Million.js: The Fastest Compiler-Augmented Virtual DOM for the Web

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ABSTRACT
Interactive web applications have increasingly dominated the modern internet, however, they are still created with tools that sacrifice both user and developer experience. This led me to create Million.js, the fastest compiler-augmented virtual Document Object Model (DOM) for the web. Million.js reduces load time and time-to-interactive by creating a compiler to pre-compute interactive regions of a web application before the user visits the page. The virtual DOM run-time optimizes interactive content through compiler flags, compute batching, scheduling, and reactive data primitives to achieve optimal performance. After comparative benchmarking, Million.js resulted in 133% to 300% faster rendering and 2347% faster load time compared with the most popular virtual DOM libraries. When Million.js is compared with a real-world web application with both comparative benchmarks and an informal user study, the initial findings show a 35% improvement in rendering speed compared to React. With Million.js, web developers can also use React’ Application Programming Interface (API) to create web applications. The findings show that through a React compatibility layer, web applications have the potential to be orders of magnitude faster than what is currently available.

Author Keywords
Web technologies; Web Frameworks; JavaScript; User interface (UI); Virtual DOM; Compilers; Optimization

CCS Concepts
•Human-centered computing → Web-based interaction;
•Information systems → Web applications;

INTRODUCTION

Web frameworks are transforming from runtime libraries into optimizing compilers ... my advice for anyone who wants to make a dent in the future of web development: time to learn how compilers work.

- Tom Dale [7]

Websites were initially written in Hypertext Markup Language (HTML) and Cascading Style Sheets (CSS) and designed to be static, which limited user interaction [35]. Eventually, browsers introduced JavaScript and the DOM to provide basic interactivity [23], however, web applications that required significant user interaction to operate suffered scaling and maintenance issues [38]. To support interactive web applications, single-page applications (SPA) were created to allow state-driven development (SDD) through the virtual DOM and its variants [12]. However, due to inefficient rendering strategies, SPA and virtual DOM based web applications have become slower to load and render on user devices [38], which can lead to worse user retention and experience [28, 11].

A wide variety of meta-frameworks (such as Next.js [32] and Astro [6]) are currently used as a solution to improve the load time of static content in web applications, but don’t address the virtual DOM’s fundamental problem of slow rendering speed on interactive content.

In fact, meta-frameworks like Next.js place the burden of rendering speed on the run-time virtual DOM, and are much less effective on highly interactive web applications. When web developers want to improve the rendering speed of interactive content, they have to fine tune their code with manual optimizations (e.g. memoization, conditional rendering, state management). This optimization process requires significant knowledge about virtual DOM internals and parity with other libraries. However, this already complex process may still not yield sufficient rendering speeds.

This paper presents Million.js, a virtual DOM that optimizes both load time and rendering speed. Million.js uses a compiler to optimize interactive content, and can be leveraged by meta-frameworks to greatly improve the performance of interactive web applications. Million.js has 133% to 300% faster rendering with the JS Framework Benchmark [20] and 2347% faster load time than React with the Chrome Devtools Performance benchmark [4].

Million.js integrates directly with React through a compatibility layer for users and projects who already use React. Million.js is implemented as an open-source JavaScript library, so web developers can use Million.js wherever they use JavaScript, primarily within browser environments. Million.js’ React compatibility layer is used in 85 open-source projects. In a real-world application using the Million.js React compe-
bility layer, there was a 35% improvement in rendering speed after migrating from React.

The paper makes the following contributions:

- Million.js—a compiler-augmented virtual DOM—released as open source software that can be downloaded and used today¹.
- the Million.js React compatibility layer, which allows web developers to use React’s existing API.
- a series of benchmarks and a real world test that measure the load time and rendering speed of Million.js.

RELATED WORK

Million.js extends prior work on SDD, SPA, and virtual DOM approaches in JavaScript UI library development.

Event-Driven Development

JavaScript library authors have created tools and libraries to simplify the process of creating web applications through more ergonomic APIs [39]. One of these libraries is jQuery, a widely used DOM utility library. jQuery was created to help developers solve issues and allow for cross-browser compatibility while providing a clean and easy syntax to use [25]. These innovations allowed jQuery to flourish in the JavaScript ecosystem, which is why it is used in many production websites today [29].

