astro";
8 import CreateForm from "../components/CreateForm.jsx";
9 import React from "react";
10 const userhandle = "@you";
```

Listing 6: Create page in Astro (Frontmatter)

```
11 <!-- create.astro -->
12 <HtmlLayout>
13     <header>
14         <a href="/"> <NotInstagramLogo /> </a>
15         <a href="/"> <XIcon /> </a>
16     </header>
17     <React.StrictMode>
18         <CreateForm userhandle={userhandle} client:load />
19     </React.StrictMode>
20 </HtmlLayout>
```

Listing 7: Create page in Astro (HTML)

```

1 // CreateForm.jsx
2 import { useState } from "react";
3 import styles from "./CreatePost.module.css";
4 import Post from "./Post";
5
6 const preloadedMedia = [
7   "canyon.mp4", "abstract-circles.webp", // ...
8 ];
9
10 const CreateForm = ({ userhandle }) => {
11   const [caption, setCaption] = useState("");
12   const [mediaUrl, setmediaUrl] = useState("");
13   const [mediaChoice, setmediaChoice] = useState("");
14
15   function mediaSource() { return mediaUrl || mediaChoice; }
16
17   return (
18     <>
19       <form id={styles.newPostForm} action="" method="post">
20         <input type="url" name="mediaUrl" id={styles.mediaUrl}
21           placeholder="Insert your media URL here..." value={mediaUrl} onChange={(event) => setmediaUrl(event.target.value)} />
22
23         <p>or</p>
24
25         <select name="preloaded-image" id="preloaded-image" value={mediaChoice} onChange={(event) => setmediaChoice(event.target.value)}>
26           <option value="">Choose one of our media files here...</option>
27           {preloadedMedia.map((media) => (
28             <option key={media} value={media}>{media}</option>
29           )));
30         </select>
31         <textarea name="caption" id={styles.caption} cols="30" rows="3" placeholder="Type your caption here" value={caption} onChange={(event) => setCaption(event.target.value)} />
32         <button type="submit" disabled={! (caption && mediaSource())}> Post it! </button>
33       </form>
34       <Post userhandle={userhandle} caption={caption} likeCount={0} mediaSource={mediaSource()} hideActionIcons={true} />
35     </>
36   );
37
38 export default CreateForm;

```

Listing 8: Create form in Astro

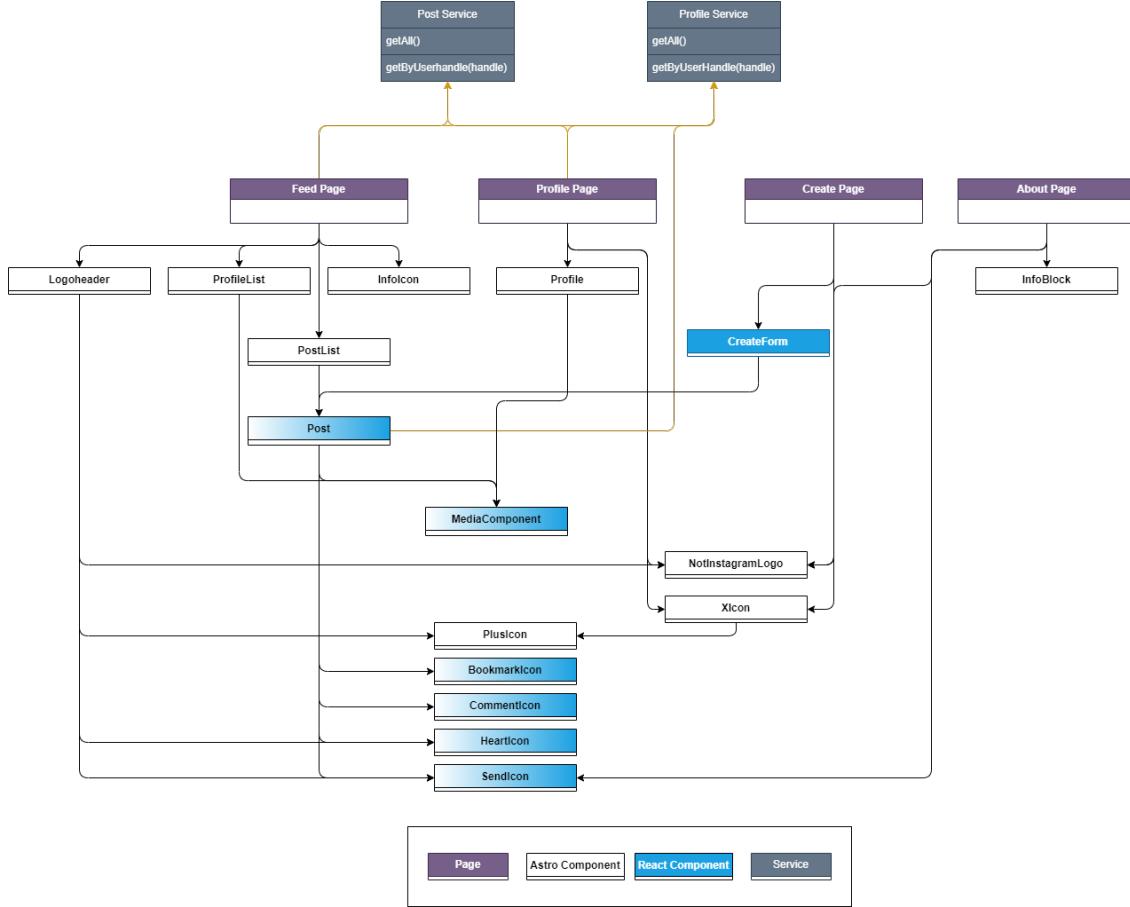


Figure 6: Adapted component structure for Astro Islands

4.1.3 MediaComponent

MediaComponent is a presenter component for multimedia content, namely an image or a video. It is used within the ProfileList, Profile and Post components (see figure 2). As described in section 3.1, the main use of this component for a developer is to centralize the optimization of multimedia files and to ensure its correct size and style. As such, it is a catch-all component for many kinds of multimedia sources. Listings 9 and 10 show parts of its implementation in Vue.js.

```

1  <!-- MediaComponent.vue -->
2  <template>
3    
4    <video ref="video" class="postMedia"
        v-else-if="mediaSource.endsWith('mp4')" :width="width"
        :preload="eagerLoading ? 'auto' : 'metadata'" controls
        controlslist="nodownload,nofullscreen,noreMOTEPLAYBACK"
        disablepictureinpicture loop muted >

```

```

5      <source :src="mediaSource" type="video/mp4" />
6  </video>
7  <div v-else class="mediaError" ref="mediaError">
8    <p>Nothing to see yet...<br />Choose an image to continue!</p>
9  </div>
10 </template>

```

Listing 9: MediaComponent in Vue.js (Template)

```

13 // MediaComponent.vue
14 import { playPauseVideo } from "@utils/autoplay.js";
15
16 export default {
17   name: "MediaComponent",
18   props: {
19     src: { type: String },
20     alt: { type: String, default: "" },
21     width: String,
22     height: String,
23     eagerLoading: { type: Boolean, default: false },
24   },
25   computed: {
26     mediaSource() {
27       if (
28         this.src == null ||
29         this.src == undefined ||
30         this.src.startsWith("http")
31       )
32         return this.src;
33       return new URL(`src/assets/stock-footage/${this.src}`,
34                     import.meta.url).href;
35     },
36   },
37   mounted() {
38     const video = this.$refs.video;
39     if (video) playPauseVideo(video);
40   },

```

Listing 10: MediaComponent in Vue.js (Script)

First, the component takes five props that can be passed to it as HTML attributes (see listing 10, line 18 ff.). The `src` string contains either the file name or URL to the file. The `alt` prop is the alternative text for an image to simple pass to the `alt` attribute of the `` tag, as well as the width and height of the image or video. These props are primarily needed for optimization of layout shifts and to optionally tell the browser which image variant is needed from a source set on the page. Lastly, the `eagerLoading` prop is a boolean indicator for whether the file needs to be loaded first (images) or preloaded fully (videos).

Second, the computed property `mediaSource` returns the correct link to either the image or video source based on the start of the `src` prop. This allows the component to identify faulty or external source URLs and only import needed

local multimedia files. This implementation design is unique to Vue.js and Nuxt. Looking at the implementation in React and Next.js, the same effect is achieved through the `useState` and `useEffect` hooks. The `ngOnChanges` hook is used in Angular. In Svelte, the `mediaSource` is defined with a leading `$:`, making it reactive. Because of its non-dynamic nature the native Astro component defines `mediaSource` statically server-side. On the other hand, the dynamic component uses the same implementation as the React application.

Third, every framework uses conditional rendering to project either an image, a video or an error message onto the DOM. Additionally, the Svelte component checks another condition: external and internal images. For image source strings starting with “http”, an HTML-native `` element is used, whereas the Svelte-native `<enhanced:img>` tag is used for all other images. The remaining frameworks use either one or the other method to insert images. Vue.js, React and Angular do not support enhanced image elements. These frameworks only include images using the `` tag. In contrast, Astro, Next.js, Nuxt and Svelte do have components that improve the performance of image elements. Astro natively supports an `<Image>` component that outputs an `` tag with optimized attributes. Next.js comes with another `<Image>` component that optimizes images with a predefined width and height and Nuxt has a `<NuxtImg>` component to optimize images and define presets for its images. Svelte is the only one of this group that does not support full URLs to be passed to its enhanced image component.

Fourth, the attributes of the `` elements are designed to optimize their load performance, size and image quality. While no way to optimize the size and quality of the source of simple `` elements is apparent, the load performance is adapted to the usage of a `<MediaComponent>`. The first Post of a PostList is always eager-loaded, whereas all other images are lazy-loaded. The size of the bounding box of the image is also defined in order to prevent layout shifts during or after the loading of the image. Enhanced image components are configured to ideally optimize the size and quality of the requested image, as well as to insert blurry placeholder images if possible.

The `<video>` elements are designed to optimize the load behaviour of the browser and to change the default presentation and styling. Each video has a defined width and height, playback behaviour and controls. In order to come as close to the application’s model, Instagram, videos should autoplay, but be muted by default. Each single behaviour is a single attribute to set, but autoplaying every video requires each to be loaded immediately on page load. This network load bears a performance decrease. For this reason, only the metadata is preloaded unless it is the first post in the PostList. To ensure the wanted autoplay feature, each `<video>` element is referenced using the framework and custom code ensures that videos play when they are in the viewport and pause when they are outside of it. This is achieved using an `IntersectionObserver` (MDN Mozilla, 2024a).

4.2 Configuration of testing tools

As described above, the implementation of tests and test configuration were the last step in the process of project creation. As such, tests were either left “as is” or not

configured until the application could be considered “done”. The test suite for this project can be split into two halves: Lighthouse CLI automation and Playwright tests (see section 3.5). Lighthouse is used to mostly cover aggregate metrics, while Playwright is used to export navigation and HTML event times.

4.2.1 Lighthouse

To this end, a script was written to automate the execution of Lighthouse tests and to store Lighthouse reports in a comprehensive way. Listing 11 shows parts of the implementation of the testing script. It reads project configurations from an external configuration file and iterates over them, executing the tests for every framework multiple times. Listing 12 contains an excerpt of the configuration file. Every project is built and hosted, if either a host command, e.g. using `npm run <script>`, or a serve command using `serve` is defined in the configuration file. While the application is hosted, a headless Google Chrome browser window is launched and multiple lighthouse tests are preformed. The report is generated using the URL as it is specified in the configuration and with static options. These options define among other things that an HTML report is to be generated, only performance metrics are to be collected and the HTTP status code is to be ignored. The last option is necessary because web servers started using `serve` return a 404 status code for files that do not exist in the hosted directory. For applications that rely on `index.html` to be returned if a requested resource is not available, this behaviour is not desired. For example, requesting the defined path `/about` results in a 404 code with the `index.html` file as the response body. Without the option `ignoreStatusCode: true`, the Lighthouse test would fail as the page is considered to be unavailable.

```
1 // testing-script/index.js
2 // ...
3
4 function build(projectConfig) {
5   return new Promise((resolve, reject) => {
6
7   if (projectConfig.buildCommand) {
8     logger.info("Starting build...")
9     exec(`${projectConfig.buildCommand}`, /* ... */)
10  }
11  else {
12    logger.info("Skipping build because buildCommand was not
13      specified")
14    resolve()
15  }
16}
17}
18
19 // ...
20
21 for (let projectConfig of config.projects) {
```

```

22  // ...
23  // BUILD PHASE
24  await build(projectConfig)
25
26  // STARTING HOST PROCESS
27  // ...
28
29  // START LIGHTHOUSE TEST
30  logger.info("Starting lighthouse tests...")
31  const url = projectConfig.url
32  const chrome = await chromeLauncher.launch( { chromeFlags:
33      ['--headless'] } );
34  const options = { logLevel: 'warn', output: 'html',
35      onlyCategories: ['performance'], port: chrome.port,
36      ignoreStatusCode: true };
37
38  for (const route of (projectConfig.paths || ["/"])) {
39      // ...
40
41      for (let i = 0; i < config.runsPerProject; i++) {
42
43          const runnerResult = await lighthouse(url + route, options);
44
45          const { report: reportHtml, artifacts, lhr } = runnerResult;
46          const { timing, fetchTime, categories, ...rest } = lhr
47
48          fs.mkdirSync(` ${projectConfig.reportDirectory}${route == "/" ?
49              "/index" : route}`, { recursive: true }, (err) => {
50              if (err) throw err;
51          });
52          fs.writeFileSync(` ${projectConfig.reportDirectory}${route == "/"
53              ? "/index" : route}/lighthouse-report-${new
54                  URL(url).hostname}-${dateToUriSafeString(new
55                  Date())}.html`, reportHtml);
56          fs.writeFileSync(` ${projectConfig.reportDirectory}${route == "/"
57              ? "/index" : route}/lighthouse-report-${new
58                  URL(url).hostname}-${dateToUriSafeString(new
59                  Date())}.json`, JSON.stringify({ artifacts, lhr }, null,
60          2));
61
62          // ...
63      }
64
65  }
66
67  await chrome.kill();
68  if (serverCommand) await stopServer(hostProcess, projectConfig)
69 }
70
71 logger.info("ALL DONE")

```

Listing 11: Automation script for Lighthouse tests

```

1 // testing-script/config.js
2 export default {
3   runsPerProject: 20,
4   preferredServeCommand: "serve",
5   projects: [
6     // ...
7     {
8       name: "Svelte on Vercel",
9       reportDirectory: "./reports/ig-clone-svelte/vercel",
10      url: "https://ig-clone-svelte.vercel.app",
11      paths: ["/", "/about", "/create", "/user/@PeterPoster"]
12    },
13    // ...
14    {
15      name: "Svelte",
16      projectPath: "../ig-clone/ig-clone-svelte",
17      buildCommand: "npm run build",
18      serveCommand: "npm run preview",
19      reportDirectory: "./reports/ig-clone-svelte/localhost",
20      url: "http://localhost:4173",
21      paths: ["/", "/about", "/create", "/user/@PeterPoster"]
22    },
23    // ...
24  ]
25 }

```

Listing 12: Test configuration for Lighthouse tests

Once the test results are available, the relevant metrics are collected, stored in a JSON file and the HTML report is stored as a means to debugging. After the tests are finished and results are stored, the Google Chrome window is killed and the webserver is stopped.

In order to evaluate and summarize the collection of tests performed using the automation script, another script was written so that test summaries are created. This report reader iterates over the list of JSON files and calculates the average per metric, route and project configuration from the configuration file. It makes it easier to compare the test results and interpret the performance of the frameworks (see chapter 5).

4.2.2 Playwright

Similar to the test method for Lighthouse, Playwright tests can be triggered using a script to unify the output files. Listing 13 shows the implementation of this trigger script. Project directories are defined and the test command is executed in the directory with the configured environment variables. Playwright is told to not open a report even if a test fails through PW_TEST_HTML_REPORT_OPEN.

