

BROWSIX: Bridging the Gap Between Unix and the Browser

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Abstract

Applications written to run on conventional operating systems typically depend on OS abstractions like processes, pipes, signals, sockets, and a shared file system. Porting these applications to the web currently requires extensive rewriting or hosting significant portions of code server-side because browsers present a nontraditional runtime environment that lacks OS functionality.

This paper presents BROWSIX, a framework that bridges the considerable gap between conventional operating systems and the browser, enabling unmodified programs expecting a Unix-like environment to run directly in the browser. BROWSIX comprises two core parts: (1) a JavaScript-only system that makes core Unix features (including pipes, concurrent processes, signals, sockets, and a shared file system) available to web applications; and (2) extended JavaScript runtimes for C, C++, Go, and Node.js that support running programs written in these languages as processes in the browser. BROWSIX supports running a POSIX shell, making it straightforward to connect applications together via pipes.

We illustrate BROWSIX's capabilities via case studies that demonstrate how it eases porting legacy applications to the browser and enables new functionality. We demonstrate a BROWSIX-enabled \LaTeX editor that operates by executing unmodified versions of pdfLaTeX and BibTeX. This browser-only \LaTeX editor can render documents in seconds, making it fast enough to be practical. We further demonstrate how BROWSIX lets us port a client-server application to run entirely in the browser for disconnected operation. Creating these applications required less than 50 lines of glue code and no code modifications, demonstrating how easily BROWSIX can be used to build sophisticated web applications from existing parts without modification.

CCS Concepts • Information systems → Browsers; • Software and its engineering → Operating systems

Keywords Browsix, browser, operating system, JavaScript

1. Introduction

Web browsers make it straightforward to build user interfaces, but they can be difficult to use as a platform to build sophisticated applications. Code must generally be written from scratch or heavily modified; compiling existing code or libraries to JavaScript is not sufficient because these applications depend on standard OS abstractions like processes and a shared file system, which browsers do not support. Many web applications are thus divided between a front-end UI that runs in the browser and a backend server. The backend runs on a traditional operating system, where the application can take advantage of familiar OS abstractions and run a wide variety of off-the-shelf libraries and programs.

As a representative example, websites like ShareLaTeX¹ and Overleaf² let users write and edit \LaTeX documents in the browser without the need to install a \TeX distribution locally. This workflow lowers the barrier for students and first-time \LaTeX authors and enables real-time collaboration, eliminating some of the complexity of creating multi-author documents. These applications achieve this functionality by providing a browser-based frontend for editing; user input is sent to the server for persistence and collaboration purposes. When the user requests a generated PDF, the website runs pdfLatex and bibtex server-side on the user's behalf, with the resulting PDF sent to the browser when complete.

These web applications generate PDFs server-side out of necessity because browsers lack the operating system services and execution environment that Unix programs expect. Creating PDFs from \LaTeX requires spawning multiple processes to run pdfLatex and bibtex, which need to read from and write to a shared file system. If PDF generation takes too long and the user cancels the request, the application needs to send a SIGTERM or SIGKILL signal to clean up any running processes. If PDF generation encounters an error, the application needs to pipe the output of the relevant process back to the client over the network. Since browsers

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¹<https://www.sharelatex.com/>

²<https://www.overleaf.com/>

do not support processes, signals, pipes, sockets, or a shared filesystem, they cannot perform any of these steps without program modification.

Previous attempts to cope with this impedance mismatch between conventional applications and the browser fall short of providing the environment needed by many programs (see Section 7). Emscripten and Doppio provide a POSIX-like runtime system for single processes, including a single-process file system, limited support for threads, synchronous I/O, and proxying support for TCP/IP sockets [13, 16]. While these single-process runtimes are useful for some applications, they are severely limited because they are unable to provide the range of operating system functionality that many legacy applications demand.

To overcome these limitations, we introduce BROWSIX, a framework that brings Unix abstractions to the browser through a shared kernel and common system-call conventions, bridging the gap between conventional operating systems and the browser. BROWSIX consists of two core components: (1) a JavaScript-only operating system that exposes a wide array of OS services that applications expect (including pipes, concurrent processes, signals, sockets, and a shared file system); and (2) extended JavaScript runtimes for C, C++, Go, and Node.js that let unmodified programs written in these languages and compiled to JavaScript run directly in the browser. Because BROWSIX’s components are written entirely in JavaScript and require no plugins, applications using BROWSIX can run in a wide range of unmodified modern web browsers including Google Chrome, Mozilla Firefox, Apple Safari, and Microsoft Edge. BROWSIX makes it possible to port a wide range of existing applications and their language runtimes to the browser by providing the core functionality of a full operating system:

- **Processes:** BROWSIX implements a range of process related system calls (including `fork`, `spawn`, `exec`, and `wait4`) and provides a process primitive on top of Web Workers, letting applications run in parallel and spawn subprocesses.
- **Signals:** BROWSIX supports a substantial subset of the POSIX signals API, including `kill` and signal handlers, letting processes communicate with each other asynchronously.
- **Shared Filesystem:** BROWSIX lets processes share state through a shared FS.
- **Pipes:** BROWSIX exposes the standard pipe API, making it simple for developers to compose processes into pipelines.
- **Sockets:** BROWSIX supports TCP socket servers and clients, making it possible to run server applications like databases and HTTP servers together with their clients in the browser.
- **Language Agnostic:** BROWSIX includes integration with the runtime libraries of Emscripten (C/C++), GopherJS

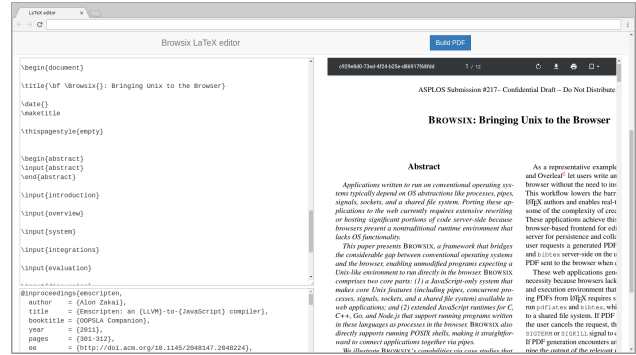


Figure 1: A \LaTeX editor built using BROWSIX. BROWSIX’s OS services and language runtimes make it possible to run complex legacy code (including `pdflatex` and `btex`) directly in the browser, without code modifications (See Section 2 for details.)

(Go), and Node.js (JavaScript) to allow unmodified applications written in these languages to run directly as processes in the browser. Through its simple system call API, developers can straightforwardly integrate BROWSIX into additional language runtimes.

BROWSIX dramatically simplifies the process of porting complex applications to the browser environment. As a demonstration, we have built a \LaTeX editor that runs entirely within the browser. When the user requests a PDF, BROWSIX runs `make` to re-build the document with `pdflatex` and `btex`, and pipes their standard output and standard error to the application. These \TeX programs use BROWSIX’s shared file system to read in the user’s source files, and any packages, class files, and fonts referenced within, as in a traditional Unix environment. The filesystem transparently loads any needed external packages from the TeX Live distribution over HTTP upon first access. Subsequent accesses to the same files are instantaneous, as the browser caches them. While a full TeX Live distribution is several gigabytes in size, a typical paper only needs to retrieve several megabytes worth of packages before it can be built. If the user cancels PDF generation, BROWSIX sends a `SIGKILL` signal to these processes. If PDF generation fails, the application can display the captured standard out and standard error. The result is serverless PDF generation composed from off-the-shelf parts, with minimal engineering effort required to glue them together.