Although jQuery had a monumental impact on web development, many web developers faced problems with the imperative and unscalable event-driven API of jQuery and the DOM. While mostly static websites benefit from simple usage of the DOM or jQuery, as interactive web applications become more complex, the implementation logic also becomes more complex. In order to manage the code-base of such an interactive web application, web developers will need to create their own abstractions [24].

SDD and Virtual DOM

In order address the limitations of JavaScript and the DOM, software engineers at Facebook created React, a JavaScript UI library to abstract implementation logic. Along with React, the virtual DOM was created for SDD of web applications through a tree diffing algorithm to minimize DOM manipulations, reflows, and repaints [21].

The purpose of the virtual DOM is to provide a declarative way to update user interfaces. Figure 1 demonstrates updating the title text with the DOM with imperative steps, and Figure 2 demonstrates how the virtual DOM only requires a virtual representation of the DOM, or the virtual node tree, to update the UI using a declarative API. The virtual DOM concept is used during run-time with novel variations during the render process.

The virtual DOM tree diffing algorithm finds differences between the current virtual DOM tree and the new virtual DOM tree and applies the changes to the real UI (see Figure 3). The creation of the virtual DOM allowed for a new way of

¹https://github.com/aidenybai/million
declaratively developing state-driven web applications, allowing developers to express the UI without needing to describe control flow. This led to the incorporation of the virtual DOM in other JavaScript UI libraries like Ember 2.0 and Vue [14].

Such implementations of the virtual DOM differ from library to library due to API abstractions: React has its own domain-specific language (DSL) called JSX, which “provides an extension to JavaScript by adding XML-like syntax that is similar to HTML” [25]. React uses the virtual DOM through JSX inside functional components, a superset of JavaScript that compiles down to the virtual DOM, while Vue uses directives and Single-File Components (SFC) to set boundaries and compile to the virtual DOM. Thus, different API abstraction decisions in libraries allow developers to choose a JavaScript UI library that fits their project through the virtual DOM at the cost of load time and rendering speed [21].

Meta-frameworks

To improve load time, techniques like Server Side Rendering (SSR) and Static Site Generation (SSG) have led to the creation of meta-frameworks like Next.js [32], which augment and improve the load time of JavaScript UI libraries like React and Vue, using pre-rendering and hydration [25]. Pre-rendering turns the web application static for initial load, and hydration turns the static page into an interactive page. Meta-frameworks like Astro [6] are exploring how SSG and SSR can be optimized with partial hydration, a subset of hydration that includes only parts of the page interactive (Figure 4). These techniques, when combined with edge computing, can significantly improve the performance of web applications that require less interactivity, such as blogs or eCommerce websites.

Compiled JavaScript UI Libraries

While meta-frameworks such as Next.js have helped optimize static content, new JavaScript UI libraries, including Svelte, leverage an optimizing compiler to address the performance constraints of the interactive content of a web application [13]. Svelte uses reactive assignments to generate DOM manipulations instead of an intermediate representation of the DOM [25]. With this technique, Svelte significantly improves the performance of value-based UI updates but suffers from large structural UI updates [8] where the virtual DOM excels [10].

With explorations into compiled frameworks, fine-grained reactivity, and efficient hydration, comparative benchmark results of virtual DOM libraries are significantly slower in contrast to JavaScript UI libraries that utilize these new techniques [5].

I extend this prior work [37] by providing the first virtual DOM that integrates with compilers.

OVERVIEW OF MILLION.JS

Million.js is a compiler-augmented virtual DOM for the web. The software is an open-source JavaScript library and is published on Node Package Manager (NPM) and various Content Delivery Networks (CDN). The tool is built using the Type-Scrip language and can be used to build new JavaScript UI libraries or modify user interfaces directly. JavaScript UI libraries built with Million.js would be composable with each other and can be compatible with JavaScript UI libraries like React.

Million.js contains two key components: the virtual DOM runtime and the optimizing compiler. The virtual DOM run-time updates the UI, similar to current mainstream virtual DOM libraries. The optimizing compiler will analyze JavaScript and compute unnecessary work during compile time to reduce load time and speed up rendering. Together, the virtual DOM and the optimizing compiler allow for declarative UI development; in particular, it gives authors access to the underlying rendering process to construct customized JavaScript UI libraries [7].