```

1 // playwright-trigger.mjs
2 import { spawn } from 'child_process'
3
4 const projects = [
5   // ...
6   {
7     name: "IG Clone Svelte",
8     cwd: "ig-clone-svelte"
9   },
10 ]
11
12 const testArguments = [/* "./change\\.spec\\.js/" */]
13 function generateUriSafeTimestamp() {/* ... */}
14 // ...
15
16 for (const project of projects) {
17   // ...
18   const now = new Date()
19   const reportDirectory =
20     'playwright-report-${generateUriSafeTimestamp()}'
21
22   await new Promise(resolve => {
23     const testProcess = spawn("npm", ["run", "test:e2e",
24       ...testArguments], {
25       cwd: project.cwd,
26       shell: true,
27       env: {
28         ...process.env,
29         PW_TEST_HTML_REPORT_OPEN: 'never'
30       }
31     })
32   // ...
33 })
34 }

```

Listing 13: Trigger script for Playwright tests

```

1 // ig-clone-vue/playwright.config.js
2 import process from 'node:process'
3 import { defineConfig, devices } from '@playwright/test',
4
5 export default defineConfig({
6   testDir: './tests',
7   timeout: 60 * 1000,
8   expect: { timeout: 5000 },
9   retries: 2,
10  workers: 1,
11  reporter: [[ 'html' ], [ 'json', { outputFile:
12    'playwright-report/test-results.json' } ]],
13  use: {
14    baseURL: 'http://localhost:3000',
15    trace: 'on',
16    headless: true
17  },
18  projects: [

```

```

19     { name: 'Chromium', use: {...devices['Desktop Chrome']} },
20     { name: 'Firefox', use: {...devices['Desktop Firefox']} },
21     { name: 'Desktop Safari', use: {...devices['Desktop Safari']} }
22     },
23     { name: 'Mobile Chrome', use: {...devices['Pixel 5']} },
24     { name: 'Mobile Safari', use: {...devices['iPhone 12']} },
25     { name: 'Microsoft Edge', use: {channel: 'msedge'} },
26     { name: 'Google Chrome', use: {channel: 'chrome'} },
27   ],
28   webServer: {
29     command: 'vite build && serve -sd dist',
30     port: 3000,
31     reuseExistingServer: true
32   }
33 })

```

Listing 14: Playwright configuration for Vue.js

The tests and test configuration are similar for all frameworks. Listing 14 shows how the test suite is configured. Timeouts are defined for all tests so that even slowly loading pages are tested properly and retries are specified to repeat failing tests twice. The reason for this specification is that fluctuating timings close to the limit of failure should be tested multiple times to ensure that the test is supposed to fail. Unfortunately, repetitions cannot be configured for the opposite case in which the test passes because of fluctuations, but is supposed to fail on average. All test executions and repetitions are configured to run in sequence to minimize the influence of the availability of resources on the testing machine. This is especially important because Playwright both opens the application in a browser and runs a webserver for local tests. It is set to start a webserver, wait for its availability and then open the application under the specified `baseURL`. The webserver command, port and `baseURL` are different for every framework. The test configuration also specifies a list of browsers to test the application in. For this study, seven browsers were chosen based on the most used browsers (StatCounter, 2024) and their mobile versions. The browsers are Chromium, Google Chrome, Mobile Chrome, Safari, Mobile Safari, Microsoft Edge and Firefox.

The tests written for this application are threefold as they reflect the separation of performance metrics (see section 3.4). Listings 15, 17 and 19 show the test files.

First, page load times are measured using `page-load.spec.js` (see listing 15). Every defined route is opened in a browser window, the navigation timings are extracted through a `page.evaluate(<evalFunction>)` method and the timings are attached and annotated so that they can be read after the test execution. The test for every page is that the timings `loadEventEnd` and `domComplete` are faster than a time budget. The paths and time budget per page configed in `pages.js` (see listing 16). To ensure a fast performance, the time budgets are defined to be under two seconds for all pages. Because no network requests are made in the design of the application on the About page, the time budget was lowered to 1.5 seconds here.

```

1 // page-load.spec.js
2 import { test, expect } from '@playwright/test';
3 import routes from './pages.js'
4
5 test.describe("Load Time", () => {
6   for (const route of routes) {
7     test(`${route.name} loads within the page load budget`, { tag:
8       ['@${route.name}', '@pageLoad'] }, async ({ page },
9       TestInfo) => {
10
11       await page.goto(route.path)
12       await page.waitForLoadState()
13
14       const timing = await page.evaluate(() =>
15         performance.getEntriesByType('navigation'));
16       TestInfo.attach("timing.json", { body:
17         JSON.stringify(timing, null, 2), contentType:
18         "application/json" })
19
20       const [responseStart, responseEnd,
21         domContentLoadedEventEnd, domComplete, loadEventEnd] =
22         timing;
23
24       test.info().annotations.push({ type: 'Page Load Budget',
25         description: 'The time budget for this page was
26         ${route.pageLoadBudgetMs}ms' });
27     // ...
28
29       expect.soft(domComplete, 'domComplete event should happen
30         within ${route.pageLoadBudgetMs}
31         ms').toBeLessThanOrEqual(route.pageLoadBudgetMs)
32       expect.soft(loadEventEnd, 'loadEventEnd event should happen
33         within ${route.pageLoadBudgetMs}
34         ms').toBeLessThanOrEqual(route.pageLoadBudgetMs)
35     })
36   }
37 })

```

Listing 15: Test file for page load times

```

1 // pages.js
2 const routes = [
3   { name: "Feed page", path: "/", pageLoadBudgetMs: 2000 },
4   { name: "About page", path: "/about", pageLoadBudgetMs: 1500 },
5   { name: "Create page", path: "/create", pageLoadBudgetMs: 2000 },
6   { name: "Profile page", path: "/user/@PeterPoster",
7     pageLoadBudgetMs: 2000 },
8 ]
9 export default routes;

```

Listing 16: Test pages configuration

Second, `dynamic-performance.spec.js` describes how component load times are measured. The same routes are opened after an initialization script is injected into the browser window. Listings 17 and 18 show parts of the test definition and the injected script. The latter waits for a specific element to appear in the DOM that does not appear in the HTML skeleton, if it exists. The element in question has a predetermined `id`. For Angular, Astro, Next.js, Svelte and Vue.js it is “`app`”, for Nuxt it is “`__nuxt`” and for React it is “`root`”. Afterwards, it initializes a `MutationObserver` on that element. Each observation is stored with an `xpath`, `id` and the last mutation time. The mutation time is overwritten every time so that only the latest update is recorded and the list of times is published as a member of the `window` object. Recorded mutations are added or removed children, addition or removal of the element itself and a `changed` attribute. Because the time of mutation is only measured as the time difference to the addition of the application-specific root element, the recorded times are an estimation of the execution time between framework initialization and the latest DOM mutation.

The test script waits for ten seconds after the injection of the recording script and then evaluates the recorded timings. The update times are also attached to the test as a JSON file so that they can be traced after the test context no longer exists. In order for the test to pass for the page the latest DOM mutation needs to happen within the page’s load time budget. In order to trace the failing components more easily, screenshots are taken of each slow HTML element. Additionally, a screenshot of the whole page is taken in which slow elements are colored. Every screenshot is then attached to the test. This method ensures that slow components can be identified visually even if the `xpath` and the `id` of the element changes between component lifecycles or application builds.

```

1 // dynamic-performance.spec.js
2 import { test, expect } from '@playwright/test';
3 import routes from './pages'
4
5 test.describe("Dynamic load time", () => {
6   for (const route of routes) {
7     test('Dynamic components on ${route.name} load within the load
8       budget', { tag: ['@${route.name}', '@componentLoad'] },
9       async ({ page }, TestInfo) => {
10       // Inject performance measurement script into the page
11       await page.addInitScript({ path: './tests/performance.js' })
12
13       // Go to the measured page
14       await page.goto(route.path)
15       await page.waitForLoadState('domcontentloaded')
16
17       // Start evaluation
18       const latestUpdateComponents = await new Promise(resolve =>
19         setTimeout(resolve, 10_000)).then(() => {
20         // Return the sorted load times
21         return page.evaluate(() => {
22           if (!window.dynamic_component_performance) return null
23           // Sort the components by their latest dom update time
24         })
25       })
26
27       // Take screenshots of the slow components
28       const slowComponents = latestUpdateComponents.filter(component =>
29         component.loadTime > 1000)
30       const slowElements = slowComponents.map(component =>
31         page.locator(component.xpath))
32
33       // Take a screenshot of the whole page with slow components highlighted
34       const screenshot = await page.screenshot({ path: 'slow-components.png' })
35       TestInfo.attach('Slow components screenshot', screenshot)
36     })
37   }
38 })

```