We demonstrate the utility of BROWSIX with two further case studies. Using BROWSIX, we build an application that dynamically routes requests to a remote server or an in-BROWSIX server, both compiled from the same source code, depending on the client’s performance and battery characteristics. We also use BROWSIX to build a UNIX terminal exposing a POSIX shell, enabling developers to launch and compose applications and inspect BROWSIX state in a familiar way.

Contributions

This paper makes the following contributions:

- **Bringing OS Abstractions and Services to the Browser.** We demonstrate that it is possible to provide a wide range of key Unix abstractions and services in the browser on top of existing web APIs. We implement these in BROWSIX, a JavaScript-only framework featuring a kernel and system calls that runs on all modern browsers (§3).
- **Runtime Integration for Existing Languages.** We extend the JavaScript runtimes of Emscripten (a C/C++ to JavaScript toolchain), GopherJS (a Go to JavaScript compiler), and Node.js with BROWSIX support, letting unmodified C, C++, Go, and Node.js programs execute and interoperate with one another within the browser as BROWSIX processes (§4).
- **Case Studies.** We demonstrate BROWSIX’s utility by building a L^AT_EX editor, a serverless client-server web application, and a Unix terminal out of off-the-shelf components without modification. We characterize BROWSIX’s performance under these case studies and with microbenchmarks (§5) and show that its overhead is low enough for real-world usage.
- **Guidance for Future Browsers.** Based on our experience writing BROWSIX, we discuss current browser limitations and propose solutions (§6).

2. BROWSIX Overview

To give an overview of BROWSIX’s features, this section walks through the process of using BROWSIX to build an in-browser L^AT_EX editor using TeX Live utilities and GNU Make. Figure 1 displays a screenshot of the editor.

2.1 L^AT_EX Editor Overview

The editor presents a split-screen view to the user, with the document’s L^AT_EX source on the left, and generated PDF preview on the right. The editor’s UI is a standard web application, and represents the only new code. When the user clicks on the “Build PDF” button, the editor uses BROWSIX to invoke GNU Make in a BROWSIX process, which rebuilds the PDF.

The process for building the PDF is familiar to anyone who has used L^AT_EX, except BROWSIX performs all of the needed steps entirely in the browser instead of server-side. It runs GNU Make to read a Makefile from BROWSIX’s file system, which contains rules for rebuilding L^AT_EX projects. Make then runs `pdflatex` and `bibtex`, depending on whether the user has updated the references file.

`pdflatex` and `bibtex` read any required L^AT_EX packages, fonts, and other system files from BROWSIX’s file system, which lazily pulls in files as needed from the network. Both of these applications write their output to BROWSIX’s file system.

Once all steps have completed (or an error has occurred), the Make process exits with an exit code indicating whether or not PDF generation succeeded. BROWSIX sends the exit code back to the web application. If GNU Make exits normally, the editor reads the PDF from BROWSIX’s shared filesystem and displays it to the user. Otherwise, it displays the standard output from `pdflatex` and `bibtex` to the user, which describes the source of the error.

2.2 Building with BROWSIX

Building any web application that runs Unix programs in BROWSIX generally consists of the same three step process: (1) compile the programs to JavaScript (using tools with BROWSIX support), (2) stage files required by the application for placement in the in-browser filesystem, and (3) add setup code to the web application to initiate BROWSIX and launch the programs.

Compiling to JavaScript: To run `pdflatex`, `bibtex`, and GNU Make in BROWSIX, the developer compiles each program to JavaScript using Emscripten, a C/C++ to JavaScript compiler [16]. We extend Emscripten’s runtime library with BROWSIX support, so standard Unix APIs map to BROWSIX primitives. We discuss this extension in more detail in Section 4.3.

Before compilation, the developer determines if any of the programs use the `fork` command. Due to browser limitations explored in Section 6, BROWSIX can only implement `fork` as an asynchronous system call, which requires the use of a variant of Emscripten’s compilation procedure that generates less efficient code. If this option is configured incorrectly, the program will fail at runtime when it attempts to invoke `fork`. For the L^AT_EX case study, only GNU Make uses `fork` and requires this setting.

From this point, the build process is mostly unchanged from a standard compilation. For programs that use the autotools build system, such as GNU Make and TeX Live, instead of running `./configure`, the developer invokes `emconfigure ./configure`. This wrapper overrides standard tools like `cc` and `ar` with `em` prefixed alternatives that compile the program with Emscripten, producing individual JavaScript files for each program.

Staging the Filesystem: The developer next configures BROWSIX’s in-browser filesystem so that it hosts all of the files that the programs require. BROWSIX’s file system extends Doppio’s BrowserFS file system with multi-process support, building on its support for files backed by cloud storage, browser-local storage, traditional HTTP servers, and more [13].

For our L^AT_EX example, both `pdflatex` and `bibtex` require read access to class, font, and other files from a L^AT_EX distribution to function properly. While a complete TeX Live distribution contains over 60,000 individual files, the average L^AT_EX document only references a small subset of these files.

To reduce load times and minimize the amount of storage required on a client’s device, the developer can leverage BROWSIX’s filesystem to load only the needed files. In this case, the developer uploads a full TeX Live distribution to an HTTP server and configures BROWSIX’s filesystem to use an HTTP-backed filesystem backend. The filesystem will then load these files on-demand from the network upon first access. The browser caches these files automatically, making subsequent access much faster.

BROWSIX Setup Code: Finally, the developer adds code to the web application to load and initialize BROWSIX, and to launch `make` to build the PDF. A `script` tag in the HTML loads `browsix.js`, and a subsequent `script` tag with inline JavaScript calls BROWSIX’s `Boot` function with the desired filesystem configuration.

Additional application-specific initialization follows as usual. Once the filesystem is ready, the developer adds code to read the contents of `main.tex` and `main.bib` from BROWSIX’s filesystem, and display the contents in the editor. Then, the application registers a callback function with the “Build PDF” button to run whenever the user clicks the button.

2.3 Execution with BROWSIX

When the application’s callback is executed in response to a user’s “Build PDF” click, the application invokes the `system` method on its kernel instance to start `make`. `Make` runs `pdflatex` and `bibtex` as described in Section 1. When the application receives a notification from BROWSIX that `Make` has exited, it inspects `Make`’s exit code. If it is zero, the PDF was generated successfully and is read from the filesystem. Otherwise, the captured standard output and standard error are displayed to the user so they can debug their markup.

This overview demonstrates how straightforward BROWSIX makes it to take existing components that were designed to work in a Unix environment and execute them seamlessly inside a web browser. The next two sections provide technical details on how BROWSIX provides Unix-like abstractions in the browser environment and integrates with language runtimes.

3. BROWSIX OS Support

The core of BROWSIX’s OS support is a kernel that controls access to shared Unix services. Unix services, including the shared file system, pipes, sockets, and task structures, live inside the kernel, which runs as a JavaScript library in the main browser thread. Processes run separately and in parallel inside Web Workers, and access BROWSIX kernel services through a system call abstraction. BROWSIX and all of its runtime services are implemented in JavaScript and TypeScript, a typed variant of JavaScript that compiles down to vanilla JavaScript. Figure 2 provides a breakdown of each of BROWSIX’s components.