To optimize for performance and developer usage, Million.js establishes three main design principles in Figure 2: fast load time, fast render speed, and ease of use. The virtual DOM suffers from slow load time and rendering speeds, so Million.js aims to improve them by increasing parity with DOM rendering speeds. Each principle is measured, and key results are established to measure the success of Million.js.

Implementation

The virtual DOM render process has three main steps: compile, diff, and patch as seen in Figure 1. Each phase is completed in different stages and has different purposes. The compile phase is executed once before the user visits the page, and the diff and patch phases are executed at run-time upon rendering.

| Principle          | DOM     | Virtual DOM | Million.js |
|--------------------|---------|-------------|------------|
| Load time          | 1x      | 27.1x slower| <1.5x slower |
| Render speed       | 1x      | 1.7x slower  | <1.1x slower |
| Developer friendly | N/A     | ~560 stars/year | 5.3k stars/year |

Table 1. Million.js design principles and Objective and Key Results (OKR) table. All objectives were achieved within one year. Million.js achieved under 1.2x load time, within <1.1x render speed, and over 5.3 thousand stars within a year. Load time is measured using Chrome DevTools and render speed with the JS Framework Benchmark.
Figure 5. Flowchart of Million.js virtual DOM render process separated into three steps. The compiler step optimizes the interactive content of a website. The diff step is a composable API that is used to calculate the changes to the UI when given the current and new UI. The patch step takes the calculated UI changes from the diff step and applies those changes to the UI.
Figure 6. Example of optimized UI update with the Million.js virtual DOM. The virtual DOM runs at run-time only, resulting in sub-optimal load and rendering speed. Million.js uses an optimizing compiler to reduce unnecessary work by rendering before the user visits the page.

Compile Step
The compile step can occur in conjunction with a meta-framework such as Next.js, or during build time with an SSG tool. Within the compile step, an optimizing compiler will statically analyze the DSL of the source code to find redundant or unnecessary code. While the meta-framework or SSG tool will pre-render the user interface (UI) and hydrate the HTML page, the compiler will optimize the interactive content as seen in Figure 5.

The optimizing compiler implements virtual node flattening and static tree hoisting to improve the load time and rendering speed of interactive content (see Figure 7). It targets the output of DSL compilation: hyperscript, a set of function calls that construct a virtual node tree at run-time. Hyperscript is used because it is an easy target for DSL compilation, but comes at the cost of unnecessary memory allocation during run-time. The virtual node flattening approach addresses this issue by flattening each function call within the hyperscript during the compile step, removing the need to allocate memory during run-time. Within virtual node flattening, compiler flags are assigned to reduce run-time computation (similar to Inferno [15, 16, 17]). Along with virtual node flattening, the static tree hoisting approach further reduces unnecessary memory allocation by moving flattened hyperscript that does not depend on the state to the global JavaScript scope.

Diff Step
The diff step occurs on the user’s device during run-time upon each render to calculate the changes to the UI when given the current and new UI. In Figure 3., the virtual DOM calculates the specific changes during the diff step and applies those changes to the UI during the patch step.

Diff and patch steps exist in some capacity within all virtual DOM implementations. However, Million.js improves the performance of the diff and patch steps by integrating fast paths for the compile step to reduce extraneous diffing. When fast paths are used during run-time, the virtual DOM allocates less memory and performs less computation, leading to faster load times and rendering speeds. These fast paths are keyed nodes, compiler flags, and delta. The methodology can be visualized in Figure 8.

```
// Hyperscript
function Component() {
  return h('div', null, 'Hello World')
}

// Flattened virtual node
function Component() {
  return {
    tag: 'div',
    children: ['Hello World'],
    flag: Flags.ONLY_TEXT_CHILDREN
  };
}

// Flattened + hoisted virtual node
const vnode = {
  tag: 'div',
  children: ['Hello World'],
  flag: Flags.ONLY_TEXT_CHILDREN
};

function Component() {
  return vnode;
}
```

Figure 7. Code samples of JSX, Hyperscript, flattened, and hoisted virtual node, ordered by less to more optimizations by the compiler. The latter two code samples are compiler optimizations exclusive to Million.js.