```

21     const sortedEntries =
22       Object.entries(window.dynamic_component_performance)
23         .map(([key, value]) => { return { id: key, ...value } })
24       .sort((a, b) => a.lastUpdated - b.lastUpdated)
25     return sortedEntries
26   })
27
28   // Attach the measurements in JSON format
29   TestInfo.attach("update-times.json", { body:
30     JSON.stringify(latestUpdateComponents, null, 2),
31     contentType: "application/json" })
32
33   latestUpdateComponents.forEach(comp => {
34     const latestUpdateTime = comp.lastUpdated
35
36     // Assert the latest update occurs in time
37     return expect.soft(latestUpdateTime, 'Component with
38       identifier ${comp.id} should load within
39       ${route.pageLoadBudgetMs}
40       ms').toBeLessThan(route.pageLoadBudgetMs)
41   })
42
43
44   // Create screenshots of slow components
45   const componentScreenshots = await Promise.all(
46     latestUpdateComponents.map((el) => {
47       if (el.lastUpdated > route.pageLoadBudgetMs) {
48         return
49         page.locator(el.id).screenshot().then(screenshot =>
50           [el, screenshot])
51       }
52     }).filter(i => i)
53   )
54
55   // Capture a screenshot of the whole page with highlighted
56   // slow components
57   if (latestUpdateComponents.some(comp => comp.lastUpdated >
58     route.pageLoadBudgetMs)){
59     // ...
60   }
61
62   // Attach the screenshots of the slow components to the test
63   await Promise.all(componentScreenshots.map(([el,
64     screenshot]) => {
65     return TestInfo.attach(
66       `${el.id}-${el.lastUpdated}ms.png`, {body:
67         screenshot, contentType: 'image/png' })
68   })
69
70   })
71
72   })
73 }
74
75   })
76
77   })
78 }
79
80   })
81
82   })
83
84   })
85
86   })
87
88   })
89
90   })
91
92   })
93
94   })
95
96   })
97
98   })
99
100  })
101
102  })
103
104  })
105
106  })
107
108  })
109
110  })
111
112  })
113
114  })
115
116  })
117
118  })
119
120  })
121
122  })
123
124  })
125
126  })
127
128  })
129
130  })
131
132  })
133
134  })
135
136  })
137
138  })
139
140  })
141
142  })
143
144  })
145
146  })
147
148  })
149
150  })
151
152  })
153
154  })
155
156  })
157
158  })
159
160  })
161
162  })
163
164  })
165
166  })
167
168  })
169
170  })
171
172  })
173
174  })
175
176  })
177
178  })
179
180  })
181
182  })
183
184  })
185
186  })
187
188  })
189
190  })
191
192  })
193
194  })
195
196  })
197
198  })
199
200  })
201
202  })
203
204  })
205
206  })
207
208  })
209
210  })
211
212  })
213
214  })
215
216  })
217
218  })
219
220  })
221
222  })
223
224  })
225
226  })
227
228  })
229
230  })
231
232  })
233
234  })
235
236  })
237
238  })
239
240  })
241
242  })
243
244  })
245
246  })
247
248  })
249
250  })
251
252  })
253
254  })
255
256  })
257
258  })
259
260  })
261
262  })
263
264  })
265
266  })
267
268  })
269
270  })
271
272  })
273
274  })
275
276  })
277
278  })
279
280  })
281
282  })
283
284  })
285
286  })
287
288  })
289
290  })
291
292  })
293
294  })
295
296  })
297
298  })
299
300  })
301
302  })
303
304  })
305
306  })
307
308  })
309
310  })
311
312  })
313
314  })
315
316  })
317
318  })
319
320  })
321
322  })
323
324  })
325
326  })
327
328  })
329
330  })
331
332  })
333
334  })
335
336  })
337
338  })
339
340  })
341
342  })
343
344  })
345
346  })
347
348  })
349
350  })
351
352  })
353
354  })
355
356  })
357
358  })
359
360  })
361
362  })
363
364  })
365
366  })
367
368  })
369
370  })
371
372  })
373
374  })
375
376  })
377
378  })
379
380  })
381
382  })
383
384  })
385
386  })
387
388  })
389
390  })
391
392  })
393
394  })
395
396  })
397
398  })
399
400  })
401
402  })
403
404  })
405
406  })
407
408  })
409
410  })
411
412  })
413
414  })
415
416  })
417
418  })
419
420  })
421
422  })
423
424  })
425
426  })
427
428  })
429
430  })
431
432  })
433
434  })
435
436  })
437
438  })
439
440  })
441
442  })
443
444  })
445
446  })
447
448  })
449
450  })
451
452  })
453
454  })
455
456  })
457
458  })
459
460  })
461
462  })
463
464  })
465
466  })
467
468  })
469
470  })
471
472  })
473
474  })
475
476  })
477
478  })
479
480  })
481
482  })
483
484  })
485
486  })
487
488  })
489
490  })
491
492  })
493
494  })
495
496  })
497
498  })
499
500  })
501
502  })
503
504  })
505
506  })
507
508  })
509
510  })
511
512  })
513
514  })
515
516  })
517
518  })
519
520  })
521
522  })
523
524  })
525
526  })
527
528  })
529
530  })
531
532  })
533
534  })
535
536  })
537
538  })
539
540  })
541
542  })
543
544  })
545
546  })
547
548  })
549
550  })
551
552  })
553
554  })
555
556  })
557
558  })
559
560  })
561
562  })
563
564  })
565
566  })
567
568  })
569
570  })
571
572  })
573
574  })
575
576  })
577
578  })
579
580  })
581
582  })
583
584  })
585
586  })
587
588  })
589
590  })
591
592  })
593
594  })
595
596  })
597
598  })
599
600  })
601
602  })
603
604  })
605
606  })
607
608  })
609
610  })
611
612  })
613
614  })
615
616  })
617
618  })
619
620  })
621
622  })
623
624  })
625
626  })
627
628  })
629
630  })
631
632  })
633
634  })
635
636  })
637
638  })
639
640  })
641
642  })
643
644  })
645
646  })
647
648  })
649
650  })
651
652  })
653
654  })
655
656  })
657
658  })
659
660  })
661
662  })
663
664  })
665
666  })
667
668  })
669
670  })
671
672  })
673
674  })
675
676  })
677
678  })
679
680  })
681
682  })
683
684  })
685
686  })
687
688  })
689
690  })
691
692  })
693
694  })
695
696  })
697
698  })
699
700  })
701
702  })
703
704  })
705
706  })
707
708  })
709
710  })
711
712  })
713
714  })
715
716  })
717
718  })
719
720  })
721
722  })
723
724  })
725
726  })
727
728  })
729
730  })
731
732  })
733
734  })
735
736  })
737
738  })
739
740  })
741
742  })
743
744  })
745
746  })
747
748  })
749
749  })
750
751  })
752
753  })
754
755  })
756
756  })
757
758  })
759
759  })
760
761  })
761
762  })
763
764  })
765
766  })
767
768  })
769
769  })
770
771  })
771
772  })
773
774  })
775
776  })
777
777  })
778
778  })
779
779  })
780
780  })
781
781  })
782
782  })
783
783  })
784
784  })
785
785  })
786
786  })
787
787  })
788
788  })
789
789  })
790
790  })
791
791  })
792
792  })
793
793  })
794
794  })
795
795  })
796
796  })
797
797  })
798
798  })
799
799  })
800
800  })
801
801  })
802
802  })
803
803  })
804
804  })
805
805  })
806
806  })
807
807  })
808
808  })
809
809  })
810
810  })
811
811  })
812
812  })
813
813  })
814
814  })
815
815  })
816
816  })
817
817  })
818
818  })
819
819  })
820
820  })
821
821  })
822
822  })
823
823  })
824
824  })
825
825  })
826
826  })
827
827  })
828
828  })
829
829  })
830
830  })
831
831  })
832
832  })
833
833  })
834
834  })
835
835  })
836
836  })
837
837  })
838
838  })
839
839  })
840
840  })
841
841  })
842
842  })
843
843  })
844
844  })
845
845  })
846
846  })
847
847  })
848
848  })
849
849  })
850
850  })
851
851  })
852
852  })
853
853  })
854
854  })
855
855  })
856
856  })
857
857  })
858
858  })
859
859  })
860
860  })
861
861  })
862
862  })
863
863  })
864
864  })
865
865  })
866
866  })
867
867  })
868
868  })
869
869  })
870
870  })
871
871  })
872
872  })
873
873  })
874
874  })
875
875  })
876
876  })
877
877  })
878
878  })
879
879  })
880
880  })
881
881  })
882
882  })
883
883  })
884
884  })
885
885  })
886
886  })
887
887  })
888
888  })
889
889  })
890
890  })
891
891  })
892
892  })
893
893  })
894
894  })
895
895  })
896
896  })
897
897  })
898
898  })
899
899  })
900
900  })
901
901  })
902
902  })
903
903  })
904
904  })
905
905  })
906
906  })
907
907  })
908
908  })
909
909  })
910
910  })
911
911  })
912
912  })
913
913  })
914
914  })
915
915  })
916
916  })
917
917  })
918
918  })
919
919  })
920
920  })
921
921  })
922
922  })
923
923  })
924
924  })
925
925  })
926
926  })
927
927  })
928
928  })
929
929  })
930
930  })
931
931  })
932
932  })
933
933  })
934
934  })
935
935  })
936
936  })
937
937  })
938
938  })
939
939  })
940
940  })
941
941  })
942
942  })
943
943  })
944
944  })
945
945  })
946
946  })
947
947  })
948
948  })
949
949  })
950
950  })
951
951  })
952
952  })
953
953  })
954
954  })
955
955  })
956
956  })
957
957  })
958
958  })
959
959  })
960
960  })
961
961  })
962
962  })
963
963  })
964
964  })
965
965  })
966
966  })
967
967  })
968
968  })
969
969  })
970
970  })
971
971  })
972
972  })
973
973  })
974
974  })
975
975  })
976
976  })
977
977  })
978
978  })
979
979  })
980
980  })
981
981  })
982
982  })
983
983  })
984
984  })
985
985  })
986
986  })
987
987  })
988
988  })
989
989  })
990
990  })
991
991  })
992
992  })
993
993  })
994
994  })
995
995  })
996
996  })
997
997  })
998
998  })
999
999  })
1000
1000  })
1001
1001  })
1002
1002  })
1003
1003  })
1004
1004  })
1005
1005  })
1006
1006  })
1007
1007  })
1008
1008  })
1009
1009  })
1010
1010  })
1011
1011  })
1012
1012  })
1013
1013  })
1014
1014  })
1015
1015  })
1016
1016  })
1017
1017  })
1018
1018  })
1019
1019  })
1020
1020  })
1021
1021  })
1022
1022  })
1023
1023  })
1024
1024  })
1025
1025  })
1026
1026  })
1027
1027  })
1028
1028  })
1029
1029  })
1030
1030  })
1031
1031  })
1032
1032  })
1033
1033  })
1034
1034  })
1035
1035  })
1036
1036  })
1037
1037  })
1038
1038  })
1039
1039  })
1040
1040  })
1041
1041  })
1042
1042  })
1043
1043  })
1044
1044  })
1045
1045  })
1046
1046  })
1047
1047  })
1048
1048  })
1049
1049  })
1050
1050  })
1051
1051  })
1052
1052  })
1053
1053  })
1054
1054  })
1055
1055  })
1056
1056  })
1057
1057  })
1058
1058  })
1059
1059  })
1060
1060  })
1061
1061  })
1062
1062  })
1063
1063  })
1064
1064  })
1065
1065  })
1066
1066  })
1067
1067  })
1068
1068  })
1069
1069  })
1070
1070  })
1071
1071  })
1072
1072  })
1073
1073  })
1074
1074  })
1075
1075  })
1076
1076  })
1077
1077  })
1078
1078  })
1079
1079  })
1080
1080  })
1081
1081  })
1082
1082  })
1083
1083  })
1084
1084  })
1085
1085  })
1086
1086  })
1087
1087  })
1088
1088  })
1089
1089  })
1090
1090  })
1091
1091  })
1092
1092  })
1093
1093  })
1094
1094  })
1095
1095  })
1096
1096  })
1097
1097  })
1098
1098  })
1099
1099  })
1100
1100  })
1101
1101  })
1102
1102  })
1103
1103  })
1104
1104  })
1105
1105  })
1106
1106  })
1107
1107  })
1108
1108  })
1109
1109  })
1110
1110  })
1111
1111  })
1112
1112  })
1113
1113  })
1114
1114  })
1115
1115  })
1116
1116  })
1117
1117  })
1118
1118  })
1119
1119  })
1120
1120  })
1121
1121  })
1122
1122  })
1123
1123  })
1124
1124  })
1125
1125  })
1126
1126  })
1127
1127  })
1128
1128  })
1129
1129  })
1130
1130  })
1131
1131  })
1132
1132  })
1133
1133  })
1134
1134  })
1135
1135  })
1136
1136  })
1137
1137  })
1138
1138  })
1139
1139  })
1140
1140  })
1141
1141  })
1142
1142  })
1143
1143  })
1144
1144  })
1145
1145  })
1146
1146  })
1147
1147  })
1148
1148  })
1149
1149  })
1150
1150  })
1151
1151  })
1152
1152  })
1153
1153  })
1154
1154  })
1155
1155  })
1156
1156  })
1157
1157  })
1158
1158  })
1159
1159  })
1160
1160  })
1161
1161  })
1162
1162  })
1163
1163  })
1164
1164  })
1165
1165  })
1166
1166  })
1167
1167  })
1168
1168  })
1169
1169  })
1170
1170  })
1171
1171  })
1172
1172  })
1173
1173  })
1174
1174  })
1175
1175  })
1176
1176  })
1177
1177  })
1178
1178  })
1179
1179  })
1180
1180  })
1181
1181  })
1182
1182  })
1183
1183  })
1184
1184  })
1185
1185  })
1186
1186  })
1187
1187  })
1188
1188  })
1189
1189  })
1190
1190  })
1191
1191  })
1192
1192  })
1193
1193  })
1194
1194  })
1195
1195  })
1196
1196  })
1197
1197  })
1198
1198  })
1199
1199  })
1200
1200  })
1201
1201  })
1202
1202  })
1203
1203  })
1204
1204  })
1205
1205  })
1206
1206  })
1207
1207  })
1208
1208  })
1209
1209  })
1210
1210  })
1211
1211  })
1212
1212  })
1213
1213  })
1214
1214  })
1215
1215  })
1216
1216  })
1217
1217  })
1218
1218  })
1219
1219  })
1220
1220  })
1221
1221  })
1222
1222  })
1223
1223  })
1224
1224  })
1225
1225  })
1226
1226  })
1227
1227  })
1228
1228  })
1229
1229  })
1230
1230  })
1231
1231  })
1232
1232  })
1233
1233  })
1234
1234  })
1235
1235  })
1236
1236  })
1237
1237  })
1238
1238  })
1239
1239  })
1240
1240  })
1241
1241  })
1242
1242  })
1243
1243  })
1244
1244  })
1245
1245  })
1246
1246  })
1247
1247  })
1248
1248  })
1249
1249  })
1250
1250  })
1251
1251  })
1252
1252  })
1253
1253  })
1254
1254  })
1255
1255  })
1256
1256  })
1257
1257  })
1258
1258  })
1259
1259  })
1260
1260  })
1261
1261  })
1262
1262  })
1263
1263  })
1264
1264  })
1265
1265  })
1266
1266  })
1267
1267  })
1268
1268  })
1269
1269  })
1270
1270  })
1271
1271  })
1272
1272  })
1273
1273  })
1274
1274  })
1275
1275  })
1276
1276  })
1277
1277  })
1278
1278  })
1279
1279  })
1280
1280  })
1281
1281  })
1282
1282  })
1283
1283  })
1284
1284  })
1285
1285  })
1286
1286  })
1287
1287  })
1288
1288  })
1289
1289  })
1290
1290  })
1291
1291  })
1292
1292  })
1293
1293  })
1294
1294  })
1295
1295  })
1296
1296  })
1297
1297  })
1298
1298  })
1299
1299  })
1300
1300  })
1301
1301  })
1302
1302  })
1303
1303  })
1304
1304  })
1305
1305  })
1306
1306  })
1307
1307  })
1308
1308  })
1309
1309  })
1310
1310  })
1311
1311  })
1312
1312  })
1313
1313  })
1314
1314  })
1315
1315  })
1316
1316  })
1317
1317  })
1318
1318  })
1319
1319  })
1320
1320  })
1321
1321  })
1322
1322  })
1323
1323  })
1324
1324  })
1325
1325  })
1326
1326  })
1327
1327  })
1328
1328  })
1329
1329  })
1330
1330  })
1331
1331  })
1332
1332  })
1333
1333  })
1334
1334  })
1335
1335  })
1336
1336  })
1337
1337  })
1338
1338  })
1339
1339  })
1340
1340  })
1341
1341  })
1342
1342  })
1343
1343  })
1344
1344  })
1345
1345  })
1346
1346  })
1347
1347  })
1348
1348  })
1349
1349  })
1350
1350  })
1351
1351  })
1352
1352  })
1353
1353  })
1354
1354  })
1355
1355  })
1356
1356  })
1357
1357  })
1358
1358  })
1359
1359  })
1360
1360  })
1361
1361  })
1362
1362  })
1363
1363  })
1364
1364  })
1365
1365  })
1366
1366  })
1367
1367  })
1368
1368  })
1369
1369  })
1370
1370  })
1371
1371  })
1372
1372  })
1373
1373  })
1374
1374  })
1375
1375  })
1376
1376  })
1377
1377  })
1378
1378  })
1379
1379  })
1380
1380  })
1381
1381  })
1382
1382  })
1383
1383  })
1384
1384  })
1385
1385  })
1386
1386  })
1387
1387  })
1388
1388  })
1389
1389  })
1390
1390  })
1391
1391  })
1392
1392  })
1393
1393  })
1394
1394  })
1395
1395  })
1396
1396  })
1397
1397  })
1398
1398  })
1399
1399  })
1400
1400  })
1401
1401  })
1402
1402  })
1403
1403  })
1404
1404  })
1405
1405  })
1406
1406  })
1407
1407  })
1408
1408  })
1409
1409  })
1410
1410  })
1411
1411  })
1412
1412  })
1413
1413  })
1414
1414  })
1415
1415  })
1416
1416  })
1417
1417  })
1418
1418  })
1419
1419  })
1420
1420  })
1421
1421  })
1422
1422  })
1423
1423  })
1424
1424  })
1425
1425  })
1426
1426  })
1427
1427  })
1428
1428  })
1429
1429  })
1430
1430  })
1431
1431  })
1432
1432  })
1433
1433  })
1434
1434  })
1435
1435  })
1436
1436  })
1437
1437  })
1438
1438  })
1439
1439  })
1440
1440  })
1441
1441  })
1442
1442  })
1443
1443  })
1444
1444  })
1445
1445  })
1446
1446  })
1447
1447  })
1448
1448  })
1449
1449  })
1450
1450  })
1451
1451  })
1452
1452  })
1453
1453  })
1454
1454  })
1455
1455  })
1456
1456  })
1457
1457  })
1458
1458  })
1459
1459  })
1460
1460  })
1461
1461  })
1462
1462  })
1463
1463  })
1464
1464  })
1465
1465  })
1466
1466  })
1467
1467  })
1468
1468  })
1469
1469  })
1470
1470  })
1471
1471  })
1472
1472  })
1473
1473  })
1474
1474  })
1475
1475  })
1476
1476  })
1477
1477  })
1478
1478  })
1479
1479  })
1480
1480  })
1481
1481  })
1482
1482  })
1483
1483  })
1484
1484  })
1485
1485  })
1486
1486  })
1487
1487  })
1488
1488  })
1489
1489  })
1490
1490  })
1491
1491  })
1492
1492  })
1493
1493  })
1494
1494  })
1495
1495  })
1496
1496  })
1497
1497  })
1498
1498  })
1499
```

```

1 // performance.js
2 let loadTimes = {}
3 let startTime = Date.now()
4
5 function observe(targetNode) {
6   // Options for the observer (which mutations to observe)
7   const config = { attributes: true, childList: true, subtree:
8     true };
9
10  // Callback function to execute when mutations are observed
11  const callback = (mutationList, observer) => {
12    for (const mutation of mutationList) {
13
14      if (mutation.type === "childList") {
15        const targetId = getId(mutation.target)
16
17        const skipAttribute =
18          mutation.target.attributes.skipperformance?.value ||
19          mutation.target.attributes.skipPerformance?.value
20
21        if (!(skipAttribute == true || skipAttribute == 'true')) {
22
23          if (mutation.addedNodes.length > 0) {
24            let addedElements =
25              Array.from(mutation.addedNodes).map(el =>
26                el.nodeName !== "#comment" && el.nodeName !==
27                "#text" ? getXPath(el) : el)
28            if (addedElements.length === 1) addedElements =
29              addedElements[0]
30
31            if (Array.from(mutation.addedNodes)) {
32              loadTimes[targetId] = { ...loadTimes[targetId],
33                lastUpdated: Date.now() - startTime, xpath:
34                loadTimes[targetId]?.xpath || getXPath(mutation.target) }
35
36            Array.from(mutation.addedNodes).forEach(node => {
37              try {
38                const nodeId = getId(node)
39                loadTimes[nodeId] = { ...loadTimes[nodeId],
40                  lastUpdated: Date.now() - startTime, xpath:
41                  loadTimes[nodeId]?.xpath || getXPath(node) }
42              } catch (e) {
43                console.warn(e)
44              }
45            })
46
47          }
48
49        else if (mutation.removedNodes.length > 0) {
50          // same as above ...
51        }
52
53      }
54
55    }
56
57  }
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145

```

```

46     } else if (mutation.type === "attributes") {
47       const targetId = getId(mutation.target)
48
49       const skipAttribute =
50         mutation.target.attributes.skipperformance?.value ||
51         mutation.target.attributes.skipPerformance?.value
52
53       if (!(skipAttribute == true || skipAttribute == 'true')) {
54         loadTimes[targetId] = { ...loadTimes[targetId],
55           lastUpdated: Date.now() - startTime, xpath:
56             loadTimes[targetId]?.xpath ||
57             getXPath(mutation.target) }
58       }
59     }
60   }
61   window.dynamic_component_performance = loadTimes
62 };
63 // Create an observer instance linked to the callback function
64 const observer = new MutationObserver(callback);
65
66 // Start observing the target node for configured mutations
67 observer.observe(targetNode, config);
68 }
69
70 function getId(element) {/* ... */}
71 function getXPath(element) {/* ... */}
72
73 function reset() {
74   loadTimes = {}
75   startTime = Date.now()
76 }
77
78 let interval;
79
80 function initObservation() {
81   // The id of the targetNode has to be adapted to the framework
82   // or application
83   const targetNode = document.getElementById("app")
84   if (targetNode) {
85     observe(targetNode)
86     if (interval) clearInterval(interval)
87   }
88
89 interval = setInterval(initObservation, 100)
90
91 // initialize window.dynamic_component_performance
92 window.dynamic_component_performance = loadTimes

```

Listing 18: Injected mutation recorder script

Third, tests in `state-change.spec.js` specify measurements for component update times (see listing 19). In this test specification, two other time budgets are defined. The first update to the DOM and the slowest update to the DOM are tested. The idea behind these time budgets is that users may perceive the “reaction time” as the time frame in which their action had any effect or as the time frame in which the effects of their actions finish. To this end, user actions are defined in combination with a route to perform these actions on. For this work, four actions are defined on the Create page: The changing of the caption, the selection of an image, the insertion of a media source URL and the creation of a new post, which is a combination of caption change and media selection.

In order to evaluate the reaction speed to those user actions, the same mutation recording script is injected as for component load times. The page is then opened and the recorded mutation timings are reset. Afterwards, the user action is performed and the new mutation times are extracted, attached to the test and evaluated. The requirements for the tests to pass are that the earliest mutation timing is within 100 ms of the user input and the latest mutation timing is within 500 ms of the user input. Again, screenshots are taken of all HTML elements that were recorded as mutated and do not pass the tests. These screenshots are also attached to the test in order to debug applications that do not pass the tests.