Component	Lines of Code (LoC)
Kernel	2,249
BrowserFS modifications	1,231
Shared syscall module	421
Emscripten integration* (C/C++ support)	1,557
GopherJS integration* (Go support)	926
Node.js integration*	1,742
TOTAL	8,126

Figure 2: BROWSIX components. * indicates these components are written in JavaScript, while the rest of the components are written in TypeScript (which compiles to JavaScript).

3.1 Kernel

The kernel lives in the main JavaScript context alongside the web application and acts as the intermediary between processes and loosely coupled Unix subsystems. Processes issue system calls to the kernel to access shared resources, and the kernel routes these requests to the appropriate subsystem. When the subsystem responds to the system call, it relays the response to the process. The kernel is also responsible for dispatching signals to processes, which we describe further in Section 3.3. Figure 3 presents a partial list of the system calls that the kernel currently supports.

In a departure from modern Unix systems, BROWSIX does not support multiple users. A traditional kernel, for example, uses user identities to check permissions on certain system calls or for access to files. Unlike a traditional kernel, BROWSIX executes as a JavaScript library on a webpage. As a result, BROWSIX can rely on the browser’s built-in sandbox and security features, such as the same origin policy, to isolate the BROWSIX kernel from the underlying operating system and other web origins. In other words, a BROWSIX application and its users enjoy the same level of protection and security as any other web application.

3.2 System Calls

The BROWSIX kernel supports two types of system calls: asynchronous and synchronous. Asynchronous system calls work in all modern browsers, but impose a high performance penalty on C and C++ programs. Synchronous system calls enable higher performance for C and C++ programs in development versions of Chrome, Firefox, and Safari via a mechanism we describe below; this mechanism is already standardized and is on track to be supported by other mainstream browsers.

Asynchronous System Calls: BROWSIX implements asynchronous system calls in a continuation-passing style (CPS). A process initiates a system call by sending a message to the kernel with a process-specific unique ID, the system call

Class	System calls
Process Management	fork, spawn, pipe2, wait4, exit
Process Metadata	chdir, getcwd, getpid
Sockets	socket, bind, getsockname, listen, accept, connect
Directory IO	readdir, getdents, rmdir, mkdir
File IO	open, close, unlink, llseek, pread, pwrite
File Metadata	access, fstat, lstat, stat, readlink, utimes

Figure 3: A representative list of the system calls implemented by the BROWSIX kernel. `fork` is only supported for C and C++ programs.

number, and arguments. BROWSIX copies all arguments, such as file descriptor or a buffer to write to a file descriptor, from the process to the kernel - no memory is shared. When the kernel sends a response, the Web Worker process executes the continuation (or callback) with response values, also copied from the kernel's heap into the process's heap.

Asynchronous system calls work well for Node.js and Go, but are only required for C and C++ programs that depend on `fork`. In Node.js, the filesystem and other APIs accept a callback function to continue execution when the API's result is available, which maps directly onto BROWSIX asynchronous system calls. The GopherJS runtime provides first-class support for suspending and resuming the call stack in order to implement goroutines (lightweight thread-like primitives), making it straightforward to resume from asynchronous system calls as well. However, C and C++ programs using `fork` must be compiled in an interpreted mode (called the Emterpreter³) in order to save and restore the stack. This mode produces bytecode that is in turn interpreted by a JavaScript program at execution time. By contrast the standard `asm.js`⁴ output Emscripten produces is directly JIT compiled and executed by the browser's JavaScript engine, which is substantially faster than executing bytecode in the Emterpreter. Most C and C++ programs do not use `fork` and are able to be compiled as `asm.js` with synchronous system calls.

Synchronous System Calls: Synchronous system calls work by sharing a view of a process's address space between the kernel and the process, similar to a traditional operating system kernel like Linux. At startup, the language runtime in a process wishing to use synchronous system calls passes to the kernel (via an asynchronous system call) a reference to the heap (a `SharedArrayBuffer` object), along

³<https://github.com/kripken/emscripten/wiki/Emterpreter/>

⁴<http://asmjs.org/>

with two offsets into the heap: where to put system call return values, and an offset to use to wake the process when the syscall is complete.

A process invokes a synchronous system call by sending a message as in the asynchronous case, but with arguments limited to integers and integer offsets (representing pointers) into the shared memory array, rather than objects (like `ArrayBuffers`) that would need to be copied between heaps. For system calls like `pread`, data is copied directly from the filesystem, pipe or socket into the process's heap, avoiding a potentially large allocation and extra copy.

After sending a message to the kernel, the process performs a blocking wait on the offset into the `SharedArrayBuffer` previously arranged with the kernel and is awakened when the system call has completed or a signal is received. This wait is provided by the `JavaScript Atomics.wait` function, part of the ECMAScript Shared Memory and Atomics specification [6]. A consequence of this approach is that `fork` is not compatible with synchronous system calls, as there is no way to rewind, continue, or jump to a particular call stack in the child Web Worker.

Synchronous system calls are faster in practice for a number of reasons. First, they only require one message to be passed between the kernel and process, which is a relatively slow operation. Second, system call arguments are numbers, rather than potentially large arrays that need to be copied between JavaScript contexts. Finally, synchronous system calls provide a blocking primitive and do not depend on language runtimes to unwind and rewind the call stack. As such, they are suitable for use with `asm.js` and WebAssembly functions on the call stack, which are faster and more amenable to optimization by the JavaScript runtime than Emscripten's interpreter.

Synchronous system calls require two features: `SharedArrayBuffers` and `Atomics`. These are available in Firefox Nightly, Safari Technology Preview, as well as Google Chrome when `SharedArrayBuffer` support is enabled in `chrome://flags`. `SharedArrayBuffers` and `Atomics` are draft web standards and are on track to be part of standard versions of all mainstream browsers [6].

3.3 Processes

BROWSIX relies on *Web Workers* as the foundation for emulating Unix processes. However, Web Workers differ substantially from Unix processes, and BROWSIX must provide a significant amount of functionality to bridge this gap.

In Unix, processes execute in isolated virtual address spaces, run in parallel with one another when the system has multiple CPU cores, and can interact with system resources and other processes via system calls. However, the web browser does not expose a process API to web applications. Instead, web applications can spawn a Web Worker that runs a JavaScript file in parallel with the application.

A Web Worker has access to only a subset of browser interfaces (notably excluding the Document Object Model

(DOM)), runs in a separate execution context, and can only communicate with the main browser context via asynchronous message passing. Web Workers are not aware of one another, cannot share memory with one another, and can only exchange messages with the main browser context that created them (see Section 6 for a discussion). Major browsers like Chrome and Safari do not support spawning sub-workers from workers, so-called *nested workers*, and have not added support for them since they were first proposed in 2009. Thus, if a Web Worker needs to perform a task in parallel, it must delegate the request to the main browser thread, and proxy all messages to that worker through the main browser thread. Perhaps unsurprisingly, the limitations and complexity of Web Workers have hindered their adoption in web applications.

