ripgrep is faster than {grep, ag, git grep, ucg, pt, sift}

Sep 23, 2016

In this article I will introduce a new command line search tool, `ripgrep`, that combines the usability of The Silver Searcher (an `ack` clone) with the raw performance of GNU grep. `ripgrep` is fast, cross platform (with binaries available for Linux, Mac and Windows) and written in Rust.

`ripgrep` is available on Github.

We will attempt to do the impossible: a fair benchmark comparison between several popular code search tools. Specifically, we will dive into a series of 25 benchmarks that substantiate the following claims:

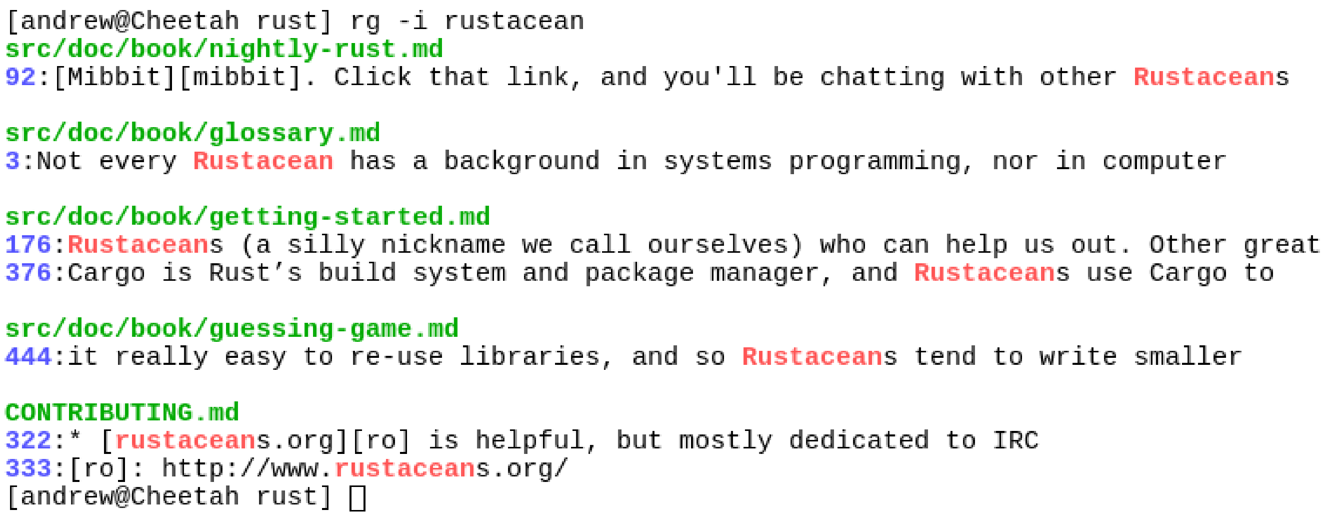
- For both searching single files *and* huge directories of files, no other tool obviously stands above `ripgrep` in either performance or correctness.
- `ripgrep` is the only tool with proper Unicode support that doesn't make you pay dearly for it.
- Tools that search many files at once are generally *slower* if they use memory maps, not faster.

As someone who has worked on text search in Rust in their free time for the last 2.5 years, and as the author of both `ripgrep` and the underlying regular expression engine, I will use this opportunity to provide detailed insights into the performance of each code search tool. No benchmark will go unscrutinized!

Target audience: Some familiarity with Unicode, programming and some experience with working on the command line.

NOTE: I'm hearing reports from some people that `rg` isn't as fast as I've claimed on their data. I'd love to help explain what's going on, but to do that, I'll need to be able to reproduce your results. If you file an issue with something I can reproduce, I'd be happy to try and explain it.

Screenshot of search results



```
[andrew@Cheetah rust] rg -i rustacean
src/doc/book/nightly-rust.md
92:[Mibbit][mibbit]. Click that link, and you'll be chatting with other Rustaceans

src/doc/book/glossary.md
3:Not every Rustacean has a background in systems programming, nor in computer

src/doc/book/getting-started.md
176:Rustaceans (a silly nickname we call ourselves) who can help us out. Other great
376:Cargo is Rust’s build system and package manager, and Rustaceans use Cargo to

src/doc/book/guessing-game.md
444:it really easy to re-use libraries, and so Rustaceans tend to write smaller

CONTRIBUTING.md
322:* [rustaceans.org][ro] is helpful, but mostly dedicated to IRC
333:[ro]: http://www.rustaceans.org/
[andrew@Cheetah rust] 
```