```

1 // state-change.spec.js
2 import { test, expect } from '@playwright/test';
3
4 const minReactionTime = 100;
5 const maxUpdateTime = 500;
6
7 const actions = [
8   {
9     route: '/create',
10    inputActions: [
11      {
12        name: 'Caption Change',
13        action: async (page) => {
14          const captionInputField = page.getByPlaceholder('Type
15          your caption here')
16          return captionInputField.fill('Lorem ipsum ...')
17        }
18      },
19      {
20        name: 'Media Selection',
21        action: async (page) => {
22          const mediaSelector = page.locator('#preloaded-image')
23          return mediaSelector.selectOption('moon.webp')
24        }
25      },
26      {
27        name: 'Media Source Insert',
28        action: async (page) => {
          const captionInputField = page.getByPlaceholder('Insert
          your media URL here...')
```

```

29         return captionInputField.fill(`${
30             new URL(await
31             page.url()).origin}/abstract-circles.webp`)
32     },
33     {
34         name: 'Post Creation',
35         action: async (page) => {
36             const mediaSelector = page.locator('#preloaded-image')
37             const captionInputField = page.getByPlaceholder('Type
38                 your caption here')
39             await mediaSelector.selectOption('moon.webp')
40             return captionInputField.fill('Lorem ipsum ...')
41         }
42     }
43 ]
44
45 for (const actionGroup of actions) {
46     for (const inputAction of actionGroup.inputActions) {
47
48         test.describe('State Change DOM Update: ${inputAction.name}', {
49             tag: ['@${inputAction.name.replace(/\s/g, '')}', '@stateChange'],
50             () => {
51                 let page;
52                 let domUpdates = null;
53
54                 test.beforeAll(async ({ browser }) => {
55                     page = await browser.newPage();
56                     await page.addInitScript({path: './tests/performance.js'})
57
58                     await page.goto(actionGroup.route)
59                     await page.waitForLoadState('domcontentloaded')
60
61                     await new Promise(resolve => setTimeout(resolve, 3_000))
62                     await page.evaluate(() => {reset()})
63
64                     await inputAction.action(page)
65
66                     await new Promise(resolve => setTimeout(resolve, 5_000))
67                     domUpdates = await page.evaluate(() => {
68                         if (!window.dynamic_component_performance) return null
69
70                         // Sort the components by their latest dom update time
71                         const sortedEntries =
72                             Object.entries(window.dynamic_component_performance)
73                             .map(([key, value]) => { return { id: key, ...value } })
74
75                             .sort((a, b) => a.lastUpdated - b.lastUpdated)
76                         return sortedEntries
77                     })
78                 });
79
80                 test.afterAll(async () => {
81                     await page.close();
82                 });
83             });
84         });
85     });
86 }

```

```
78
79
80  test('User input triggers first update within
81    ${minReactionTime} ms', { tag: ['@minimalReactionTime'] }
82    }, async ({ }, TestInfo) => {
83      expect(domUpdates).not.toBeNull()
84      expect(domUpdates).not.toEqual([])
85      const minReactionComp = domUpdates[0]
86
87      await TestInfo.attach(`domUpdates${TestInfo.retry > 0 ? '_retry_${TestInfo.retry}' : ''}.json`, { body:
88        JSON.stringify(domUpdates, null, 2), contentType:
89        "application/json" })
90      await test.info().annotations.push({ type: 'Fastest Update
91        ${TestInfo.retry > 0 ? '(retry #' + TestInfo.retry + ')' : ''}', description: 'Component with id
92        ${minReactionComp.id} loaded
93        ${minReactionComp.lastUpdated}ms after user input
94        (xPath: ${minReactionComp.xpath})' });
95      expect.soft(minReactionComp.lastUpdated, 'Fastest updated
96        component with identifier ${minReactionComp.id} should
97        update within ${minReactionTime}
98        ms').toBeLessThanOrEqual(minReactionTime)
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
559
560
561
562
563
564
565
566
567
568
569
569
570
571
572
573
574
575
576
577
578
579
579
580
581
582
583
584
585
586
587
588
589
589
590
591
592
593
594
595
596
597
598
599
599
600
601
602
603
604
605
606
607
608
609
609
610
611
612
613
614
615
616
617
618
619
619
620
621
622
623
624
625
626
627
628
629
629
630
631
632
633
634
635
636
637
638
639
639
640
641
642
643
644
645
646
647
648
649
649
650
651
652
653
654
655
656
657
658
659
659
660
661
662
663
664
665
666
667
668
669
669
670
671
672
673
674
675
676
677
678
679
679
680
681
682
683
684
685
686
687
688
689
689
690
691
692
693
694
695
696
697
698
699
699
700
701
702
703
704
705
706
707
708
709
709
710
711
712
713
714
715
716
717
718
719
719
720
721
722
723
724
725
726
727
728
729
729
730
731
732
733
734
735
736
737
738
739
739
740
741
742
743
744
745
746
747
748
749
749
750
751
752
753
754
755
756
757
758
759
759
760
761
762
763
764
765
766
767
768
769
769
770
771
772
773
774
775
776
777
778
779
779
780
781
782
783
784
785
786
787
788
789
789
790
791
792
793
794
795
796
797
798
799
799
800
801
802
803
804
805
806
807
808
809
809
810
811
812
813
814
815
816
817
818
819
819
820
821
822
823
824
825
826
827
828
829
829
830
831
832
833
834
835
836
837
838
839
839
840
841
842
843
844
845
846
847
848
849
849
850
851
852
853
854
855
856
857
858
859
859
860
861
862
863
864
865
866
867
868
869
869
870
871
872
873
874
875
876
877
878
879
879
880
881
882
883
884
885
886
887
888
889
889
890
891
892
893
894
895
896
897
898
899
899
900
901
902
903
904
905
906
907
908
909
909
910
911
912
913
914
915
916
917
918
919
919
920
921
922
923
924
925
926
927
928
929
929
930
931
932
933
934
935
936
937
938
939
939
940
941
942
943
944
945
946
947
948
949
949
950
951
952
953
954
955
956
957
958
959
959
960
961
962
963
964
965
966
967
968
969
969
970
971
972
973
974
975
976
977
978
979
979
980
981
982
983
984
985
986
987
987
988
989
989
990
991
992
993
994
995
996
997
998
999
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1189
1190
1191
1192
1193
1194
1195
1196
1197
1197
1198
1199
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1497
1498
1499
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1597
1598
1599
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1697
1698
1699
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1797
1798
1799
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1897
1898
1899
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2097
2098
2099
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2197
2198
2199
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2219
2220
2221
2222
2223
2224
2225
2226
2227
2228
2229
2229
2230
2231
2232
2233
2234
2235
2236
2237
2238
2239
2239
2240
2241
2242
2243
2244
2245
2246
2247
2248
2249
2249
2250
2251
2252
2253
2254
2255
2256
2257
2258
2259
2259
2260
2261
2262
2263
2264
2265
2266
2267
2268
2269
2269
2270
2271
2272
2273
2274
2275
2276
2277
2278
2279
2279
2280
2281
2282
2283
2284
2285
2286
2287
2288
2288
2289
2290
2291
2292
2293
2294
2295
2296
2297
2297
2298
2299
2299
2300
2301
2302
2303
2304
2305
2306
2307
2308
2309
2309
2310
2311
2312
2313
2314
2315
2316
2317
2318
2319
2319
2320
2321
2322
2323
2324
2325
2326
2327
2328
2329
2329
2330
2331
2332
2333
2334
2335
2336
2337
2338
2339
2339
2340
2341
2342
2343
2344
2345
2346
2347
2348
2349
2349
2350
2351
2352
2353
2354
2355
2356
2357
2358
2359
2359
2360
2361
2362
2363
2364
2365
2366
2367
2368
2369
2369
2370
2371
2372
2373
2374
2375
2376
2377
2378
2379
2379
2380
2381
2382
2383
2384
2385
2386
2387
2388
2388
2389
2390
2391
2392
2393
2394
2395
2396
2397
2397
2398
2399
2399
2400
2401
2402
2403
2404
2405
2406
2407
2408
2409
2409
2410
2411
2412
2413
2414
2415
2416
2417
2418
2419
2419
2420
2421
2422
2423
2424
2425
2426
2427
2428
2429
2429
2430
2431
2432
2433
2434
2435
2436
2437
2438
2439
2439
2440
2441
2442
2443
2444
2445
2446
2447
2448
2449
2449
2450
2451
2452
2453
2454
2455
2456
2457
2458
2459
2459
2460
2461
2462
2463
2464
2465
2466
2467
2468
2469
2469
2470
2471
2472
2473
2474
2475
2476
2477
2478
2479
2479
2480
2481
2482
2483
2484
2485
2486
2487
2488
2488
2489
2490
2491
2492
2493
2494
2495
24
```