By contrast, BROWSIX implements Unix processes on top of Web Workers, giving developers a familiar and full-featured abstraction for parallel processing in the browser. Each BROWSIX process has an associated task structure in the kernel that contains its process ID, parent’s process ID, Web Worker object, current working directory, and map of open file descriptors. Processes have access to the system calls in Figure 3, and invoke them by sending a message with the system call name and arguments to the kernel. As a result, processes can share state via the file system, send signals to one another, spawn sub-processes to perform tasks in parallel, and connect processes together using pipes. Below, we describe how BROWSIX maps familiar OS interfaces onto Web Workers.

spawn: BROWSIX supports `spawn`, which constructs a new process from a specified executable on the file system. `spawn` is the primary process creation primitive exposed in modern programming environments such as Go and Node.js, as `fork` is unsuitable for general use in multithreaded processes. `spawn` lets a process specify an executable to run, the arguments to pass to that executable, the new process’s working directory, and the resources that the subprocess should inherit (such as file descriptors). In BROWSIX, executables include JavaScript files, file beginning with a shebang line, and WebAssembly files. When a process invokes `spawn`, BROWSIX creates a new task structure with the specified resources and working directory, and creates a new Web Worker that runs the target executable or interpreter.

There are two technical challenges to implementing `spawn`. First, the Web Worker constructor takes a URL to a JavaScript file as its first argument. Files in BROWSIX’s file system may not correspond to files on a web server. For example, they might be dynamically produced by other BROWSIX processes. To work around this restriction, BROWSIX generates a JavaScript *Blob* object that contains the data in the file, obtains a dynamically-created URL for the blob from the browser’s window object, and passes that URL as a parameter to the Web Worker constructor. All modern web browsers now support constructing Workers from blob URLs.

The second challenge is that there is no way to pass data to a Worker on startup apart from sending a message. As processes synchronously access state like the arguments vector and environment map, BROWSIX-enabled runtimes delay execution of a process’s `main()` function until after the worker has received an “init” message from the kernel containing the process’s arguments and environment.

fork: The `fork` system call creates a new process containing a copy of the current address space and call stack. `Fork` returns twice – first with a value of zero in the new process, and with the PID of the new process in the original. Web Workers do not expose a cloning API, and JavaScript lacks the reflection primitives required to serialize a context’s entire state into a snapshot. Thus, BROWSIX only supports `fork` when a language runtime is able to completely enumerate and serialize its own state. Section 4 describes how we extend Emscripten to provide `fork` support for C/C++ programs compiled to JavaScript.

wait4: The `wait4` system call reaps child processes that have finished executing. It returns immediately if the specified child has already exited, or the `WNOHANG` option is specified. `Waiting` requires that the kernel not immediately free task structures, and required us to implement the zombie task state for children that have not yet been waited upon. The C library used by Emscripten, `musl`, uses the `wait4` system call to implement the C library functions `wait`, `wait3`, and `waitpid`.

exit: Language runtimes with BROWSIX-support are required to explicitly issue an `exit` system call when they are done executing, as the containing Web Worker context has no way to know that the process has finished. This is due to the event-based nature of JavaScript environments – even if there are no pending events in the Worker’s queue, the main JavaScript context could, from the perspective of the browser, send the Worker a message at any time.

getpid, getppid, getcwd, chdir: These four system calls operate on data in the current process’s task structure, which lives in the BROWSIX kernel. `getpid` returns the process’s ID, `getppid` returns the parent process’s ID, `getcwd` returns the process’s working directory, and `chdir` changes the process’s working directory.

3.4 Pipes

BROWSIX pipes are implemented as in-memory buffers with wait queues. If there is no data to be read when a process issues a `read` system call, BROWSIX enqueues the callback encapsulating the system call response which it invokes when data is written to the pipe. Similarly, if there is not enough free space in a pipe’s internal buffer for a write request, BROWSIX waits until enough space frees up in the buffer from read requests to complete the write.

3.5 Sockets

BROWSIX implements a subset of the BSD/POSIX socket API, with support for `SOCK_STREAM` (TCP) sockets for communicating between BROWSIX processes. These sockets enable servers that bind, listen and then accept new connections on a socket, along with clients that connect to a socket server, with both client and server reading and writing from the connected file descriptor. Sockets are sequenced, reliable, bi-directional streams.

3.6 Shared File System

BROWSIX builds on and significantly extends BrowserFS's file system, part of Doppio [13]. BrowserFS already included support for multiple mounted filesystems in a single hierarchical directory structure. BrowserFS provides multiple file system backend implementations, such as in-memory, zip file, XMLHttpRequest, Dropbox, and an overlay filesystem. BrowserFS provides a unified, encapsulated interface to all of these backends.

BROWSIX extends BrowserFS in two key ways: it adds multi-process support and incorporates improved support for loading files over HTTP. To provide multi-process support, BROWSIX's file system adds locking operations to the overlay filesystem to prevent operations from different processes from interleaving. In addition, BROWSIX incorporates domain-specific optimizations into its file system; for example, it avoids expensive operations like recording the call stack when a path lookup fails (a common event).

BROWSIX modifies BrowserFS's overlay backend to lazily load files from its read-only underlay; the original version eagerly read all files from the read-only filesystem upon initialization. BROWSIX's approach drastically improves the startup time of the kernel, minimizes the amount of data transferred over the network, and enables applications like the \LaTeX editor where only a small subset of files are required for a given end user.

Finally, BROWSIX implements system calls that operate on paths, like `open` and `stat`, as method calls to the kernel's BrowserFS instance. When a system call takes a file descriptor as an argument, the kernel looks up the descriptor in the tasks's file hashmap and invokes the appropriate method on that file object, calling into BrowserFS for regular files and directories. Child processes inherit file descriptor tables, and BROWSIX explicitly manages each object (whether it is a file, directory, pipe or socket) with reference counting.

4. BROWSIX Runtime Support

Applications invoke BROWSIX system calls indirectly through their runtime systems. This section describes the runtime support we added to GopherJS, Emscripten, and Node.js along with the APIs exposed to web applications so they can execute programs in BROWSIX.

```
kernel.system(  
  'pdflatex example.tex',  
  function(pid, code) {  
    if (code === 0) {  
      displayPDF();  
    } else {  
      displayLatexLog();  
    }  
  }, logStdout, logStderr);
```

Figure 4: Creating a BROWSIX process from JavaScript.

4.1 Browser Environment Extensions

Web applications run alongside the BROWSIX kernel in the main browser context, and have access to BROWSIX features through several global APIs. BROWSIX exposes new APIs for process creation, file access, and socket notifications, and an XMLHttpRequest-like interface to send HTTP requests to BROWSIX processes.

To start a BROWSIX process the client application invokes an API similar to C's `system`, as seen in Figure 4. In addition to specifying the program to run and arguments, callbacks are passed to BROWSIX that are invoked when data is available on standard out, standard error and upon program exit. BROWSIX additionally provides APIs to enable the client to create, read, and write files.

Socket notifications let applications register a callback to be invoked when a process has started listening on a particular port. These notifications let web applications launch a server as a process and appropriately delay communicating with the server until it is listening for messages. Web applications do not need to resort to polling or ad hoc waiting.

BROWSIX provides an XMLHttpRequest-like API for sending requests from the web application to in-browser HTTP servers running in BROWSIX. This allows JavaScript to interact with HTTP 1.1 servers running as BROWSIX processes as if they were remote HTTP servers. The API encapsulates the details of connecting a BROWSIX socket to the server, serializing the HTTP request to a byte array, sending the byte array to the BROWSIX process, processing the (potentially chunked) HTTP response, and generating the expected web events.