Figure 8. Example of fast path optimization represented as a to-do list. Step 1 is occurs during the compile step, step 2 is occurs during the diff step, and step 3 occurs during the patch step. Every step works together to optimize the rendering speed and load time of UI updates.
The keyed nodes approach is a run-time optimization that reduces the amount of computation needed by identifying virtual children nodes with a key. Each key represents a unique virtual node, meaning nodes can be moved instead of basic update and delete operations. Moving keyed nodes is a technique used in a special algorithm to reduce computation based off of [26], as seen in Figure 9. By removing the need to diff head and tail nodes, a key map can be generated to efficiently move nodes to reduce computation when changes between virtual children nodes are minimal.

Compiler flags are generated during the compile step to change the behavior of the diff step. They are used to infer the shape of virtual nodes during run-time to skip conditions of the diff step or invoke more efficient algorithms. By default, virtual nodes have the same flag, but when virtual children node edge cases are met, such as no children, only text children, or only keyed children, less computation is used to diff the virtual node.

Delta is special data that can be attached to virtual nodes that provide an escape hatch for imperative UI changes. Delta can be used by the compile step to skip the diff step entirely, or in run-time by the web developer. This is useful for list-like UI, such as post feeds or to-do lists.

Along with the aforementioned fast paths, Million.js amortizes computation with strategies like scheduling and batching. Traditionally, virtual DOM implementations use a single, uninterrupted, synchronous render. Once an update starts rendering, nothing can interrupt it until the user can see the result on the screen. This includes user interactions, meaning that the user cannot interact with the page until rendering is complete. Million.js introduces scheduling, which prioritizes more urgent CPU-bound updates (such as creating DOM nodes and running component code) and defers less important updates to user interactions. Batching is also used to cancel intermediate renders when similar updates are executed in succession and should be used in conjunction with scheduling.

The React Compatibility Layer
Million.js provides a fast underlying virtual DOM to update user interfaces. However, the virtual DOM is not intended to be directly used by web developers, as it does not provide concepts like state or components that define JavaScript UI libraries. Thus, I created a React compatibility layer that allows web developers to start existing or migrate React projects to Million.js, without having to re-learn a new API.

The React compatibility layer integrates with existing React projects like Vite and meta-frameworks like Next.js through a plugin. The plugin injects a run-time that imitates the React API implemented with Million.js internals. Some limitations of the API include new React version 18 features like concurrent mode features like Suspense [27], HTML streaming, and React Server Components [31].

One notable feature Million.js provides through the React compatibility layer is the useList hook (see Figure 10), a reactive data primitive (similar to Preact Signals [30]) that performs at optimal speeds with constant time complexity by bypassing the diff step altogether. Feeds or list-like UI have the potential for optimization. With traditional virtual DOM, lists have linear time complexity, meaning rendering speed and memory allocation gets worse as more entries are loaded. Through the Delta optimization, direct imperative UI changes can be made using the JavaScript Proxy API, greatly reducing the computation and increasing rendering speed.

EVALUATION
Three benchmarks are used to determine the performance of Million.js: a re-implementation of a subset of the JS Frame-
work Benchmark [20] measuring rendering speed, a Devtools performance benchmark measuring load time, and real-world application performance.

**JS Framework Benchmark**
I tested ten different measurement benchmark suites on seven different implementations of web page rendering using a subset of the JS Framework Benchmark, as seen in Figure 2. The first type of method is the raw rendering method:

- **DOM**
- **innerHTML**

The second type of method is the virtual DOM library:

- **Million.js**
- **snabbdom** [33]
- **virtual-dom** [9]
- **tiny-vdom** [3]
- **simple-virtual-dom** [22]

The virtual DOM libraries, except for Million.js and snabbdom, had fewer operations per second when compared with raw DOM rendering implementations, with the worst performing implementations being tiny-vdom and simple-virtual-dom.

Raw rendering implementations, like DOM and innerHTML had relatively higher operations per second in aggregate insertions or deletions, but relatively lower operations per second in partial or complex updates when compared to virtual DOM implementations. Additionally, implementations with keyed diffing, specifically Million.js and snabbdom, had higher operations per second when compared to the other virtual DOM libraries.

Additionally, Million.js has a much smaller bundle size at 0.75 kilobytes compared to snabbdom and virtual-dom, but slightly larger than tiny-vdom at 0.32 kilobytes (see Figure 3). Since Million.js has a composable API, the bundle size can become even lower through tree shaking and dead code elimination.