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Introducing ripgrep

Pitch

Why should you use `ripgrep` over any other search tool? Well…

- It can replace many use cases served by other search tools because it contains most of their features and is generally faster. (See the FAQ for more details on whether ripgrep can truly replace grep.)
- Like other tools specialized to code search, ripgrep defaults to recursive directory search and won't search files ignored by your `.gitignore` files. It also ignores hidden and binary files by default. ripgrep also implements full support for `.gitignore`, whereas there are many bugs related to that functionality in other code search tools claiming to provide the same functionality.
- ripgrep can search specific types of files. For example, `rg -tpy foo` limits your search to Python files and `rg -Tjs foo` excludes Javascript files from your search. ripgrep can be taught about new file types with custom matching rules.
- ripgrep supports many features found in `grep`, such as showing the context of search results, searching multiple patterns, highlighting matches with color and full Unicode support. Unlike GNU grep, ripgrep stays fast while supporting Unicode (which is always on).
- ripgrep has optional support for switching its regex engine to use PCRE2. Among other things, this makes it possible to use look-around and

backreferences in your patterns, which are not supported in ripgrep's default regex engine. PCRE2 support is enabled with `-P`.
- ripgrep supports searching files in text encodings other than UTF-8, such as UTF-16, latin-1, GBK, EUC-JP, Shift_JIS and more. (Some support for automatically detecting UTF-16 is provided. Other text encodings must be specifically specified with the `-E/--encoding` flag.)
- ripgrep supports searching files compressed in a common format (gzip, xz, lzma, bzip2 or lz4) with the `-z/--search-zip` flag.
- ripgrep supports arbitrary input preprocessing filters which could be PDF text extraction, less supported decompression, decrypting, automatic encoding detection and so on.

In other words, use ripgrep if you like speed, filtering by default, fewer bugs and Unicode support.

Anti-pitch

I'd like to try to convince you why you *shouldn't* use `ripgrep`. Often, this is far more revealing than reasons why I think you *should* use `ripgrep`.

Despite initially not wanting to add every feature under the sun to ripgrep, over time, ripgrep has grown support for most features found in other file searching tools. This includes searching for results spanning across multiple lines, and opt-in support for PCRE2, which provides look-around and backreference support.

At this point, the primary reasons not to use ripgrep probably consist of one or more of the following:

- You need a portable and ubiquitous tool. While ripgrep works on Windows, macOS and Linux, it is not ubiquitous and it does not conform to any standard such as POSIX. The best tool for this job is good old grep.
- There still exists some other feature (or bug) not listed in this README that you rely on that's in another tool that isn't in ripgrep.
- There is a performance edge case where ripgrep doesn't do well where another tool does do well. (Please file a bug report!)
- ripgrep isn't possible to install on your machine or isn't available for your platform. (Please file a bug report!)

Installation

The binary name for `ripgrep` is `rg`.

Binaries for `ripgrep` are available for Windows, Mac and Linux. Linux binaries are static executables. Windows binaries are available either as built with MinGW (GNU) or with Microsoft Visual C++ (MSVC). When possible, prefer MSVC over GNU, but you'll need to have the Microsoft VC++ 2015 redistributable installed.

If you're a **Homebrew** user, then you can install it like so:

```
$ brew install ripgrep
```

If you're an **Archlinux** user, then you can install `ripgrep` from the official repos:

```
$ pacman -Syu ripgrep
```

If you're a **Rust programmer**, `ripgrep` can be installed with `cargo`:

```
$ cargo install ripgrep
```

If you'd like to build `ripgrep` from source, that is also easy to do. `ripgrep` is written in Rust, so you'll need to grab a Rust installation in order to compile it. `ripgrep` compiles with Rust 1.9 (stable) or newer. To build:

```
$ git clone git://github.com/BurntSushi/ripgrep
$ cd ripgrep
$ cargo build --release
$ ./target/release/rg --version
0.1.2
```

If you have a Rust nightly compiler, then you can enable optional SIMD acceleration like so, which is used in all benchmarks reported in this article.

```
RUSTFLAGS="-C target-cpu=native" cargo build --release --features simd-acc
```

Whirlwind tour

The command line usage of `ripgrep` doesn't differ much from other tools that perform a similar function, so you probably already know how to use `ripgrep`. The full details can be found in `rg --help`, but let's go on a whirlwind tour.

`ripgrep` detects when its printing to a terminal, and will automatically colorize your output and show line numbers, just like The Silver Searcher. Coloring works on Windows too! Colors can be controlled more granularly with the `--color` flag.

One last thing before we get started: generally speaking, `ripgrep` assumes the input is reading is UTF-8. However, if ripgrep notices a file is encoded as UTF-16, then it will know how to search it. For other encodings, you'll need to explicitly specify them with the `-E/--encoding` flag.