4.2 Common Services

BROWSIX provides a small `syscall` layer as a JavaScript module that runs in a Web Worker. This layer provides a concrete API for asynchronous system calls over the browser's message passing primitives. Language runtimes use this module to communicate with the kernel. Methods provided by the `syscall` layer take the same arguments as Linux system calls of the same name, along with an additional argument: a callback function. This callback is executed when the `syscall` module receives a message response from the kernel. Unlike a traditional single-threaded process, a BROWSIX process can have multiple outstanding system calls, which enables

```
function sys_getdents64(cb, trap, fd, dirp, len) {
  var done = function (err, buf) {
    if (!err)
      dirp.set(buf);
    cb([err ? -1 : buf.byteLength, 0, err ? err : 0]);
  };
  syscall_1.syscall.getdents(fd, len, done);
}
```

Figure 5: Implementing the `getdents64` system call in GopherJS.

runtime like GopherJS to implement user-space threads on top of a single Web Worker execution context.

Signals are sent over the same message passing interface as system calls. The common `syscall` module provides a way to register signal handlers for the standard Unix signals, such as `SIGCHLD`.

4.3 Runtime-specific Integration

For many programming languages, existing language runtimes targeted for the browser must bridge the impedance mismatch between synchronous APIs present on Unix-like systems and the asynchronous world of the browser. Compile-to-JavaScript systems like Emscripten, ClojureScript [8], Scala.js [3], `js_of_ocaml` [14], WhaleSong (Racket) [15], and GopherJS all employ different approaches. Since BROWSIX supports both synchronous and asynchronous system calls, language runtimes can choose the system call convention most appropriate for their implementation.

This section describes the runtime support we added to language runtimes for Go, C/C++, and Node.js. Extending BROWSIX support to additional language runtimes remains as future work.

Go: Go is a systems language developed at Google designed for readability, concurrency, and efficiency. To run Go programs under BROWSIX, we extended the existing GopherJS compiler and runtime to support issuing and waiting for system calls under BROWSIX. GopherJS already provides full support for Go language features like goroutines (lightweight threads), channels (communication primitives), and delayed functions.

We extended the GopherJS runtime with support for BROWSIX through modifications to the runtime. The main integration points are a BROWSIX-specific implementation of the `syscall.RawSyscall` function (which handles syscalls in Go), along with overrides of several Go runtime functions.

The replacement for `RawSyscall` is implemented in Go. It allocates a Go channel object, and this function calls into the BROWSIX JavaScript `syscall` library, passing the system call number, arguments, and a callback to invoke. `RawSyscall` then performs a blocking read on the Go channel, which suspends the current goroutine until the callback is invoked. When the system call response is received from the BROWSIX kernel, GopherJS’s existing runtime takes care of

```
__syscall220: function(which, varargs) {
  #if EMTERPRETIFY_ASYNC
    return EmterpreterAsync.handle(function(resume) {
      var fd = SYSCALLS.get(), dirp = SYSCALLS.get(),
          count = SYSCALLS.get();
      var done = function(err, buf) {
        if (err > 0)
          HEAPU8.subarray(dirp, dirp+buf.byteLength).set(buf);
        resume(function() {
          return err;
        });
      };
      SYSCALLS.browsix.syscall.async(done, 'getdents', [fd, count]);
    });
  #else
    var fd = SYSCALLS.get(), dirp = SYSCALLS.get(),
        count = SYSCALLS.get();
    return SYSCALLS.browsix.syscall.sync(220, fd, dirp, count);
  #endif
},
```

Figure 6: Implementing the BROWSIX `getdents64` syscall in Emscripten.

re-winding the stack and continuing execution. The `syscall` library invokes a function specific to each supported system call to marshal data to and from the BROWSIX kernel. Adding support for any new system call is a matter of writing a small handler function and registering it; an example is shown in Figure 5

BROWSIX replaces a number of low-level runtime functions; the most important are `syscall.forkAndExecInChild` and `net.Listen`. The former is overridden to directly invoke BROWSIX’s `spawn` system call, and the latter to provide access to BROWSIX socket services. Additional integration points include an explicit call to the `exit` system call when the main function exits, and waiting until the process’s arguments and environment have been received before starting `main()` (see §3.3).

C and C++: We also extend Emscripten, Mozilla Research’s LLVM-based C and C++ compiler that targets JavaScript, with support for BROWSIX. BROWSIX-enhanced Emscripten supports two modes - synchronous system calls and asynchronous system calls (described in Section 3.2), one of which is selected at compile time. Asynchronous system calls require use of Emscripten’s interpreter mode (named the “Emterpreter”) to save and restore the C stack. All functions that may be on the stack during a system call must be interpreted to ensure the stack can be restored when the system call completes. Emscripten can selectively compile other functions in an application to `asm.js`, which will be JIT-compiled and run as native JavaScript by the browser. Synchronous system calls do not have this limitation.

As with GopherJS, Emscripten provides a clear integration point at the level of system calls. Emscripten provides implementations for a number of system calls, but is restricted to performing in-memory operations that do not block. We re-

place Emscripten system call implementations with ones that call into the BROWSIX kernel, such as in Figure 6. In the case of `getdents` and `stat`, padding was added to C structure definitions to match the layout expected by the BROWSIX kernel.

When a C process invokes `fork`, the runtime sends a copy of the global memory array, which includes the C stack and heap, along with the current program counter (PC) to the kernel. After the kernel launches a new Web Worker, it transfers this copy of global memory and PC to the new Worker as part of the initialization message. When the Emscripten runtime in the new BROWSIX process receives the initialization message, if a memory array and PC are present the runtime swaps them in and invokes the Emterpreter to continue from where `fork` was invoked.

Node.js: Node.js (a.k.a. “Node”) is a platform for building servers and command line tools with JavaScript, implemented in C, C++ and JavaScript on top of the V8 JavaScript engine. Node.js APIs are JavaScript modules that are loaded into the current JavaScript context by invoking the `require` built-in function. These high-level APIs are implemented in platform-agnostic JavaScript and call into lower-level C++ bindings, which in turn invoke operating system interfaces like filesystem IO, TCP sockets, and child process management. Node.js embraces the asynchronous, callback-oriented nature of JavaScript – most Node APIs that perform system calls take a callback parameter that is invoked when results are ready.

To run servers and utilities written for Node.js under BROWSIX, we provide a `browser-node` executable that packages Node’s high-level APIs with pure-JavaScript replacements for Node’s C++ bindings that invoke BROWSIX system calls. `browser-node` is a single file that runs in a BROWSIX process. BROWSIX also replaces several other native modules, like the module for parsing and generating HTTP responses and requests, with pure JavaScript implementations. Node executables can be invoked directly, such as `node server.js`, or will be invoked indirectly by the kernel if `node` is specified as the interpreter in the shebang line of a text file marked as executable.

5. Evaluation

Our evaluation answers the following questions: (1) Does bringing Unix abstractions into the browser enable compelling use cases? (2) Is the performance impact of running programs under BROWSIX acceptable?