The geometric mean of benchmark results is visualized in Figure 3. Additionally, due to uncertainties with benchmark measurements, an average deviation of 1.856 operations per second is also visualized in Figure 11. The DOM method has the highest operations per second of the implementations tested, with a geometric mean of 105.7 operations per second. Million.js is relatively comparable to the DOM method and significantly outperforms the latter implementations by 133% to 300%.

**Devtools Performance Flamegraph**
I used the Chrome Devtools Performance benchmark [4] in order to measure the load time of common interactive UI-like feeds 2. The benchmark tests the total scripting time of different implementations to add 5000 DOM nodes to the UI consecutively with one iteration after a warm up round. I tested four different implementations:

- **Direct DOM updates**
- **Delta rendering**
- **Keyed rendering**
- **Virtual DOM rendering**

The latter three implementations use the React compatibility layer for Million.js, with Delta rendering using reactive data primitives, keyed rendering using the keyed nodes optimization, and virtual DOM being the default method of rendering Million.js provides.

Direct DOM updates yielded the lowest scripting time at 149 milliseconds as seen in Figure 12, with a small and consistent call stack. Delta rendering yielded a scripting time of 172 milliseconds as seen in Figure 13, and is 15% longer compared to direct DOM updates. Delta rendering showed characteristics of batching, with some scripting occurring before and after delta calculation shown in green and pink, which is what allows for such low overhead compared to direct DOM. The keyed rendering yielded a scripting time of 4022 milliseconds as seen in Figure 14, with a large call stack due to diff computation and is 2238% longer than direct DOM updates. The virtual DOM rendering yielded 4036 milliseconds as seen in Figure 15, with slightly more memory allocation than keyed rendering and is 2247% longer than direct DOM updates.

While direct DOM updates yielded the lowest scripting time of all implementations tested, Delta rendering was the fastest implementation that used the React compatibility layer, being 24 times faster than virtual DOM rendering.

**Real World Application Performance**
In order to assess real-world performance, I integrated the React compatibility layer into the Wyze Web View [36] web application (see Figure 16). The Wyze Web View runs on Next.js and displays a live video feed of smart home cameras. The Wyze Web View regularly receives thousands of unique sessions daily, and as a result, is a critical component in the Wyze smart home ecosystem. One of the main issues reported by many Wyze users was that the camera feed would take upwards of several minutes to load cameras completely.

By migrating the Next.js project from React to Million.js, the Wyze Web View experienced a 35.11% decrease in compute time taken to render all five cameras as seen in Figure 17. The React based implementation experienced a total compute time of 10126 milliseconds and a scripting time of 7497 milliseconds, and the new Million.js implementation experienced a total compute time of 6571 milliseconds, with a scripting time of 1650 milliseconds.

After migrating to the new Million.js implementation, an informal user study was conducted on ten active Wyze Web View users. All reported that they experienced a reduction in load time and less perceived lag with the new improvements.

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2 https://github.com/aidenybai/million-delta-react-test
### Table 2. JS Framework Benchmark compatible benchmarks tested on Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/94.0.4606.71 Safari/537.36. Green colors signify more operations per second, and red colors signify fewer operations per second. Million.js ranked the second best scores overall in the benchmark of seven implementations with the geometric mean of benchmarks at 98.8 operations per second.

| Method                                         | DOM   | million | innerHTML | snabbdom | virtual-dom | tiny-vdom | simple-virtual-dom |
|-----------------------------------------------|-------|---------|-----------|----------|-------------|-----------|-------------------|
| Append 1,000 rows to a table of 10,000 rows (ops/s) | 21.7  | 21.8    | 9.4       | 6.6      | 5.9         | 5.1       | 4.6               |
| Clear a table with 1,000 rows (ops/s)         | 207.0 | 190.0   | 172.0     | 128.0    | 97.7        | 93.7      | 64.1              |
| Create 10,000 rows (ops/s)                    | 36.8  | 30.5    | 36.1      | 22.2     | 22.3        | 12.9      | 9.3               |
| Create 1,000 rows (ops/s)                     | 36.0  | 30.3    | 35.8      | 22.2     | 22.4        | 12.7      | 9.0               |
| Update every 10th row for 1,000 rows (ops/s)  | 220.0 | 221.0   | 135.0     | 76.4     | 69.8        | 58.7      | 51.2              |
| Remove a random row from 1,000 rows (ops/s)   | 225.0 | 202.0   | 138.0     | 74.2     | 57.6        | 41.7      | 31.4              |
| Update 1000 rows (ops/s)                      | 119.0 | 127.0   | 123.0     | 50.7     | 55.5        | 42.3      | 33.2              |
| Select a random row from 1,000 rows (ops/s)   | 210.0 | 208.0   | 123.0     | 72.5     | 66.6        | 46.8      | 45.4              |
| Swap 2 rows for table with 1,000 rows (ops/s) | 224.0 | 198.0   | 118.0     | 73.5     | 57.9        | 46.8      | 31.6              |
| Geometric mean (ops/s)                        | 105.7 | 98.8    | 74.3      | 44.1     | 39.8        | 29.7      | 23.1              |