```

        ms').toBeLessThanOrEqual(maxUpdateTime)
107    })
108
109    if (domUpdates.some(comp => comp.lastUpdated >=
110        maxUpdateTime))
110        await test.info().annotations.push({ type: 'Hint',
111            description: 'Screenshots below show slow updating
112            components' });
113
114        // take screenshots of all elements in domUpdates
115        await Promise.all(
116            // ...
117        )
118    }
119 }

```

Listing 19: Test file for component update times

5 Evaluation

The results of the tests are presented in this chapter. Each section describes the test results as they correlate to the metric categories and load times. These results are presented as summaries of results of the described test implementations.

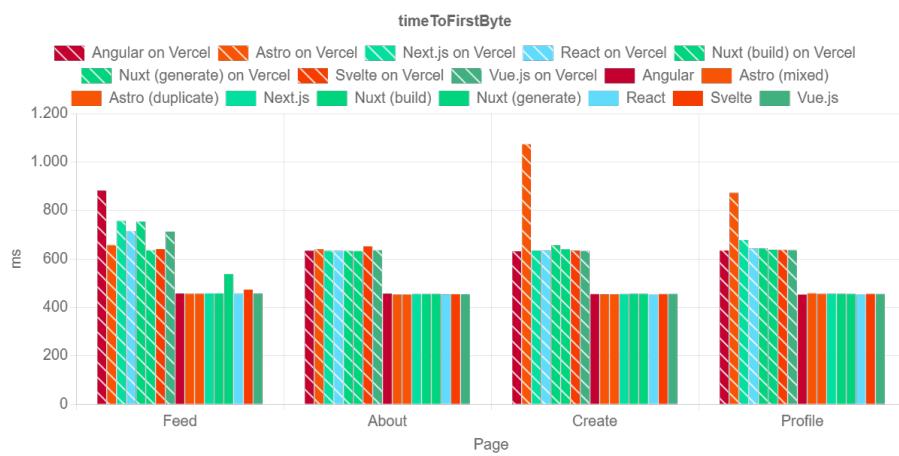
5.1 Page Load Times

For page load times, the Total Byte Weight (TBW), Time To First Byte (TTFB), observed `domContentLoaded`, Total Blocking Time (TBT), Observed Last Visual Change (OLVC) and Largest Contentful Paint (LCP) are presented from the Lighthouse reports and the `loadEventEnd` is deduced from the Playwright tests relating to page load times. The results of Lighthouse tests are visualized per path in figure 7. On every path, each framework's application is tested once on Vercel and once hosted locally with two exceptions. Nuxt is tested with its `nuxt build` and `nuxt generate` build scripts (see table 2). Astro is tested locally with both duplicate components (similar Astro and React components) and its mixed version, in which the React components do not have Astro duplicates even if the component is not dynamic. The version of Astro hosted on Vercel is the version with duplicate components.

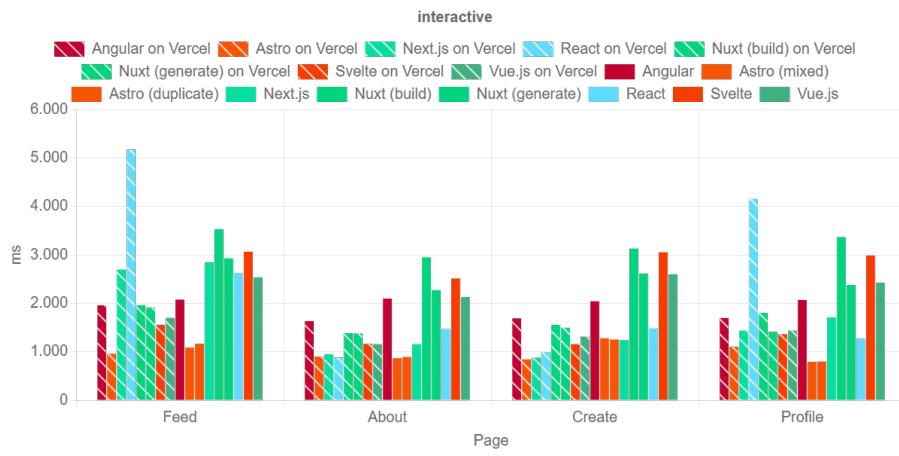
(a) The Total Byte Weight is presented in figure 7a. Primarily, the great size of the pages build with Nuxt stand out. Out of all four pages, this is mainly surprising for the Create page because on initial load only one image has to be loaded. Yet the Create page and the Profile page appear to be equal in byte size although the latter has decidedly more images on it. Moreover, the byte size of the Profile page decreases for Nuxt-generate, a characteristic of the two build structures that



(a) Total Byte Weight (TBW)



(b) Time To First Byte (TTFB)

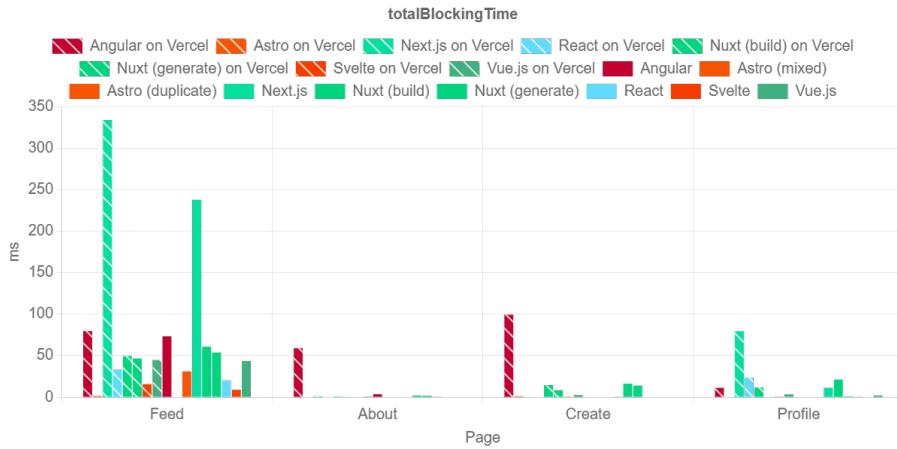


(c) Time To Interactive (TTI)

Figure 7: Lighthouse test results in Google Chrome



(d) Observed DomContentLoaded

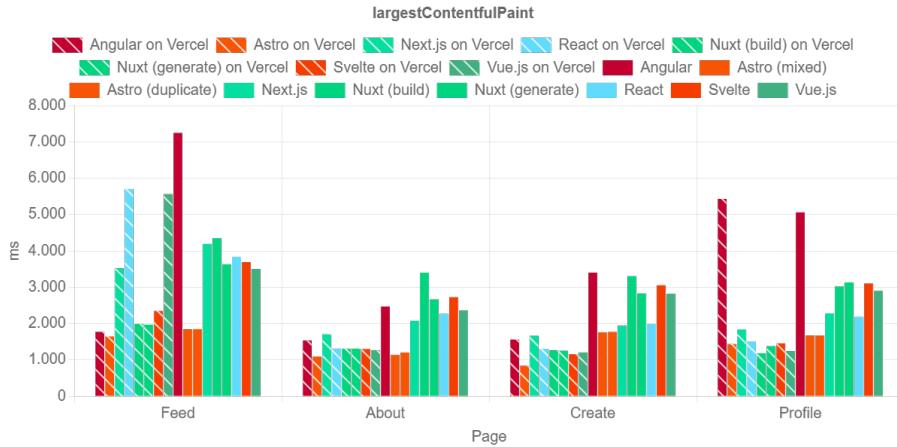


(e) Total Blocking Time (TBT)

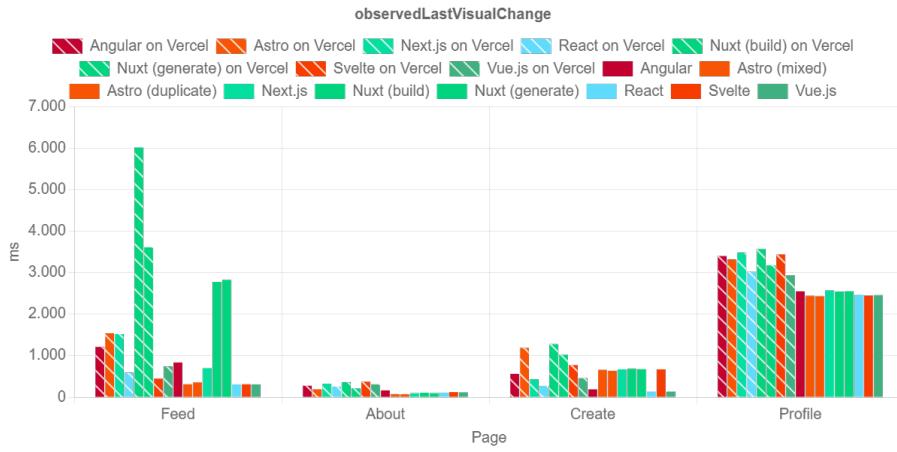
Figure 7: Lighthouse test results in Google Chrome

cannot be found on the Feed page. The property of Nuxt, that the Create page is as heavy as the Profile page, can be explained through the implementation of the `MediaComponent` (see listing 21). All preconfigured image files are imported using `import.meta.glob()` (see listing 21, line 14). For this reason, the byte size of the page is at least the size of all images on pages that use `MediaComponent`. Although this import method is used with Nuxt, Astro and Svelte, Nuxt is the only framework with which this behaviour seems to have such a detrimental impact. Secondly, the About page has a small byte size, which is not surprising because it has only one SVG as an image.

In general, pages from Next.js, Astro and Svelte have a small byte weight on the Feed page as well as the Profile page, most likely due to successful image compression. The byte weight of the Create page and the Profile page is a representation of how well the framework handles selecting which parts of the application have to be loaded. For the Create page, eight out of the 15 components of the app have to be loaded (nine out of 16 for Astro-duplicate) and five of 15 for the Profile page.



(f) Largest Contentful Paint (LCP)



(g) Observed Last Visual Change (OLVC)

Figure 7: Lighthouse test results in Google Chrome

Interestingly, the Create page weighs less than the Profile page for most frameworks except Nuxt.

(b) The measurements of the Time To First Byte indicate clearly the response time difference from locally hosted applications to applications hosted on Vercel (see figure 7b). To this end, the timings of the About page should be examined. The difference in TTFB between local and Vercel lies around 185 ms with local applications responding within 452-457 ms and Vercel responding within 632-651 ms. Taking this difference as reference for the normal time difference, additional measurements stand out. Although the local webserver returns the first byte almost equally fast on all paths, Nuxt-generate takes 80 ms longer than its sibling Nuxt-build on the Feed page. The first response byte is registered 19 ms later on the Feed page with Svelte than the other paths.

On Vercel, the TTFB fluctuates more between the frameworks. On the Feed page, the frameworks can be separated into three groups. Astro, Nuxt-generate

and Svelte are the fastest with response times between 635 and 657 ms. Between 712 and 756 ms lie the times for Next.js, React, Nuxt-build and Vue.js. Angular has the slowest response time on Vercel and on the Feed page with 882 ms. The response times on Vercel on the Create page are increased for Astro to 10730 ms by about 430 ms compared to its competitors. A similar increase is measured on the Profile page with a TTFB for Astro on Vercel of 872 ms, about 230 ms later than other frameworks.

(c) The Time To Interactive of the applications is shown in figure 7c. In contrast to the TTFB, the TTI is faster on Vercel with the exception of React on the Feed page and both React and Astro on the Profile page. Possible reasons for this phenomenon include the content encoding, which is missing from local hosting, or simply better traditional webserver performance such as parallelization of request handling on Vercel. With these faster applications on Vercel, Astro, Svelte, Next.js and Vue.js turn out to be the fastest frameworks for the Time To Interactive of the application. In general, Astro appears to be the framework from which the application has the fastest TTI across pages and hosting environments. Interestingly, Vue.js, Nuxt, Svelte, Angular and Astro show small fluctuations between pages of 500 ms or less which is relatively little compared to Next.js and React.

(d) Figure 7d shows the average of observed times of the domContentLoaded event. Two general characteristics stand out of the data. First, the timing of the applications that are hosted locally are at least 45 ms earlier than the applications hosted on Vercel. Second, the observedDomContentLoaded is measured to be much earlier than the TTFB. The first observation can be explained by the slower network speed. The order of TTFB and observed timing of the domContentLoaded event goes back to throttling not being applied for Lighthouse metrics starting with “observed” (Raine, 2024).

Astro on Vercel shows the latest domContentLoaded on Vercel except on the About page. On the other hand, Astro locally shows some of the fastest times on the About page and the Create page. Angular, Nuxt-build, Next.js and Svelte are the other frameworks with late times for the event. In contrast, React, Vue.js and Nuxt-generate build applications with earlier event times. Both measurement characteristics can be explained by the rendering behaviour of the applications. Astro returns the fully complete DOM in its initial HTML document, whereas the frameworks of the second fastest group return half-complete HTML documents. These frameworks demonstrate their rendering capabilities here. The fastest frameworks for this metric respond to the request with HTML skeletons, which naturally results in early domContentLoaded events. Interestingly, Angular and Nuxt-generate break this pattern. Angular generates an HTML skeleton for all pages that references CSS and JS files. The main difference to Vue.js, for example, is that the JS modules are included in the HTML `<body>` for Angular and in the HTML `<head>` for Vue.js. Additionally, all imports are lazy-loading with Vue.js and the scripts for the Angular application are packed into fewer and bigger JS files. Nuxt-generate on the other hand does not return an empty HTML skeleton and is still in the group of fastest frameworks for this metric. The main difference to other frameworks is that

JS files are included in the HTML document with `rel="modulepreload"`. Both of these strategies appear to have a noticeable impact on the timing of the `domContentLoaded` event.

(e) The results of measurements for the Total Blocking Time show drastic differences between the frameworks (see figure 7e). On the one hand, the blocking time is practically negligible for most frameworks on the About, Create and Profile page indicating no unnecessary code execution before rendering. On the other hand, some frameworks show relatively large TBT, especially on the Feed page. Firstly, Astro and Svelte are among the fastest frameworks in the TBT, although Astro with duplicate components demonstrates a blocking time of 31 ms on the Feed page. Secondly, the application built with React and Vue.js also have a short blocking time. Thirdly, Angular produces an application with very low blocking time when hosted locally using the `serve` command, but high blocking time when hosted on Vercel. The latter two can be explained through an analysis of the scripts and modules loaded and executed on page load. While Vue.js and React include their scripts in smaller files and only import scripts when needed, Angular bundles JavaScript in fewer and bigger files. This increases the blocking time, especially for code that is not needed for the page.

The main outlier, however, is Next.js on the Feed and the Profile page. The TBT of the application surpasses its next competitor's TBT by 254 ms on the Feed page on Vercel, 164 ms on the Feed page locally and 56 ms on the Profile page on Vercel. This is not definitively explainable, but the fact that this effect only greatly affects pages in which images are included using the `MediaComponent` is an indicator. Images and videos are loaded using `require('@/assets/stock-footage/${src}').default`, which is similar to React's `require('src/assets/stock-footage/${src}')` (see listing 20, line 16 and listing 22, line 13). The interpreted behaviour then is that both applications load the multimedia files synchronously, but Next.js also loads the components synchronously, which results in such a high Total Blocking Time. This would also explain why the effect is less on the local webserver.

(f) Unsurprisingly, the measurements for the Observed Last Visual Change (OLVC) are also in general faster when the application is hosted locally (see figure 7g). Next.js is the only exception to that on the Create page. Amongst the frameworks, no clear separation can be identified across the pages or hosting environment, although Vue.js and React are always among the fastest in this metric compared to other frameworks with the same hosting method. Additionally, Nuxt has the slowest OLVC across pages, especially on the Feed page. However, the average of Nuxt-build on Vercel is deceiving. The distribution of the OLVC measurements of Nuxt-build throughout the 20 test runs clearly shows that most measurements lie around 4500 ms rather than the average of all values which is 6012 ms. Nonetheless, the OLVC of Nuxt is still far above the average of other frameworks.

(g) The average measurements for Largest Contentful Paint (LCP) are shown in figure 7f. In contrast to other presented metrics, the time of the LCP is in general earlier for applications hosted on Vercel. However, both Astro implementations

regularly have a faster LCP locally than other frameworks on Vercel. Other than that, Angular is the only framework with outlier measurements. The LCP measurements are extraordinarily high on the Feed page when hosted locally and on the Profile page independently from the hosting environment. There is no apparent explanation for either characteristic at this time.

Angular	28/28
Astro	24/28
Next.js	28/28
Nuxt (build)	28/28
Nuxt (generate)	28/28
React	28/28
Svelte	24/28
Vue.js	28/28

Table 5: Passed Playwright page load tests per framework

The numbers of passed page load tests with Playwright are listed in table 5. The only frameworks with which the application does not pass the tests are Astro and Svelte. For both frameworks the page load budget is exceeded on all four pages when opened in Firefox. The repetitions of failed tests also exceed the time budget, which causes the tests to be marked as failed. Figure 8a shows the timings of `loadEventEnd` across browsers, frameworks and pages, including test runs. It is clear that these test results are outliers compared to other frameworks and browsers. The load speed in Firefox is slower than the budget only for Astro and Svelte. Upon inspection of other navigation event times, the reason for this results becomes clear. The time of `requestStart` for the failing frameworks in Firefox is already above 2000 ms for all pages. Interestingly, the timing of this navigation event is not late for all other frameworks. This differentiating behaviour could not be explained in the time frame of this study. However, the next step in the analytic process was to inspect a dapted `LoadEventEnd` metric instead of inspecting the raw measurement of the `loadEventEnd`. This balanced `loadEventEnd` time can be described as

$$loadEventEnd_{balanced} = loadEventEnd_{raw} - requestStart \quad (1)$$

Figure 8b shows the new balanced values. Using the balanced metric, all pages from all frameworks are loaded within the page load time budgets and the tests should pass. Still, differences can be found between frameworks and between browsers. The overview over all results shows four different patterns within a browser. Unsurprisingly, Chromium and Mobile Chrome as well Desktop Safari and Mobile Safari have similar results. They differ mainly in the load times of Astro, Svelte and Angular pages. The third pattern can be found in Microsoft Edge and Google Chrome. Pages load relatively fast in these two browsers especially with Astro. The measurements made in Firefox do not resemble the ones made in other browsers. This might indicate, that its rendering engine “Gecko” behaves differently to “Blink” and “WebKit” which are used in the other browsers. First, the results are

slower on average and it is the only browser in which the load times of React pages fluctuate more than 30 ms between pages. Second, the fastest times with React are slower than the fastest times with Astro, Nuxt and Vue.js.

As for the frameworks, React is clearly the fastest relating to its loadEventEnd in Chromium, Mobile Chrome, Desktop Safari and Mobile Safari and second fastest in Microsoft Edge and Google Chrome. Vue.js is second fastest in most browsers and also fluctuates very little. Nuxt, Next.js and Svelte are the next-fastest frameworks across all browsers. Angular is one of the slowest frameworks for most pages and browsers except some measurements of Astro. The fastest or the slowest measured times are measured with Astro depending on the browsers, but always fluctuate relatively much compared to other frameworks.

5.2 Component Load Times

The load time of components is an indicator for how well frameworks split resources for the load of their applications between part of the pages. The relevant metrics for the component load are Observed Last Visual Change (OLVC), Total Blocking Time (TBT), Time To Interactive (TTI), the timing of loadEventEnd, Observed First Visual Change (OFVC) and the measured DOM mutation times immediately after the initial page load. To measure these metrics, the tests are executed as described previously and documented as described in section 5.1. The same rules for the presentations of the results apply in this section.

Because the same time frame is inspected as in the previous section, the relevant metrics TBT, OLVC, TTI and balanced loadEventEnd can be used to analyze the behaviour of component load (see figures 7e, 7c, 7g and 8b). However, no new interpretations can be taken for component load times because every measurement that includes the complete page load might or might not be caused by slowly loading components. Therefore, failed tests due to the time budget being exceeded cannot be unequivocally attributed to either slow network speeds, browser behaviour, client behaviour, the used framework or single components. Additional metrics are needed to identify component load times.

The OFVC is the time after which the first visual change is made within the viewport (see figure 9a). It can be either the time after which prerendered HTML elements appear or the time after which an empty DOM gets filled through JS and visual changes are made. The measurements of the OFVC show that, in general, the first visual change is earlier for locally hosted applications, which is unsurprising because the resources load earlier. Frameworks with an early OFVC are Astro, React and Next.js with the only exception being Astro on Vercel on the Create page. The Angular application on the other hand displays late OFVC values compared to its competitors locally. On Vercel, Nuxt-build has relatively late values across all pages.

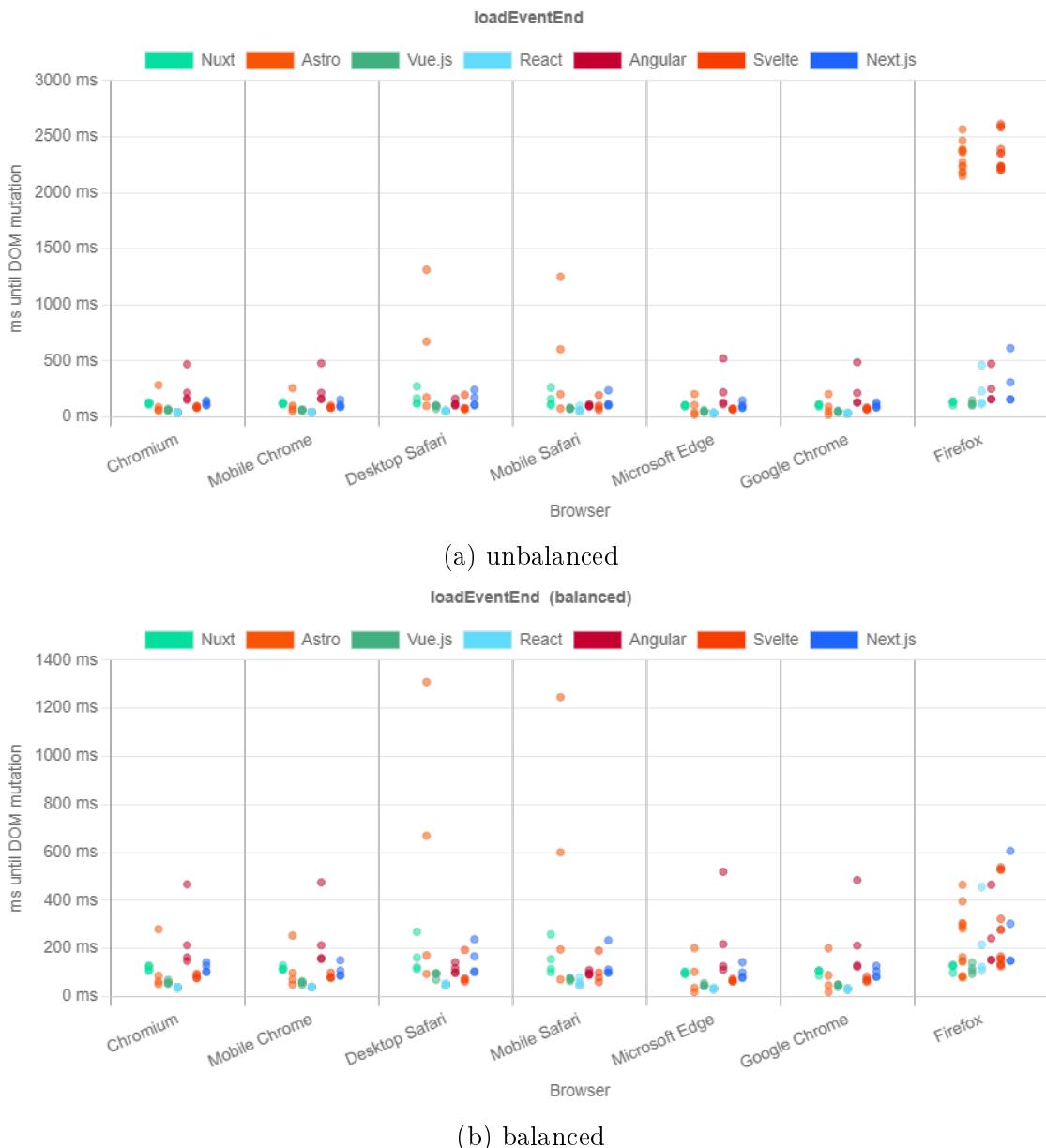
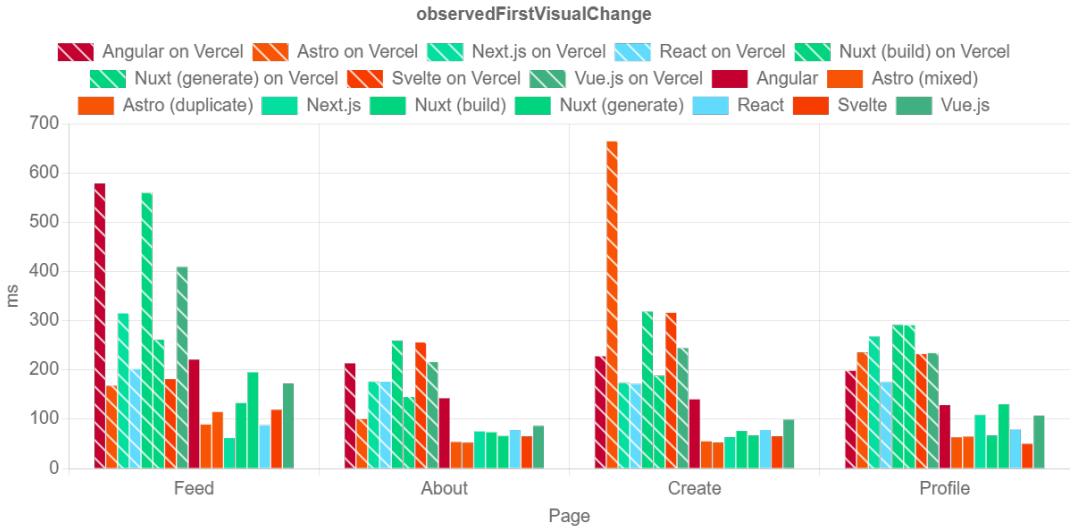
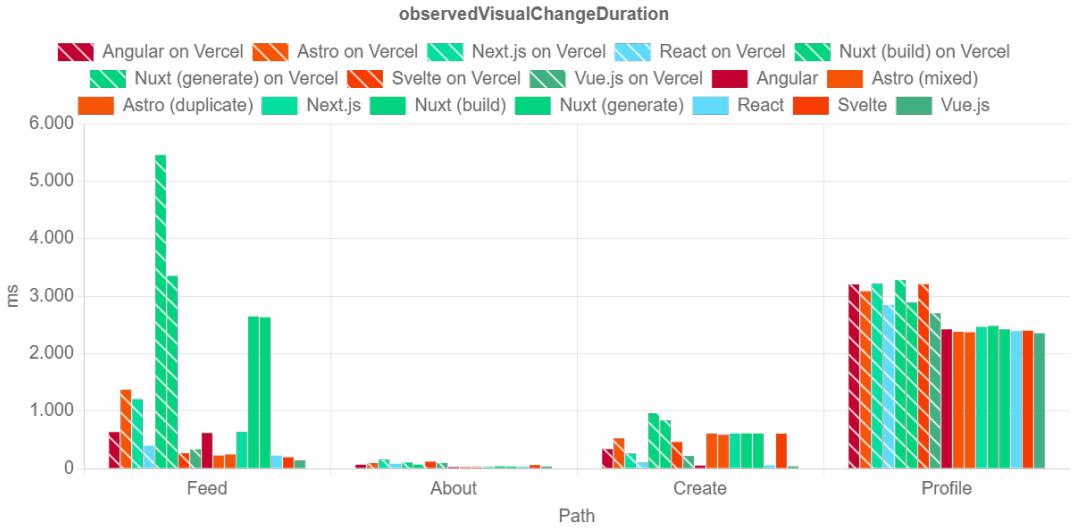


Figure 8: Measured loadEventEnd timings



(a) Observed First Visual Change (OFVC)



(b) Observed Visual Change Duration (OVCD)

Figure 9: Observed First Visual Change (OFVC) (a) and Observed Visual Change Duration (OVCD) (b)

More interesting than the raw OLVC and OFVC values is the difference between the measurements. This thesis defines a new metric “Observed Visual Change Duration”. It shows the time after the first visual mutation to the page has been made until the last visual change. It is simply deferred from the OLVC and OFVC and is defined as

$$\begin{aligned} \text{observedVisualChangeDuration} = \\ \text{observedLastVisualChange} - \text{observedFirstVisualChange} \quad (2) \end{aligned}$$

Figure 9b shows the resulting values for the Observed Visual Change Duration (OVCD) from this study. The great difference between locally tested applications and applications on Vercel means that visual changes, especially the last, are dependent on network delay or JavaScript execution speed. Vue.js, React and Angular produce low OVCD measurements except on the Profile page. This is even the case if the OFVC is late. The reason for this result is that no visual changes are made to the page until the HTML and JS is parsed and executed. This stands in contrast to prerendered, server-side rendered or semi-rendered pages. With these pages, the first visual update can already be made after only the HTML is parsed. Therefore CSR frameworks can achieve faster OVCD values on the pages without components that have differently fast loading components. Notably, the Profile page is an outlier among the pages. This is because the static header of the page can be displayed as soon as possible, but the rest of the page needs two additional service functions to finish before images and videos can be loaded. The effect of those chained JavaScript executions can clearly be identified using the OVCD.

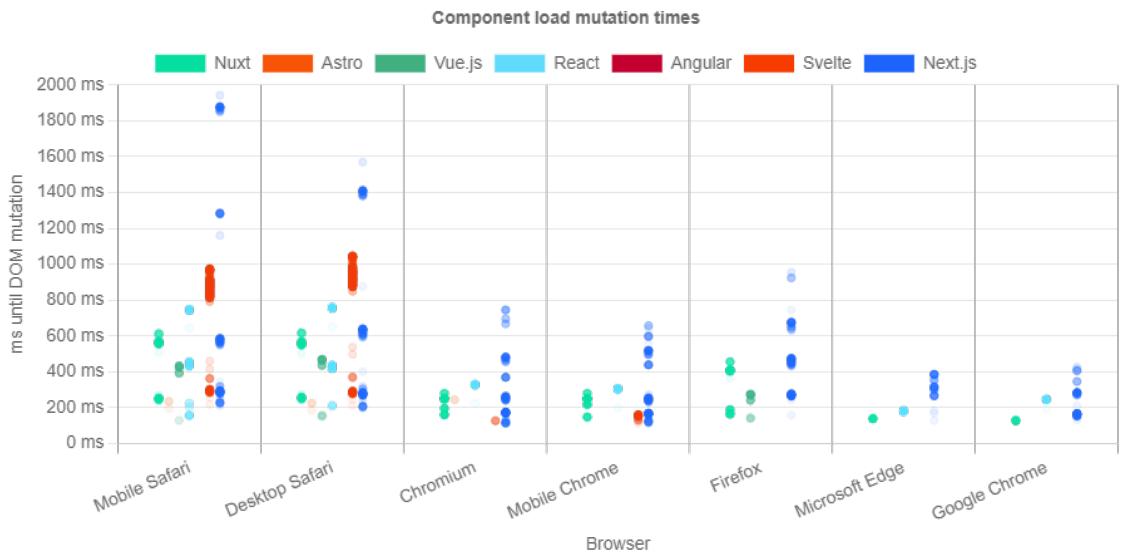


Figure 10: Component load mutation times

Figure 10 shows the DOM mutation times of elements that were registered through Playwright right after the initial page load. Primarily, the most noticeable result of these measurements is that some results appear to be missing. For example, there are no measurements from the Angular application at all. The reason for missing measurements could be that all DOM mutations have taken place before the MutationObserver could be initialized because the injection of the recording script through Playwright takes longer than the page load or all changes take place before the first interval of 100 ms (see listing 18, line 89). The other possible reason for this phenomenon could be that mutations are slower than the manually defined recording time of ten seconds (see listing 17, line 16), but it is less likely because no mutation is recorded to be over 1900 ms with any browser, page or framework. Therefore, missing recordings indicate the framework is either loading too fast or too

slow to record DOM mutations. In addition, other results match the interpretation (see section 5.3). Because the applications have differences in the DOM structure and render time, the number of mutations fluctuates naturally. Adjusting for possible variations here, four frameworks seem to have missing measurements. The applications built with Angular (no mutations), Astro (11 mutations), Vue.js (174 mutations) and React (527 mutations) have surprisingly few mutations. The applications built with Nuxt (1011 mutations), Next.js (1654 mutations) and Svelte (1857 mutations) have over 1000 mutations. Although the latter numbers could indicate full recording coverage of the mutations, the distribution of recordings between browsers and pages prove that not all mutations were recorded, even with these latter three frameworks. For example, no mutations were recorded on the About page with Nuxt and Next.js. In fact, Svelte is the only framework with which mutations were recorded on the About page, but only in Mobile Chrome, Chromium, Mobile Safari and Desktop Safari. Then again, there are apparently no mutations with Svelte on the Profile page in any browser.