5.1 Case Studies

We evaluate the applicability and advantages of bringing Unix abstractions into the browser with two case studies in addition to the \LaTeX editor from the overview (§2). First, we build a web application for creating memes that can run its unmodified server in BROWSIX. The meme generator transparently switches between generating memes in-browser or

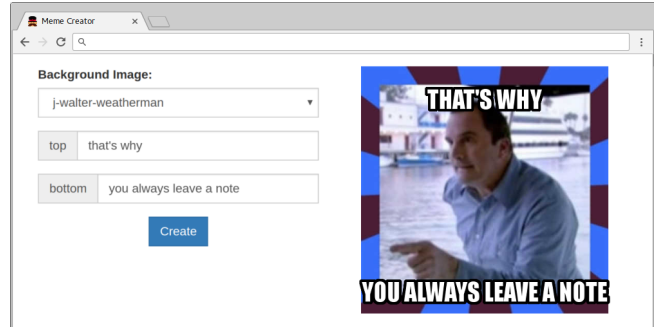


Figure 7: A meme generator built using BROWSIX. All server-side functionality was moved into the browser without modifying any code.

server-side depending on network and device characteristics. Second, we build a Unix terminal that lets application developers use `dash`, a widely-used POSIX shell, to interact with BROWSIX in a familiar manner.

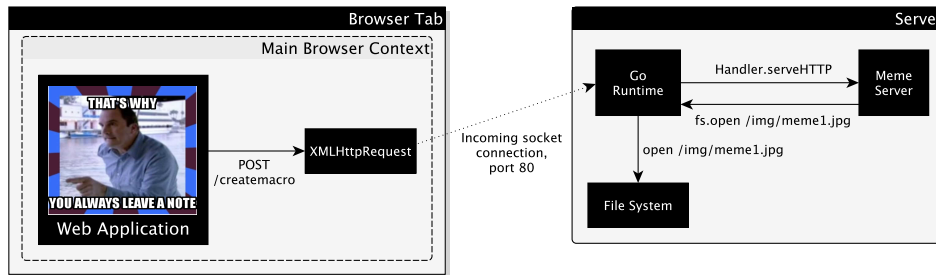
5.1.1 Meme Generator

Our meme generator lets users create *memes* consisting of images with (nominally) humorous overlaid text. Figure 7 contains a screenshot. Existing services, such as `MemeGenerator.net`, perform meme generation server-side. Moving meme creation into the browser would reduce server load and reduce latency when the network is overloaded or unreliable, but doing so would normally present a significant engineering challenge. The meme generation server uses sockets to communicate with the browser over HTTP and reads meme templates from the file system. Before BROWSIX, the client and server code would need to be re-architected and rewritten to run together in the browser.

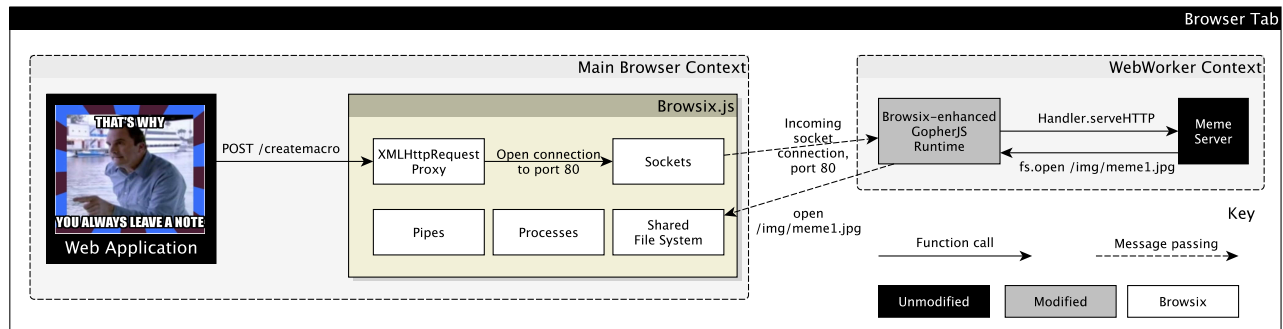
To demonstrate BROWSIX’s ability to quickly port code from the server to the web, we implement our meme creator as a traditional client/server web application; Figure 8a contains a system diagram. The client is implemented in HTML5 and JavaScript, and the server is written in Go. The server reads base images and font files from the filesystem, and uses off-the-shelf third-party Go libraries for image manipulation and font rendering to produce memes [5]. The server also uses Go’s built-in `http` module to run its web server. Note that this server is stateless, following best practices [10]; porting a stateful server would naturally require more care.

To port the server to BROWSIX, we follow the process outlined in Section 2. First, we compile the Go server to a single JavaScript file using `GopherJS`. Then, we stage the font and images for the `BrowserFS` filesystem. Finally, we augment the client application to load the BROWSIX JavaScript module, initialize a kernel instance, and start the meme-server.

Next, we augment the web application to dynamically route meme generation requests to a server running in BROWSIX or to the cloud. We add a function to the ap-



(a) Meme creator running without BROWSIX



(b) Meme creator running with BROWSIX

Figure 8: System diagram of the meme generator application with and without BROWSIX, demonstrating how the client and server interact with one another. With BROWSIX, the server runs in the browser without code modifications.

application that implements a simple policy: if the network is inaccessible, or the browser is running on a desktop (which is a proxy for a powerful device), the application routes meme generation requests to the server running in BROWSIX. Otherwise, it sends the requests to the remote server. In both cases, the web application uses an XMLHttpRequest-like interface to make the request, requiring little change to the existing code.

Figure 8b displays a system diagram of the modified meme generator. With this modification, meme generation works even when offline. The code required to implement this policy and dynamic behavior amounted to less than 30 lines of JavaScript.

5.1.2 The BROWSIX Terminal

To make it easy for developers to interact with and test programs in BROWSIX, we implement an in-browser Unix terminal that exposes a POSIX shell. The terminal uses the Debian Almquist shell (dash), the default shell of Debian and Ubuntu. We compile dash to JavaScript using BROWSIX-enhanced Emscripten, and run it in a BROWSIX process.

Since the BROWSIX terminal uses a standard shell, developers can use it to run existing and new shell scripts in BROWSIX. Developers can pipe programs together (e.g. `cat file.txt | grep apple > apples.txt`), execute programs in a subshell in the background with `&`, run shell scripts, and change environment variables. Developers can

also execute Go, C/C++, and Node.js programs from the shell as expected.

The terminal includes a variety of Unix utilities on the shell’s PATH that we wrote for Node.js: `cat`, `cp`, `curl`, `echo`, `exec`, `grep`, `head`, `ls`, `mkdir`, `rm`, `rmdir`, `sh`, `sha1sum`, `sort`, `stat`, `tail`, `tee`, `touch`, `wc`, and `xargs`. These programs run equivalently under Node and BROWSIX without any modifications, and were used heavily during development to debug BROWSIX functionality.

Summary: BROWSIX makes it trivial to execute applications designed to run in a Unix environment within the browser, enabling the rapid development of sophisticated web applications. These applications can incorporate server code into the browser and harness the functionality of existing applications.

5.2 Performance

We evaluate the performance overhead of BROWSIX on our case studies. All experiments were performed on a late-2013 Macbook Pro with an Intel i7-4558U CPU and 16 GB of RAM, running Linux 4.8. Safari performance numbers are from the same machine running macOS Sierra.