Table 3. Raw qualitative observations and quantitative JS Framework Benchmark compatible benchmarks with deviations. Million.js had a faster rendering than the DOM, the most optimal implementation, in the Update every 10th row for 1,000 rows and Update 1000 rows benchmarks. The geometric mean of benchmarks for Million.js was 98.76 operations per second with 3.88% deviation.

### Table 3

| Method                     | DOM   | million | innerHTML | snabbdom | virtual-dom | tiny-vdom | simple-virtual-dom |
|----------------------------|-------|---------|-----------|----------|-------------|-----------|-------------------|
| Append 1,000 rows to a table of 10,000 rows (ops/s) | 21.7  | 0.90%   | 21.78     | 3.33%    | 9.38        | 2.91%     | 6.6               |
| Clear a table with 1,000 rows (ops/s)               | 207.0 | 3.15%   | 207       | 4.32%    | 172.0       | 2.87%     | 128.0             |
| Create 10,000 rows (ops/s)                           | 36.83 | 4.56%   | 36.04     | 4.84%    | 36.05       | 4.57%     | 22.2             |
| Create 1,000 rows (ops/s)                            | 35.99 | 5.21%   | 35.82     | 4.57%    | 35.82       | 4.57%     | 22.2             |
| Update every 10th row for 1,000 rows (ops/s)        | 220.0 | 3.55%   | 220       | 3.31%    | 221.0       | 3.31%     | 135.0            |
| Remove a random row from 1,000 rows (ops/s)         | 225.0 | 5.22%   | 225       | 5.55%    | 221.0       | 3.31%     | 135.0            |
| Update 1000 rows (ops/s)                             | 119.0 | 1.91%   | 119       | 2.38%    | 127.0       | 3.33%     | 135.0            |
| Select a random row from 1,000 rows (ops/s)         | 210.0 | 5.88%   | 210       | 5.73%    | 210         | 5.73%     | 123.0            |
| Swap 2 rows for table with 1,000 rows (ops/s)       | 224.0 | 6.77%   | 224       | 4.41%    | 198.0       | 4.41%     | 118.0            |
| Geometric mean (ops/s)                               | 105.7 | 4.16%   | 105.7     | 3.88%    | 74.33       | 3.88%     | 44.1             |

Figure 11. Geometric means of render speeds for benchmarks measured in operations per second. Green colors signify more operations per second, and red colors signify fewer operations per second (higher is better). Million.js ranked the second best scores overall in the benchmark of seven implementations, ranging from 133% to 300% faster rendering speed.
Figure 12. Devtools performance results of node append benchmark of direct DOM updates tested on Mozilla/5.0 (Macintosh; Intel Mac OS X 10.15.7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/94.0.4606.71 Safari/537.36. Direct DOM update benchmark finished in 149 milliseconds.

Figure 13. Devtools performance results of node append benchmark of Delta rendering tested on Mozilla/5.0 (Macintosh; Intel Mac OS X 10.15.7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/94.0.4606.71 Safari/537.36. Delta rendering benchmark finished in 172 milliseconds.

Figure 14. Devtools performance results of node append benchmark of keyed rendering tested on Mozilla/5.0 (Macintosh; Intel Mac OS X 10.15.7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/94.0.4606.71 Safari/537.36. Keyed rendering benchmark finished in 4022 milliseconds.