Although the missing data prevents some unambiguous comparisons between frameworks, the presence of some recordings indicates load speed differences between frameworks and browsers. First, many relatively late recordings could be made in Desktop Safari and Mobile Safari. This indicates that the method of measurement results in slow DOM mutation times in these browsers, especially with Svelte and Next.js. Additionally, in Microsoft Edge and Google Chrome only very few measurements could be made, so the two browsers can be considered especially fast for this measurement method. Second, Next.js appears to be the slowest of the frameworks in this metric. Svelte also demonstrates slow mutations, but only in Desktop Safari and Mobile Safari. The other frameworks that appear in the summary of mutations, Nuxt, React and Vue.js, also have some relatively high recorded mutation times, but all recorded times are below 760 ms. With these frameworks, the most interesting observation is that not only are the mutation times faster with Microsoft Edge and Google Chrome, but they are also more bundled together than with other browsers.

The last possible observation from the data is that no mutation time is below 100 ms. The implementation of the MutationObserver is the reason for this. Because the start time is defined immediately and the interval callback is executed first after a 100 ms delay, no mutation times below 100 ms can be recorded. Changing the implementation to an interval of 20 ms and executing the initialization function once immediately does allow for earlier recording times for few frameworks. The tested applications built with Astro, Next.js, React, Svelte and Vue.js then have recorded mutation times below 100 ms. The earliest recorded time with the 20 ms interval is 41 ms with Vue.js on the About page in Microsoft Edge. Naturally, the number of recordings also increases drastically for all frameworks except Angular. 42 mutations with Astro, 640 mutations with Vue.js, 1309 mutations with Nuxt, 1704 mutations with React, 2260 mutations with Next.js and 6412 mutations with Svelte were recorded. The increase in early recordings and the minimum times per framework support two interpretations relating to the interval time. First, quick initialization intervals do make the recording more complete because fewer fast mutations are not recorded. If these fast mutations are required to be present in

the test or its report, then decreasing the interval speed is a requirement. Second, the minimal time becomes dependent on the initialization behaviour and speed. The presence of fast data points for some frameworks cannot be definitively traced back to the framework being faster than others because fast data points might still be missing for other frameworks due to unreliable injection behaviour. In addition, rapid initialization attempts require more resources and therefore might actually decrease the performance of any code execution or rendering. For these reasons, the configuration of a initialization interval is a balance between the completeness of DOM mutation recordings and comparability of fast mutations.

5.3 Component Update Times

Section 4.2 defines the update time of a component using the user input time and the time of the DOM mutation. Only the mutation times were used in this study to keep the method of measurement valid for as many applications frameworks as possible. Because the user input action is delayed and the zero-time is reset beforehand (see listing 19, lines 59 - 62), the punctual initialization of the MutationObserver is not an issue when testing DOM mutations triggered by user inputs (as described in section 5.2).

The number of mutation types to the DOM per user action are displayed in table 6. It is clear that the frameworks can be split into three distinct groups by number of different mutations. This list intentionally does not count identical mutations such as appending another element to the list of `` elements in the post caption of the preview. Angular and Next.js make the most changes to the DOM during the user actions with 14 and 15 recorded mutations, respectively. Then, both Astro and React have a similar number of mutations with nine mutations in total. This similarity is not surprising because the Astro island of the CreateForm consists of identical React components to the pure React application. The group of frameworks with the least DOM mutations changes on six different elements in the DOM in total. They are Nuxt, Vue.js and Svelte. Tables 11, 12, 13 and 14 list the HTML elements that were mutated after user input for all four user actions. Surprisingly, the grouping of the frameworks does not translate directly to the specific mutated elements. In general, each described group does update similar elements with similar mutations, but they are not exact copies of each other in this regard.

	Angular	Astro	Next.js	Nuxt	React	Vue.js	Svelte
Caption change	3	2	3	1	2	1	1
Media selection	3	1	3	1	1	1	1
Source insertion	3	2	3	1	2	1	1
Post creation	5	4	6	3	4	3	3
Total	14	9	15	6	9	6	6

Table 6: Total number of DOM mutation types per framework and user action

Figure 11 presents the mutation times of each framework per browser with all recorded times across user actions. The first results for this study is that almost all frameworks do finish mutating the DOM within the predefined time budget of

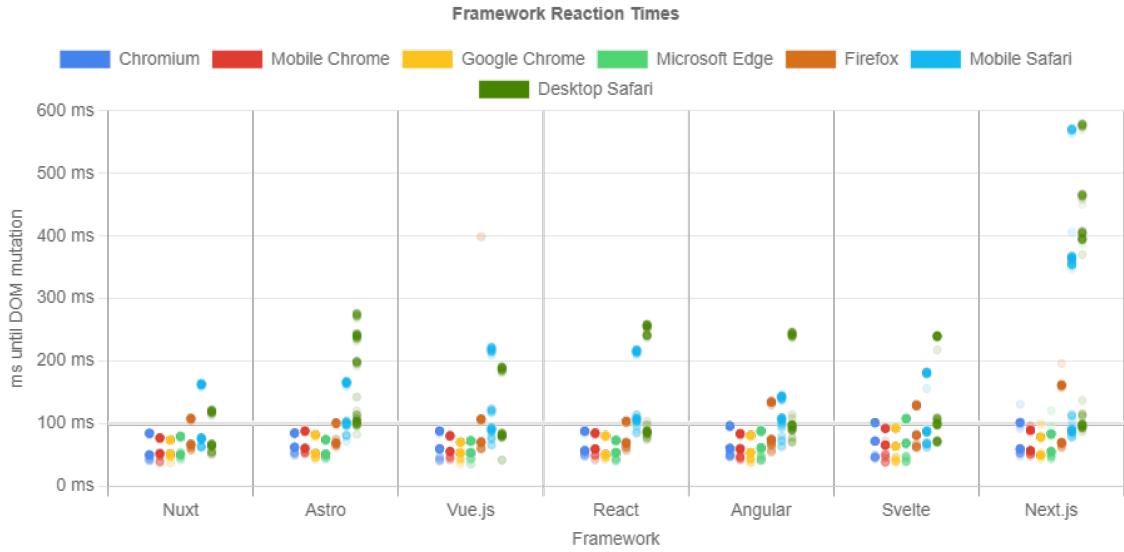
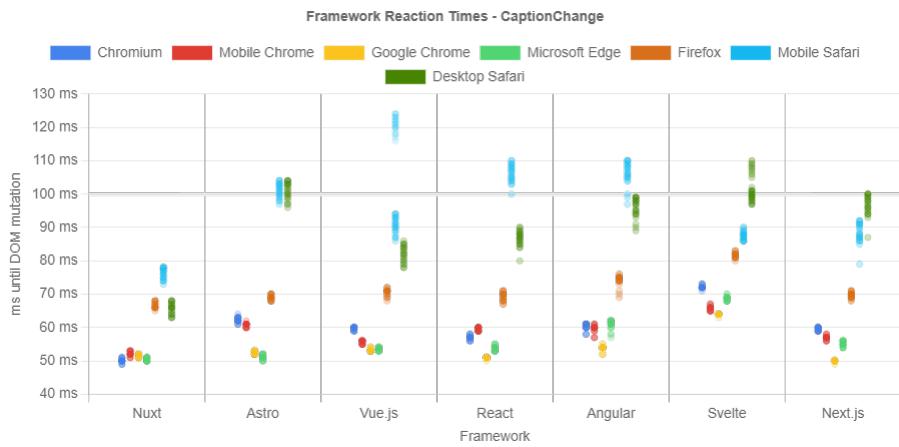


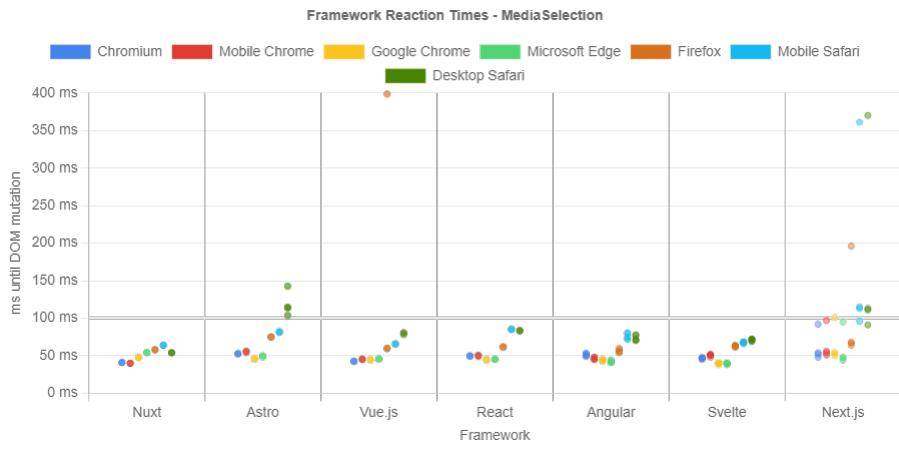
Figure 11: Recorded DOM mutation timings after user actions

500 ms. Slower mutations do speed up in test runs. As a result, the Playwright tests pass. In addition, the maximum time for mutations is decidedly dependent on the browser. While Desktop Safari apparently is the slowest browser for DOM mutations triggered by the user, especially with Next.js, almost all mutations in Chromium, Microsoft Edge and Google Chrome even finish within the time limit for earliest mutations of 100 ms. Mobile Chrome also shows the same characteristics with the exception of some mutations by Svelte and Next.js after the Post Creation action.

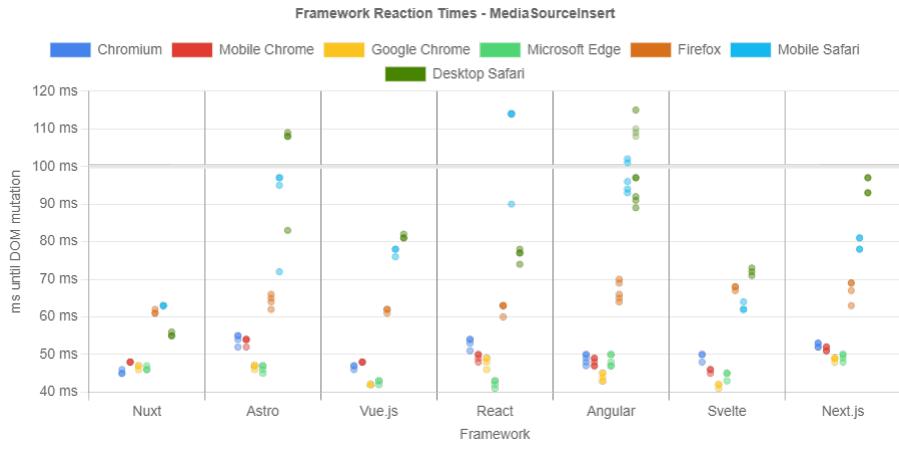
Figure 12 contains the update times of the four user actions per browser and framework. A few generalizations are possible to extract from these results. For the Caption Change (see figure 12a), Nuxt appears to be the fastest framework on all browsers except on Google Chrome where Next.js makes faster DOM mutations. Astro is also a relatively fast framework in Microsoft Edge and Google Chrome, but is is one of the slowest frameworks in Desktop Safari and Mobile Safari. In general, Nuxt, Next.js, Vue.js, React and Angular make DOM mutations in under 70 ms in Chromium, Mobile Chrome, Microsoft Edge and Google Chrome. Svelte on the other hand is apparently the slowest framework for this user action on average. The recorded DOM mutation times for Media Selection can be found in figure 12b. Most of the mutations are below the 100 ms time limit with only few exceptions. Astro is slower than the limit in Desktop Safari, Next.js is slower in Google Chrome, Mobile Safari and Desktop Safari and Vue.js has an outlier measurement in Firefox. Here, Nuxt, Vue.js, React, Angular and Svelte have similarly well to each other. Apart from the mentioned outliers, the results from these frameworks lie between 38 and 85 ms. The measurements for the Media Source Insert action are very similar to the Media Selection action (see figure 12c). Again, Nuxt performs very fast in all browsers and all frameworks are somewhat similar to each other except in Firefox, Mobile Safari and Desktop Safari. The latter two are again the slowest browsers on average and Firefox is the third slowest. In these browsers, Nuxt and Svelte



(a) Mutations after Caption Change

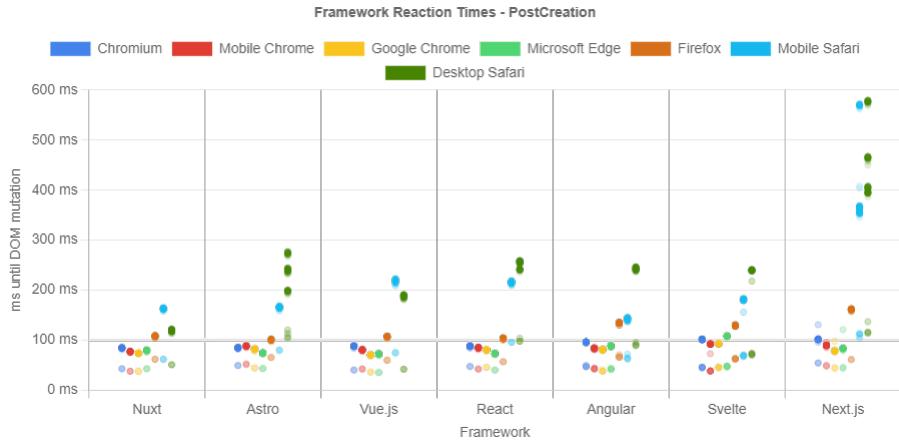


(b) Mutations after Media Selection



(c) Mutations after Media Source Insert

Figure 12: Recorded DOM mutation timings per framework



(d) Mutations after Post Creation

Figure 12: Recorded DOM mutation timings per framework

are the fastest frameworks. The Post Creation action is the slowest user action to finish (see figure 12d), which is unsurprising because it is combined from two other actions. It is therefore impossible to finish faster than either single user action. The update times for each user action can even be seen in two distinct groupings in the recordings. For this action, Next.js is clearly the slowest framework in relation to its competitors, but this difference is only significant on Desktop Safari and Mobile Safari.

Across all user actions, applications mutate the DOM slowest in Mobile Safari and Desktop Safari, closely followed by Firefox. The other browsers Chromium, Mobile Chrome, Google Chrome and Microsoft Edge lie very close to each other and the average mutations times differ from each other at a maximum of 15 ms.

Table 8 lists the minimal and maximal mutation times of the frameworks in each browser, as well as the mean average for each combination. In addition, the mean average and weighted averages of all minima, maxima and averages of mutation times in each framework are calculated. The weighted averages are based on the usage percentages of browsers (see table 7). These results indicate clearly that Next.js produces the slowest mutations both on average and weighted average. In contrast, Nuxt makes the fastest updates across browsers. Then, Angular comes in second, Vue.js is third and React is the fourth-fastest framework. The second-slowest framework on average is Astro, but it comes in faster than Svelte in the ranking of frameworks when the weights are calculated in.

Browser	Usage quota
Google Chrome	65.68 %
Desktop Safari	17.96 %
Microsoft Edge	5.26 %
Firefox	2,75 %
Chromium	NA
Mobile Chrome	NA
Mobile Safari	NA

Table 7: Browser usage (StatCounter, 2024)

As indicated earlier, Google Chrome and Microsoft Edge are the fastest and Desktop Safari and Mobile Safari are the slowest browsers across frameworks on average. The highlighted fastest and slowest values for minimum, mean average and maximum recorded mutation times verify these assessments. The fastest times are all recorded in Google Chrome and slowest in Desktop Safari. Notably, both the slowest first mutation and the fastest average and last mutation are recorded in Astro. Based on the average per browser, the ranking of fastest browsers by component update time is as follows:

1. Google Chrome
2. Microsoft Edge
3. Chromium
4. Mobile Chrome
5. Firefox
6. Mobile Safari
7. Desktop Safari

6 Summary

The previous chapter has presented the results to the proposed measurements. The purpose of this chapter is to summarize the results as to which framework performs well in which metric category and in which browser the applications perform well. Table 9 displays the number of passed, failed and flaky tests. Flaky tests fail at least once, but pass in any of the test runs. Across all Playwright tests, Angular and Nuxt share the first place of most passed tests. Next.js is third and the fourth place is shared by React and Vue.js. The fewest tests are passed by Svelte and Astro with 4 failed tests and 6 failed tests, respectively.

Page Load Time. Concerning the Page Load behaviour, the results do not favor any one framework. Frameworks that have fast load times when being inspected through one metric, demonstrate worse performances in other metrics. In

	Angular	Astro	Next.js	Nuxt	React	Svelte	Vue.js	Framework Avg.
Chromium	44	51	47	39	44	38	51	45
	69	71	75	66	58	74	77	70
Firefox	54	63	59	59	54	60	52	57
	89	99	142	83	84	94	82	96
Desktop Safari	77	87	79	51	84	70	47	71
	123	170	304	86	169	164	136	146
Mobile Chrome	44	49	47	42	44	45	46	45
	67	69	94	61	67	81	69	73
Mobile Safari	52	78	73	47	67	56	52	51
	106	154	196	110	126	126	133	136
Microsoft Edge	43	44	46	37	41	40	40	42
	70	64	73	61	62	74	61	67
Google Chrome	41	43	41	34	40	39	37	39
	62	57	69	60	59	64	61	62
Browser Avg.	51	59	56	44	53	50	46	
Weighted Br. Avg.	84	98	136	75	89	97	88	
	115	142	226	105	138	146	123	
	45	48	45	35	45	42	36	
	69	74	107	60	75	78	70	
	94	103	167	80	110	118	93	

	Framework
Browser	minimum with framework in browser average with framework in browser maximum with framework in browser
Browser Average	average of minima across browsers total average across browsers average of maxima across browsers

Table 8: Minimum, average and maximum of recorded mutation times after user input in milliseconds (fastest times are highlighted green, slowest red)

	Passed	Flaky	Failed
Angular	112	0	0
Nuxt	112	0	0
Next.js	111	0	1
React	110	2	0
Vue.js	110	2	0
Svelte	108	0	4
Astro	103	3	6

Table 9: Total passed, flaky and failed Playwright tests per framework

their Total Byte Weight, Next.js, Astro and Svelte are the leading frameworks with their small byte size. Svelte, Next.js, Vue.js and especially Astro have fast Time To Interactive results in this application. In Addition, Astro, Angular, Svelte, Nuxt and Vue.js stand out through little fluctuations in TTI across pages and test runs. Astro and Svelte also beat their competition in Total Blocking Time. In contrast, Vue, React and Nuxt are the fastest frameworks when the domContentLoaded or raw loadEventEnd events are timed. These metrics show the weaknesses of Astro and Svelte. Vue.js and React are also the fastest frameworks in OLVC. Within these metrics, rankings of the frameworks can be created, even if the rankings do not match across metrics. Other metrics in the category do not support such a ranking. For example, the Time To First Byte also shows a dependency on the page content and host, which often influences the results more than the chosen framework. However, Astro, Next.js and Angular show slow results. The balanced loadEventEnd highlights Vue.js and React positively, but also demonstrates the differences between browsers clearly.

Component Load Time. The metrics for the Component Load Time have similar characteristics as with the Page Load Times. Overlapping metrics (TBT, OLVC, TTI and loadEventEnd) focus positively on Astro, Svelte, Vue.js, React and Next.js, but they do not all have good results in every one of those metrics. The OFVC of the applications are early in Astro, React and Next.js. Only React translates this dominant property over its competitors to OVCD, where it is joined by Vue.js and Angular. These groupings of frameworks in OFVC, OLVC and OVCD is due to the fact that performing well in all three metrics is very difficult to achieve. The recordings of early DOM mutations favor Angular, Astro, Vue.js and React based on their CSR.

Component Update Time In contrast, the measurements made for the Component Update Times do indicate clear rankings of frameworks and browsers. Nuxt, Vue.js and Svelte are economical with DOM mutations. The other tested frameworks Next.js, React, Angular and Astro mutate the DOM more often. However, the times of mutations are close to each other, except in Mobile Safari and Desktop Safari. In only these two browsers, Next.js is the slowest and Nuxt is the fastest framework. The recorded times of DOM mutations permit the creation of rankings of browsers and frameworks. The browsers rank fastest to slowest Google Chrome,

Microsoft Edge, Chromium, Mobile Chrome, Firefox and Mobile Safari and then Desktop Safari. Judging from this ranking, it is the easiest to test below a predefined time budget in Google Chrome and hardest in Desktop Safari. The resulting ranking of frameworks for the Component Update Times of the example application is from fastest to slowest Nuxt, Angular, Vue.js, React, Astro/Svelte and Next.js. This ranking can influence the choice of frameworks for user input heavy applications. For this kind of web application, Nuxt, Angular, Vue.js and React present themselves as the best choices in regard of Component Update Times.

1. Nuxt
2. Angular
3. Vue.js
4. React
5. Astro & Svelte
6. Next.js

7 Concluding remarks

This thesis has presented a study comparing mainstream JavaScript frameworks based on an example application. To this end, a web application was designed based on the Android mobile app of Instagram and three rendering phases were identified to categorize measurement: the page load as representative for pure HTML websites, the load time of JavaScript components and the update time of JavaScript components. In this study, Angular, Astro, Next.js, Nuxt, React, Svelte and Vue.js were contrasted with each other. The measurement results show that the results are not clear-cut towards any framework, but rather indicate tendencies of load and update speeds of frameworks, browsers, page types, hosting environments and implementation. All frameworks display strengths in at least one metric relating to page and component load. Component update time is the only metric category outlining fast and slow frameworks, as well as browsers. Google Chrome and Microsoft Edge turn out to be the fastest of the compared browsers. Nuxt appears to be the fastest framework. On the other end of the spectrum, Mobile Safari and Desktop Safari as well as Next.js produce slow component update times.

For real-word business projects it is commendable to see about additional constraint beyond the mere greenfield performance of web development frameworks. Obviously as seen in this study, the browser usage of users should be taken into consideration, especially with Mobile Safari and Desktop Safari. If the used browsers are known, budgets for any tested metrics should be adapted to match expectations based on the results presented in this study. Additionally, results have shown that performance measurements fluctuate to up to 30 % in either direction. Therefore, all performance tests should be executed multiple times before a test should be considered passing. This recommendation should especially be considered when

comparing frameworks, as shown in this work.

Future works might find solutions for uncovered difficulties with testing strategies and missing data in this study.

First, the measurements do not cover navigation between the pages, but only the load behaviour of single pages. The current expectation is that navigation measurements would favor Angular applications because no additional JavaScript files have to be loaded on navigation to another page. Especially the byte weight of pages might be compensated in favor of Angular for this reason.

Second, the actual time between updates to the application's state and visual changes in the user's viewport are skipped in this study with the goal of keeping measurement methods as open as possible. Solutions to this end include white-box testing and might involve triggering custom events on state updates that are registerable in a testing suite.

Third, the interpretations of test results uncovered trade-offs relating to the initialization and end of recording. A slow interval for initialization of the MutationObserver for DOM mutations makes results comparable to other test execution, but also leads to missing data for early mutations between injection of the recording script and initialization of the MutationObserver. This might be solved through a different initialization process, e.g. including the recording script into the application's code. Additionally, the end of the recording time frame has two possible conflicts. Components that load slower than ten seconds are not recorded at all and components that update periodically, such as a digital clock component, are also not properly recorded. For the former, no solution is currently apparent except a longer recording, which does not fully solve the problem. A solution for the latter conflict is implemented by setting a custom HTML attribute `skipPerformance="true"` to elements that should be ignored for the recording. A different approach might open opportunities to improve the registration of a fully loaded application in test suites apart from the events of the HTML standard.

Lastly, this study only covers four pages of a single application, two hosting environments and up to 20 repetitions per Lighthouse test and three repetitions of Playwright tests if the test fails. Future work should verify the results by repeating the measurements of the example application of this study with more test runs to eliminate fluctuations. Also, insights into differences in performance and considerations for tests might be gained through the addition of pages for all page types and the usage of other hosting environments.

A Acknowledgements

I would like to thank the following people, without whom I would not have been able to complete this thesis, and without whom I would not have made it through my masters degree: My supervisors Prof. Dr. Toenniessen, for his enthusiasm and patience and the opportunity to pursue this topic, and Stephan Soller for his humorous approach to web development, his guidance and his ability to put problems into context.

Nikolai Thees, M.Sc, and Dominik Ratzel, B.Sc, for their support in the creation process of this thesis, without whom it would never have this few errors it has now (hopefully). To my best friend Erik for reminding me that it could always be worse. My partner Anna-Lena - I simply could not have done it without your calmness and straight-forwardness, special thanks. My father Dr. Bernhard Nicklaus for never letting any of my laziness slide. And to my loving parents, who supported and encouraged me to embark on this M.Sc. endeavour - what feels like a long time ago.

B Listings

1	About page in Vue.js (as displayed in figure 5)	25
2	Create page in Vue.js (Template)	26
3	Create page in Vue.js (Script)	27
4	Post in Vue.js (Template)	27
5	Post in Vue.js (Script)	28
6	Create page in Astro (Frontmatter)	29
7	Create page in Astro (HTML)	29
8	Create form in Astro	30
9	MediaComponent in Vue.js (Template)	31
10	MediaComponent in Vue.js (Script)	32
11	Automation script for Lighthouse tests	34
12	Test configuration for Lighthouse tests	36
13	Trigger script for Playwright tests	37
14	Playwright configuration for Vue.js	37
15	Test file for page load times	39
16	Test pages configuration	39
17	Test file for component load times	40
18	Injected mutation recorder script	41
19	Test file for component update times	44
20	MediaComponent in Next.js	69
21	MediaComponent in Nuxt (Script)	70
22	MediaComponent in React	70