LaTeX Editor: Running `pdflatex` under BROWSIX imposes an order of magnitude slowdown, as shown in Figure 9. A native execution of `pdflatex` under Linux takes around 86 milliseconds on a single page document with a bibliography. When using synchronous system calls (as sup-

Platform	Runtime
Linux	0.086s
Chrome Beta 56	2.0s (24×)
Firefox Nightly 54	2.6s (31×)
Firefox Nightly 54*	0.79s (9×)
Safari Tech Preview 22	1.8s (21×)

Figure 9: Execution times for compiling a single-page document with a bibliography with `pdf1atex` from TeX Live 2015. Times reported are the mean of 10 executions. (* Indicates Firefox was built with an 8-line patch enabling `asm.js` validation with the use of `SharedArrayBuffers`.)

ported by Chrome, Firefox, and Safari), the same document builds in BROWSIX in between 0.79 and 2.6 seconds, a slowdown of between 9× and 31×. Firefox has `asm.js` specific optimizations that are enabled when a JavaScript module passes `asm.js` validation. Using a `SharedArrayBuffer` for the `asm.js` module’s heap, as BROWSIX does for synchronous system calls, currently causes Firefox to fail validation and fall back to the standard JIT⁵. The modified Firefox results show that if the rules for `asm.js` are slightly relaxed to allow `SharedArrayBuffers` for the heap, performance is improved by over 3×. Building `pdf1atex` with asynchronous system calls and the Emterpreter for broader compatibility with today’s browsers increases runtime to around 12 seconds.

Meme Generator: The meme generator performs two types of HTTP requests to the server: requests for a list of available background images, and requests to generate a meme. We benchmark the performance of the meme generator server running natively and running in Browsersix in both Google Chrome 52 and Mozilla Firefox 48. Times reported are the mean of 100 runs following a 20-run warmup.

On average, a request for a list of background images takes 1.7 milliseconds natively, 9 ms in Chrome, and 6 ms in Firefox. While requests to a server running natively on the same machine as the client are faster than those served by BROWSIX, BROWSIX is faster once a network connection and roundtrip latencies are factored in. When comparing an instance of the meme-server running on an EC2 instance, the in-BROWSIX request completed three times as fast as the request to the remote machine.

The in-BROWSIX HTTP request to generate a meme takes approximately two seconds, compared to 200 ms when running server-side. We believe this slowdown is primarily due to the lack of native 64-bit integer primitives when numerical code is compiled to JavaScript with GopherJS rather than overhead introduced by BROWSIX; we expect this to improve when future browsers support native access to 64-bit integers (through WebAssembly), and with independent improvements to the GopherJS compiler.

⁵https://bugzilla.mozilla.org/show_bug.cgi?id=1334941

Command	Native	Node.js	BROWSIX
<code>sha1sum</code>	0.002s	0.067s	0.189s
<code>ls</code>	0.001s	0.044s	0.108s

Figure 10: Execution time of utilities under BROWSIX, compared to the same utilities run under Node.js, and the native GNU/Linux utilities. `sha1sum` is run on `/usr/bin/node`, and `ls` is run on `/usr/bin`. Running in JavaScript (with Node.js and BROWSIX) imposes most overhead; running in the BROWSIX environment adds roughly another 3× overhead.

BROWSIX Terminal and Utilities: Unix utilities provide a mechanism to compare the performance of real-world programs under Linux and BROWSIX. Figure 10 shows the results of running the same JavaScript utility under BROWSIX and on Linux under Node.js, and compares this to the execution time of the corresponding GNU Coreutils utility (written in C, running on Linux). Most of the overhead can be attributed to JavaScript (the basis of Node.js and BROWSIX); subsequently running in the BROWSIX environment imposes roughly a 3× overhead over Node.js on Linux. Nonetheless, execution time (completion in under 200 milliseconds) is low enough that it should be generally acceptable to users.

Microbenchmarks: We ran four benchmarks from the HBench-OS benchmark suite [2] to characterize the relative performance of the operating system services provided by BROWSIX. The results are in Figure 11. The first two benchmarks, `lat_syscall` and `lat_fslayer`, perform simple system calls, `getpid` and a single-byte write to `/dev/null` respectively. These calls, which run three orders of magnitude slower under BROWSIX, accentuate BROWSIX’s overhead: the host OS must schedule several userspace threads to complete each BROWSIX system call. In Linux, these system calls typically do not block or cause a task reschedule. Benchmarks that perform more work in the kernel result in lower overhead. The latter two benchmarks, `lat_fs` and `lat_tcp`, respectively create a 1024-byte file and perform a pair of single-byte read and writes over a socket on the loopback interface between two processes. The resulting overhead is between 99 – 125× for file creation and 10 – 24× for TCP. In these cases, BROWSIX’s system call overhead is amortized across useful work done in the kernel. The `lat_tcp` benchmark is the only benchmark that requires scheduling multiple processes under Linux, which BROWSIX execution more closely matches.

Summary: While BROWSIX’s performance is limited by the performance of underlying browser primitives (notably, the lack of native 64-bit integers and message passing performance), it provides acceptable performance for a range of applications.

Benchmark	Linux	Chrome	Firefox	Safari
lat_syscall:getpid	0.04 μ s	32.68 μ s (767 \times)	36.27 μ s (851 \times)	25.48 μ s (598 \times)
lat_fs:slayer	0.06 μ s	33.64 μ s (548 \times)	38.56 μ s (628 \times)	26.84 μ s (437 \times)
lat_fs:create 1024	25.57 μ s	3204.73 μ s (125 \times)	2963.42 μ s (116 \times)	2520.64 μ s (99 \times)
lat_tcp:localhost	16.98 μ s	374.09 μ s (22 \times)	415.18 μ s (24 \times)	174.16 μ s (10 \times)

Figure 11: Results of running several HBench-OS latency benchmarks under Linux and under BROWSIX. Numbers in parentheses are relative slowdown compared to native. Each benchmark was run 25 times per environment and the mean is displayed. All benchmarks used synchronous BROWSIX system calls (Section 3.2) except for `lat_tcp`, which requires asynchronous system calls for `fork` support. Browsers tested were Chrome Beta 56, Firefox Nightly 54, and Safari Technology Preview 22.

6. Discussion

The process of implementing BROWSIX has highlighted opportunities for improvement in the implementation and specification of browser APIs, especially Web Workers. We outline a number of optimizations and natural extensions that are generally useful, and would extend BROWSIX’s reach.

Worker Priority Control: The parent of a Web Worker has no way to lower the priority of a created worker. As workers are implemented on top of OS threads, this concept maps cleanly onto OS-level priorities/niceness. Providing this facility would let web applications prevent a low-priority CPU-intensive worker from interfering with the main browser thread.

postMessage() Backpressure: Traditional operating systems attempt to prevent individual processes from affecting system stability in a number of ways. One of these is providing backpressure, wherein the process attempting to write to a pipe or socket is suspended (the system call blocks) until the other end of the pipe reads the data or the data fits into a fixed size buffer. This approach prevents unbounded resource allocation in the kernel. In the browser, the `postMessage()` function can be called from a JavaScript context an unbounded number of times and can eventually cause the browser to run out of allocatable memory.

Message Passing Performance: Message passing is three orders of magnitude slower than traditional system calls in the three browsers we evaluate, Chrome, Firefox, and Safari. A more efficient message passing implementation would improve the performance of BROWSIX’s system calls and other inter-process communication.

Memory Mapping: BROWSIX is currently unable to support C/C++ applications like PostgreSQL that use `mmap`. Emscripten uses a single typed array to represent the unmanaged C/C++ heap. While recent browser interfaces make it possible to share this typed array among BROWSIX processes [6], browsers cannot yet map regions of the typed array into another typed array, which would be necessary to fully emulate `mmap`. Features on the WebAssembly roadmap, which aim for

implementation across browsers, would enable BROWSIX to support additional features like shared `mmap` and `shm`⁶.