Figure 15. Devtools performance results of node append benchmark of virtual DOM rendering tested on Mozilla/5.0 (Macintosh; Intel Mac OS X 10.15.7) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/94.0.4606.71 Safari/537.36. Virtual DOM rendering benchmark finished in 4022 milliseconds.

Figure 16. Example of Wyze Web View product page with five cameras. Wyze Web View is an interactive web application made by Wyze to view security camera footage and live feed. The web application receives thousands of unique daily users and is a good candidate to test real-world benchmarks.

Figure 17. Wyze Web View compute time breakdown, left is Million.js’ React compatibility layer and right is React. The React based implementation experienced a total compute time of 10126 milliseconds and the new Million.js implementation experienced a total compute time of 6571 milliseconds. Switching to Million.js resulted in a 35.11% faster load time.
DISCUSSION & FUTURE WORK

While the JS Framework Benchmark and the Devtools performance benchmark both are good indicators of rendering speed and load time for large page navigation occurs [18], the real-world application performance benchmark is important for assessing the viability of Million.js in a product application scenario.

In real-world web applications, it is the user code that often is the bottleneck to rendering. For instance, the Wyze Web View uses much of the load time to establish a connection to create video feeds. Furthermore, the real-world application benchmark and the Devtools performance benchmark primarily measure load time and don’t necessarily account for subsequent renderings, such as page navigations. Despite this, well-maintained and standardized benchmarks, such as the ones presented in this paper, can lead researchers to learn a lot about how Million.js behaves.

There is still much work to be done in this area. Million.js is open source and other researchers may use Million.js as a starting point for further extensions like new JavaScript UI libraries or high-performance web applications. In the future, more effort will go towards exploring more complex optimization techniques during compilation like static analysis to further improve load time and render speed for UI, increase compatibility with the React ecosystem, and integrate Million.js into more real-world web applications.

CONCLUSION

We presented Million.js, the fastest compiler-augmented virtual DOM for the web. The initial objectives (see Figure 1) of Million.js were to create a novel virtual DOM implementation with fast load time, fast render speed, and to make it easy for developers to use.

By leveraging an optimizing compiler and reactive data primitives to improve load time and render speed of UI, I successfully was able to achieve fast load time and fast render speed. I conducted two benchmarks to measure load time and render speed, showing that Million.js loads 23.47 times faster compared to virtual DOM and renders 133% to 300% faster than existing virtual DOM implementations.

I was also successfully able to increase developer use. Within one year, Million.js received over 5.1 thousand stars, becoming the third most starred virtual DOM library on GitHub (see Figure 18), and was featured in major developer publications like JavaScript Weekly, React Status, and React Newsletter. Furthermore, Million.js is actively used in 80 open-source projects on GitHub. The GitHub repository culminated in 1.5 thousand contributions, 166 pull requests, and 70 feature requests.

In the next decade, web users will continue to see improvement in load and rendering speeds for better user retention and experience [28, 11]. With inequality already exacerbated in low-income countries, being able to provide fast website load would provide better opportunities for people around the world. Places like India, whose population accesses the internet through low-end devices and Wi-Fi connections, suffer from a lack of UI rendering efficiency. As internet traffic rapidly shifts towards underdeveloped regions of the world, UI performance has never been more important.

USING MILLION.JS

Million.js is an open-source JavaScript package that users can download using NPM, a Node.js package manager. Million.js can be used in any JavaScript run-time with the JavaScript DOM API. Information on how to download Million.js and the source code can be accessed at https://millionjs.org.

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REFERENCES

[1] Markus Ast. 2016. Incremental DOM for Web Components. (2016). https://core.ac.uk/download/pdf/153229902.pdf#page=163
[2] Aiden Bai. 2022a. Contributors to aidenybai/million. (2022). https://github.com/aidenybai/million/graphs/contributors
[3] Aiden Bai. 2022b. tiny-vdom. (Sep 2022). https://github.com/aidenybai/hundred
[4] Kayce Basques. 2017. Analyze runtime performance. (Apr 2017). https://developer.chrome.com/docs/devtools/evaluate-performance/
[5] Ryan Carniato. 2021. A Look at Compilation in JavaScript Frameworks. DEV Community (Jun 2021). https://dev.to/this-is-learning/a-look-at-compilation-in-javascript-frameworks-3caj