```

1 // MediaComponent.js
2 import { createRef, useEffect, useState } from "react";
3 import styles from "./MediaComponent.module.css"
4 import Image from "next/image";
5 import { playPauseVideo } from "@utils/autoplay";
6
7 const MediaComponent = ({ src, alt, width, height, className, id,
8   priority = false }) => {
9   let [mediaSource, setMediaSource] = useState("")
10  let videoRef = createRef()
11
12  useEffect(() => {
13    if (videoRef.current) playPauseVideo(videoRef.current)
14    try {
15      if (src.startsWith('http')) setMediaSource(src)
16      else setMediaSource(
17        require(`@/assets/stock-footage/${src}`).default
18      )
19    } catch (error) {
20      setMediaSource("")
21    }
22  }, [videoRef, src])
23
24  if (
25    mediaSource &&
26    (
27      (mediaSource.src && mediaSource.src.endsWith('jpg')) ||
28      (src.startsWith('http') && src.endsWith('jpg'))
29    )
30  ) return (
31    <div style={{ position: "relative", aspectRatio: 1, width:
32      width == "100%" ? width : `${width}px`, overflow: "hidden"
33      }} id={id} className={[className, styles.postMedia].join(" "
34      )}>
35      <Image priority={priority}
36        placeholder={src.startsWith('http') ? "empty" : "blur"}
37        quality={50} src={mediaSource} alt={alt}
38        width={width.endsWith("%") ? 600 : width} height={height
39        || (width.endsWith("%") ? 600 : width)} />
40    </div>
41  )
42  else if (mediaSource && mediaSource.endsWith('mp4')) return (
43    <video ref={videoRef} key={mediaSource} className={[className,
44      styles.postMedia].join(" ")} id={id} width={width}
45      preload="metadata" controls
46      controlsList="nodownload,nofullscreen,noreMOTEplayback"
47      disablePictureInPicture loop muted >
48      <source src={mediaSource} type="video/mp4" />
49    </video>
50  )
51  else return (
52    <div className={styles.mediaError}>
53      <p>Nothing to see yet...<br />Choose an image to
54      continue!</p>

```