Stack Management: C provides the ability to save and change the current thread’s context with the `setcontext` and `getcontext` functions. While rarely useful or advisable for applications, it enables specialized low-level libraries to save and restore the C stack. A similar JavaScript primitive coupled with the use of `SharedArrayBuffers` would let BROWSIX support `fork` in Emscripten applications as a synchronous system call.

7. Related Work

In-Browser Execution Environments: BROWSIX significantly extends past efforts to bring traditional APIs and general-purpose languages to the browser; Table 1 provides a comparison. Doppio’s focus is providing single-process POSIX abstractions [13]. BROWSIX builds on and extends its filesystem component, `BrowserFS`, to support multiple processes. Emscripten compiles LLVM bytecode to JavaScript, enabling the compilation of C and C++ to JavaScript [16]; as Section 4 describes, BROWSIX augments its runtime system so that unmodified C and C++ programs compiled with Emscripten can take full advantage of its facilities. BROWSIX provides similar runtime support for Go programs through `GopherJS` [11].

The Illinois Browser Operating System (IBOS) makes key browser APIs like HTTP requests and cookie storage OS primitives, removing library and OS code not necessary for those APIs from the trusted computing base [12]. Embassies refactors the web browser to separate the client execution interface from the developer programming interface [9]. Embassies models the client as a pico-datacenter, running each tenant (web page) in a separate VM. In addition to providing improved isolation and security for traditional web pages, Embassies enables safely executing arbitrary native code on the client in addition to a traditional WebKit HTML stack. Browsersix provides OS abstractions on top of browser APIs, and could be run in IBOS or Embassies for improved isolation and security.

⁶<https://github.com/WebAssembly/design/blob/master/FutureFeatures.md>

		<i>File system</i>	<i>Socket clients</i>	<i>Socket servers</i>	<i>Processes</i>	<i>Pipes</i>	<i>Signals</i>
ENVIRONMENTS	BROWSIX	✓	✓	✓	✓	✓	✓
	DOPPIO [13]	†	†				
	asm.js						
	WebAssembly						
LANGUAGE RUNTIMES	Emscripten (C/C++)	†	†	†			
	GopherJS (Go)						
	BROWSIX + Emscripten	✓	✓	✓	✓	✓	✓
	BROWSIX + GopherJS	✓	✓	✓	✓	✓	✓

Table 1: Feature comparison of JavaScript execution environments and language runtimes for programs compiled to JavaScript. † indicates that the feature is only accessible by a single running process. BROWSIX provides multi-process support for all of its features. Both asm.js and WebAssembly are pure computational environments and as such don't provide any of the OS features listed.

Xax is a browser plugin model designed to ease porting legacy code to the web [4]. It shares a similar focus on OS independence and legacy support along with an asynchronous system-call ABI, but runs native code in a hardware-isolated picoprocess. The Xax model requires developers to compile and host binaries for all architectures an end user might use, while BROWSIX leverages the cross-platform nature of JavaScript and WebAssembly to enable a compile-once, run-everywhere development workflow.

Kernel Design and OS Interfaces: BROWSIX resembles a Linux kernel task running on a microkernel [7], as it relies on an underlying system for messaging, scheduling and context switching. Barrelfish, a many-core, heterogenous OS [1] showed that asynchronous, shared-nothing system calls could be practical. BROWSIX somewhat mirrors the per-core, shared nothing structure of a multikernel, as individual BROWSIX processes do not use inter-domain communication for tasks like memory allocation and timers.

8. Conclusion

This paper introduces BROWSIX, a framework that brings the essence of Unix to the browser. BROWSIX makes it almost trivial to build complex web applications from components written in a variety of languages without modifying any code, and promises to significantly reduce the effort required to build highly sophisticated web applications. BROWSIX is open source, and is freely available at <https://browsix.org>.

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References

- [1] A. Baumann, P. Barham, P.-E. Dagand, T. Harris, R. Isaacs, S. Peter, T. Roscoe, A. Schüpbach, and A. Singhanian. The multikernel: a new OS architecture for scalable multicore systems. In *Proceedings of the ACM SIGOPS 22nd symposium on Operating systems principles*, pages 29–44. ACM, 2009.
- [2] A. B. Brown and M. I. Seltzer. Operating system benchmarking in the wake of lmbench: A case study of the performance of netbsd on the intel x86 architecture. In *Proceedings of the 1997 ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems*, SIGMETRICS '97, pages 214–224, New York, NY, USA, 1997. ACM.
- [3] S. Doeraene. Scala.js: Type-Directed Interoperability with Dynamically Typed Languages. Technical report, École polytechnique fédérale de Lausanne, 2013.
- [4] J. R. Douceur, J. Elson, J. Howell, and J. R. Lorch. Leveraging legacy code to deploy desktop applications on the web. In *Proceedings of the 8th USENIX Conference on Operating Systems Design and Implementation*, OSDI'08, pages 339–354, Berkeley, CA, USA, 2008. USENIX Association.
- [5] M. Fogleman. *fogleman/gg: Go Graphics - 2D rendering in Go with a simple API*, 2016. <https://github.com/fogleman/gg>.
- [6] L. T. Hansen and J. Fairbank. *ECMAScript Shared Memory and Atomics*, 2016. https://tc39.github.io/ecmascript_sharedmem/shmem.html.
- [7] H. Härtig, M. Hohmuth, J. Liedtke, J. Wolter, and S. Schönberg. The performance of μ -kernel-based systems. In *Proceedings of the Sixteenth ACM Symposium on Operating Systems Principles*, SOSP '97, pages 66–77, New York, NY, USA, 1997. ACM.

- [8] R. Hickey. Clojurescript. <http://clojurescript.org/about/rationale>, 2016.
- [9] J. Howell, B. Parno, and J. R. Douceur. Embassies: Radically refactoring the web. In *Proceedings of the 10th USENIX Conference on Networked Systems Design and Implementation*, nsdi' 13, pages 529–546, Berkeley, CA, USA, 2013. USENIX Association.
- [10] T. Mauro. *Adopting Microservices at Netflix: Lessons for Architectural Design*, 2015.
<https://www.nginx.com/blog/microservices-at-netflix-architectural-best-practices/>.
- [11] R. Musiol. *gopherjs/gopherjs: A compiler from Go to JavaScript for running Go code in a browser*, 2016. <https://github.com/gopherjs/gopherjs>.
- [12] S. Tang, H. Mai, and S. T. King. Trust and protection in the illinois browser operating system. In *Proceedings of the 9th USENIX Conference on Operating Systems Design and Implementation*, OSDI' 10, pages 17–31, Berkeley, CA, USA, 2010. USENIX Association.
- [13] J. Vilk and E. D. Berger. DOPPIO: Breaking the browser language barrier. In *Proceedings of the 2014 ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI 2014)*, pages 508–518. ACM, 2014.
- [14] J. Vouillon and V. Balat. From bytecode to JavaScript: the Js_of_ocaml compiler. *Software: Practice and Experience*, 44(8):951–972, 2014.
- [15] D. Yoo and S. Krishnamurthi. Whalesong: running racket in the browser. In *DLS'13, Proceedings of the 9th Symposium on Dynamic Languages, part of SPLASH 2013, Indianapolis, IN, USA, October 26-31, 2013*, pages 97–108, 2013.
- [16] A. Zakai. Emscripten: an LLVM-to-JavaScript compiler. In *OOPSLA Companion*, pages 301–312, 2011.