```

43     </div>
44 }
45
46 export default MediaComponent

```

Listing 20: MediaComponent in Next.js

```

13 // MediaComponent.vue
14 const glob = import.meta.glob("~/assets/stock-footage/*.mp4", {
15   eager: true });
16 const media = Object.fromEntries(
17   Object.entries(glob).map(([key, value]) => [
18     key.split("/")[key.split("/").length - 1],
19     value.default,
20   ]));
21
22 export default {
23   name: "MediaComponent",
24   props: {
25     src: { type: String },
26     alt: { type: String, default: "" },
27     width: String,
28     height: String,
29     preset: String,
30     priority: { type: Boolean, default: false },
31   },
32   computed: {
33     mediaSource() {
34       if (this.src.endsWith(".mp4")) return media[this.src];
35       return this.src;
36     },
37   },
38   mounted() {
39     const video = this.$refs.video;
40     if (video) playPauseVideo(video);
41   },
42 };

```

Listing 21: MediaComponent in Nuxt (Script)

```

1 // MediaComponent.js
2 import { createRef, useEffect, useState } from "react";
3 import styles from "./MediaComponent.module.css"
4 import { playPauseVideo } from "src/utils/autoplay";
5
6 const MediaComponent = ({ src, alt, width, height, className, id,
7   priority = false }) => {
8   let [mediaSource, setMediaSource] = useState("")
9   const videoRef = createRef()
10  useEffect(() => {

```

```

11     if (videoRef.current) playPauseVideo(videoRef.current)
12     try {
13       setMediaSource(src.startsWith('http') ? src :
14         require('src/assets/stock-footage/${src}'))
15     } catch (error) {
16       setMediaSource('')
17     }
18   }, [src, mediaSource, videoRef])
19
20   if (mediaSource.endsWith('webp')) return (
21     <img loading={priority ? "eager" : "lazy"} src={mediaSource}
22       alt={alt} width={width} height={height}
23       className={[className, styles.postMedia].join(" ")} id={id}
24     />
25   )
26   else if (mediaSource.endsWith('mp4')) return (
27     <video ref={videoRef} className={[className,
28       styles.postMedia].join(" ")} id={id} width={width}
29       preload="metadata" controls
30       controlsList="nodownload,nofullscreen,noreMOTEplayback"
31       disablePictureInPicture loop muted>
32       <source src={mediaSource} type="video/mp4" />
33     </video>
34   )
35   else return (
36     <div className={styles.mediaError} styles={{ height: (height ?
37       height + 'px' : '300px'), width: width.endsWith("%") ?
38       width : width + "px" }}>
39       <p>Nothing to see yet...<br />Choose an image to
40       continue!</p>
41     </div>
42   )
43 }
44
45 export default MediaComponent

```

Listing 22: MediaComponent in React

C List of Figures

1	Screenshots of the NotInstagram application's pages (path in parentheses)	10
2	Pages, components and services of the NotInstagram application	11
3	Classes used by the NotInstagram services	11
4	Timing attributes defined by the PerformanceTiming interface and the PerformanceNavigation interface (W3C, 2012)	14
5	Graphical subdivision of the About page into components	24
6	Adapted component structure for Astro Islands	31
7	Lighthouse test results in Google Chrome	48
7	Lighthouse test results in Google Chrome	49
7	Lighthouse test results in Google Chrome	50
8	Measured loadEventEnd timings	55
9	Observed First Visual Change (OFVC) (a) and Observed Visual Change Duration (OVCD) (b)	56
10	Component load mutation times	57
11	Recorded DOM mutation timings after user actions	60
12	Recorded DOM mutation timings per framework	61
12	Recorded DOM mutation timings per framework	62

D Acronyms

CI/CD	Continuous Integration and Continuous Delivery.
CLI	Command Line Interface.
CSR	Client-side Rendering.
CSS	Cascading Style Sheet.
DOM	Document Object Model.
FVC	First Visual Change.
HTML	Hypertext Markup Language.
HTTP	Hypertext Transfer Protocol.
JS	JavaScript.
JSON	JavaScript Object Notion.
LCP	Largest Contentful Paint.
LVC	Last Visual Change.
OFVC	Observed First Visual Change.
OLVC	Observed Last Visual Change.
OVCD	Observed Visual Change Duration.
PWA	Progressive Web App.
SEO	Search Engine Optimization.
SSR	Server-side Rendering.
SVG	Support Vector Graphic.
TBT	Total Blocking Time.
TBW	Total Byte Weight.
TTFB	Time To First Byte.
TTI	Time To Interactive.
URL	Uniform Resource Locator.

E References

Aqeel, W., Chandrasekaran, B., Feldmann, A., and Maggs, B. M. (2020). On landing and internal web pages: The strange case of jekyll and hyde in web performance measurement. In *Proceedings of the ACM Internet Measurement Conference*, IMC '20, page 680–695, New York, NY, USA. Association for Computing Machinery.

Bierman, G., Abadi, M., and Torgersen, M. (2014). Understanding typescript. In Jones, R., editor, *ECOOP 2014 – Object-Oriented Programming*, pages 257–281, Berlin, Heidelberg. Springer Berlin Heidelberg.

Chopin, S., Parsa, P., Roe, D., Fu, A., Licher, A., Wilton, H., Lucie, and Huang, J. (2024). Installation. <https://nuxt.com/docs/getting-started/installation>. accessed 08/07/2024.

Crook, T., Frasca, B., Kohavi, R., and Longbotham, R. (2009). Seven pitfalls to avoid when running controlled experiments on the web. In *Proceedings of the 15th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, KDD '09, page 1105–1114, New York, NY, USA. Association for Computing Machinery.

Devographics (2024). State of javascript 2023. <https://2023.stateofjs.com/en-US/libraries/front-end-frameworks/>. accessed 07/29/2024.

Domènech, J., Gil, J. A., Sahuquillo, J., and Pont, A. (2006). Web prefetching performance metrics: A survey. *Performance Evaluation*, 63(9):988–1004.

Gerpott, T. J. (2018). Relative fixed internet connection speed experiences as antecedents of customer satisfaction and loyalty: An empirical analysis of consumers in germany. *Management & Marketing*, 13(4):1150–1173.

Google (2019a). Eliminate render-blocking resources. <https://developer.chrome.com/docs/lighthouse/performance/render-blocking-resources>. accessed 08/01/2024.

Google (2019b). Lighthouse variability. <https://developers.google.com/web/tools/lighthouse/variability>. accessed 08/01/2024.

Google (2020). Largest contentful paint. <https://developer.chrome.com/docs/lighthouse/performance/lighthouse-largest-contentful-paint>. accessed 07/28/2024.

Google LLC (2024). Setting up the local environment and workspace. <https://angular.dev/tools/cli/setup-local>. accessed 08/07/2024.

Grigorik, I. (2013). *High Performance Browser Networking*. O'Reilly Media, Inc., 1005 Gravensetin Hwy North, Sebastopol, CA 95472.

Instagram from Meta (2024). Instagram. <https://www.instagram.com/>. accessed 08/02/2024.

Krishnamurthy, B. and Wills, C. E. (2000). Analyzing factors that influence end-to-end web performance. *Computer Networks*, 33(1):17–32.

Li, Z., Zhang, M., Zhu, Z., Chen, Y., Greenberg, A., and Wang, Y.-M. (2010). Webprophet: automating performance prediction for web services. In *Proceedings of the 7th USENIX Conference on Networked Systems Design and Implementation*, NSDI’10, page 10, USA. USENIX Association.

MDN Mozilla (2024a). Intersectionobserver. <https://developer.mozilla.org/en-US/docs/Web/API/IntersectionObserver>. accessed 08/06/2024.

MDN Mozilla (2024b). Render-blocking. https://developer.mozilla.org/en-US/docs/Glossary/Render_blocking. accessed 08/09/2024.

Meenan, P., Visconti, R., Calvano, P., Pollard, B., and Ostapenko, M. (2024). Http archive: Page weight. <https://httparchive.org/reports/page-weight>. accessed 09/03/2024.

Menasce, D. (2002). Load testing of web sites. *IEEE Internet Computing*, 6(4):70–74.

Meta Platforms, Inc. (2024). Getting started. <https://legacy.reactjs.org/docs/getting-started.html>. accessed 08/07/2024.

Pourghassemi, B., Amiri Sani, A., and Chandramowliswaran, A. (2019). What-if analysis of page load time in web browsers using causal profiling. *Proc. ACM Meas. Anal. Comput. Syst.*, 3(2).

Raine, A. (2024). Why are the metric values with observed different from those without observed? <https://github.com/GoogleChrome/lighthouse/discussions/14190#discussioncomment-3093932>. accessed 08/18/2024.

Schott, F. K. (2024a). Astro islands. <https://docs.astro.build/en/concepts/islands/>. accessed 09/03/2024.

Schott, F. K. (2024b). Install and set up astro. <https://docs.astro.build/en/install-and-setup/>. accessed 08/07/2024.

StatCounter (2024). Quick start. <https://gs.statcounter.com/>. accessed 07/18/2024.

Subraya, B. (2006). *Integrated Approach to Web Performance Testing: A Practitioner’s Guide*. Idea Group Inc., 701 E Chocolate Avenue, Suite 200, Hershey PA 17033-1240.

Sundaresan, S., Feamster, N., Teixeira, R., and Magharei, N. (2013). Community contribution award – measuring and mitigating web performance bottlenecks in broadband access networks. In *Proceedings of the 2013 Conference on Internet Measurement Conference*, IMC ’13, page 213–226, New York, NY, USA. Association for Computing Machinery.

Svelte (2024). Introduction. <https://svelte.dev/docs/introduction>. accessed 08/07/2024.

Vercel, Inc. (2024). Installation. <https://nextjs.org/docs/getting-started/installation>. accessed 08/07/2024.

W3C (2012). Navigation timing. <https://www.w3.org/TR/navigation-timing/>. accessed 07/10/2024.

Web Hypertext Application Technology Working Group (2024). Html living standard. <https://html.spec.whatwg.org/multipage/dom.html#current-document-readiness>. accessed 07/30/2024.

You, Evan (2024). Quick start. <https://vuejs.org/guide/quick-start.html>. accessed 08/07/2024.

Zhou, M., Giyane, M., and Nyasha, M. (2013). Effects of web page contents on load time over the internet. *International Journal of Science and Research (IJSR)*, pages 2319–7064.

GitHub repository: All code and additional material can be found under <https://github.com/andreasnicklaus/master>.

F List of Tables

1	List of selected frameworks. Items with both Client-side Rendering (CSR) and Server-side Rendering (SSR) render some pages or components upon request, but also require Client-side Rendering (CSR). Previous Experience refers to the author's experience in developing web applications with the framework.	12
2	Build and host command for each used framework as used for testing the applications hosted locally	15
3	Assignment of metrics to the metric categories	17
4	Assignment of metrics to the test tools	22
5	Passed Playwright page load tests per framework	53
6	Total number of DOM mutation types per framework and user action	59
7	Browser usage (StatCounter, 2024)	63
8	Minimum, average and maximum of recorded mutation times after user input in milliseconds (fastest times are highlighted green, slowest red)	64
9	Total passed, flaky and failed Playwright tests per framework	65
11	List of recorded mutations during caption change (empty cells indicate that an element is not present, “-” indicates no mutations) . . .	78
12	List of recorded mutations during media selection (empty cells indicate that an element is not present, “-” indicates no mutations) . . .	79
13	List of recorded mutations during Source insertion (empty cells indicate that an element is not present, “-” indicates no mutations) . . .	80
14	List of recorded mutations during post creation (empty cells indicate that an element is not present, “-” indicates no mutations)	81

HTML element	Angular	Astro	Next.js	Nuxt	React	Vue.js	Svelte
<main>	-	-	-	-	-	-	-
Create-Component	-	-	-	-	-	-	-
<form>	attribute	-	-	-	-	-	-
<input>	-	-	attribute	-	-	-	-
<select>	-	-	-	-	-	-	-
<textarea>	attribute	text-content	text-content	-	text-content	-	-
<button>	-	-	-	-	-	-	-
Post-<div>	-	-	-	-	-	-	-
MediaComponent-<div>	-	-	-	-	-	-	-
 / <picture>	-	-	-	-	-	-	-
Caption-<p>	child	child	child	child	child	child	child
Caption-	added	added	added	added	added	added	added
- (not updated)	8	7	6	7	6	8	8
attribute	2	0	1	0	0	0	0
text-content	0	1	1	0	1	0	0
added	1	1	1	1	1	1	1
Total Changes	3	2	3	1	2	1	1

Table 11: List of recorded mutations during caption change (empty cells indicate that an element is not present, “-” indicates no mutations)

HTML element	Angular	Astro	Next.js	Nuxt	React	Vue.js	Svelte
<main>	-	-	-	child	-	-	-
Create-Component	-	child					
<form>	attribute	-	-	-	-	-	-
<input>	-	-	attribute	-	-	-	-
<select>	attribute	-	-	-	-	-	-
<textarea>	-	-	-	-	-	-	-
<button>	-	-	-	-	-	-	-
Post-<div>	-			child	child		
MediaComponent-<div>	child		child & attribute				
 / <picture>	added	added		added	added	added	added
Caption-<p>	-	-	-	-	-	-	-
Caption-	-	-	-	-	-	-	-
- (not updated)	8	7	7	7	7	8	8
attribute	2	0	2	0	0	0	0
text-content	0	0	0	0	0	0	0
added	1	1	1	1	1	1	1
Total Changes	3	1	3	1	1	1	1

Table 12: List of recorded mutations during media selection (empty cells indicate that an element is not present, “-” indicates no mutations)

HTML element	Angular	Astro	Next.js	Nuxt	React	Vue.js	Svelte
<main>	-	-	child	child	-	-	-
Create-Component	-	child					
<form>	attribute	-		-	-	-	-
<input>	attribute	attribute	attribute	-	attribute	-	-
<select>	-	-	-	-	-	-	-
<textarea>	-	-	-	-	-	-	-
<button>	-	-	-	-	-	-	-
Post-<div>	-			child	child		
MediaComponent-<div>	child		child & attribute				
 / <picture>	added	added		added	added	added	added
Caption-<p>	-	-		-	-	-	-
Caption-	-	-	-	-	-	-	-
- (not updated)	8	7	7	7	6	8	8
attribute	2	1	2	0	1	0	0
text-content	0	0	0	0	0	0	0
added	1	1	1	1	1	1	1
Total Changes	3	2	3	1	2	1	1

Table 13: List of recorded mutations during Source insertion (empty cells indicate that an element is not present, “-” indicates no mutations)

HTML element	Angular	Astro	Next.js	Nuxt	React	Vue.js	Svelte
<main>	-	-	-	child	child	-	-
Create-Component	-	child					
<form>	attribute	-	-	-	-	-	-
<input>	-	-	attribute	-	-	-	-
<select>	attribute	-	-	-	-	-	-
<textarea>	-	text-content	text-content	-	text-content	-	-
<button>	attribute	attribute	attribute	attribute	attribute	attribute	attribute
Post-<div>	-				child	child	child
MediaComponent-<div>	child		child & attribute				
 / <picture>	added	added	added	added	added	added	added
Caption-<p>	child	child	child	child	child	child	child
Caption-	added	added	added	added	added	added	added
- (not updated)	5	4	3	4	3	5	6
attribute	3	1	3	1	1	1	1
text-content	0	1	1	0	1	0	0
added	2	2	2	2	2	2	2
Total Changes	5	4	6	3	4	3	3

Table 14: List of recorded mutations during post creation (empty cells indicate that an element is not present, “-” indicates no mutations)