To recursively search the current directory, while respecting all `.gitignore` files, ignore hidden files and directories and skip binary files:

```
$ rg foobar
```

The above command also respects all `.rgignore` files, including in parent directories. `.rgignore` files can be used when `.gitignore` files are insufficient. In all cases, `.rgignore` patterns take precedence over `.gitignore`.

To ignore all ignore files, use `-u`. To additionally search hidden files and directories, use `-uu`. To additionally search binary files, use `-uuu`. (In other words, "search everything, dammit!") In particular, `rg -uuu` is similar to `grep -a -r`.

```
$ rg -uu foobar  # similar to `grep -r`
$ rg -uuu foobar  # similar to `grep -a -r`
```

(Tip: If your ignore files aren't being adhered to like you expect, run your search with the `--debug` flag.)

Make the search case insensitive with `-i`, invert the search with `-v` or show the 2 lines before and after every search result with `-C2`.

Force all matches to be surrounded by word boundaries with `-w`.

Search and replace (find first and last names and swap them):

```
$ rg '([A-Z][a-z]+)\s+([A-Z][a-z]+)' --replace '$2, $1'
```

Named groups are supported:

```
$ rg '(?P<first>[A-Z][a-z]+)\s+(?P<last>[A-Z][a-z]+)' --replace '$last, $f
```

Up the ante with full Unicode support, by matching any uppercase Unicode letter followed by any sequence of lowercase Unicode letters (good luck doing this with other search tools!):

```
$ rg '(\p{Lu}\p{Ll}+)\s+(\p{Lu}\p{Ll}+)' --replace '$2, $1'
```

Search only files matching a particular glob:

```
$ rg foo -g 'README.*'
```

Or exclude files matching a particular glob:

```
$ rg foo -g '!*.min.js'
```

Search only HTML and CSS files:

```
$ rg -thtml -tcss foobar
```

Search everything except for Javascript files:

```
$ rg -Tjs foobar
```

To see a list of types supported, run `rg --type-list`. To add a new type, use `--type-add`, which must be accompanied by a pattern for searching (`rg` won't persist your type settings):

```
$ rg --type-add 'foo:*.{foo,foobar}' -tfoo bar
```

The type `foo` will now match any file ending with the `.foo` or `.foobar` extensions.

Regex syntax

The syntax supported is documented as part of Rust's regex library.

Anatomy of a grep

Before we dive into benchmarks, I thought it might be useful to provide a high level overview of how a grep-like search tool works, with a special focus on `ripgrep` in particular. The goal of this section is to provide you with a bit of context that will help make understanding the analysis for each benchmark easier.

Background

Modulo parsing command line arguments, the first "real" step in any search tool is figuring out what to search. Tools like `grep` don't try to do anything smart: they simply search the files given to it on the command line. An exception to this is the `-r` flag, which will cause `grep` to recursively search all files in the current directory. Various command line flags can be passed to control which files are or aren't searched.

`ack` came along and turned this type of default behavior on its head. Instead of trying to search everything by default, `ack` tries to be smarter about what to search. For example, it will recursively search your current directory *by default*, and it will automatically skip over any source control specific files and directories (like `.git`). This method of searching undoubtedly has its own pros and cons, because it tends to make the tool "smarter," which is another way of saying "opaque." That is, when you really do need the tool to search everything, it can sometimes be tricky to know how to speak the right incantation for it to do so. With that said, being smart by default is incredibly convenient, especially when "smart" means "figure out what to search based on your source control configuration." There's no shell alias that can do that with `grep`.

All of the other search tools in this benchmark share a common ancestor with either `grep` or `ack`. `sift` is descended from `grep`, while `ag`, `ucg`, and `pt` are descended from `ack`. `ripgrep` is a bit of a hybrid because it was specifically built to be good at searching huge files just like `grep`, but at the same time, provide the “smart” kind of default searching like `ack`. Finally, `git grep` deserves a bit of a special mention. `git grep` is very similar to plain `grep` in the kinds of options it supports, but its default mode of searching is clearly descended from `ack`: it will only search files checked into source control.

Of course, both types of search tools have *a lot* in common, but there are a few broad distinctions worth making if you allow yourself to squint your eyes a bit:

- `grep`-like tools need to be really good at searching large files, so the performance of the underlying regex library is paramount.
- `ack`-like tools need to be really good at recursive directory traversal while also applying ignore rules from files like `.gitignore` quickly. `ack`-like tools are built to run many searches in parallel, so the raw performance of the underlying regex library can be papered over somewhat while still being faster than single-threaded “search everything” tools like `grep`. If the “smarts” of `ack` also mean skipping over that 2GB artifact in your directory tree, then the performance difference becomes even bigger.
- `ripgrep` tries hard to combine the best of both worlds. Not only is its underlying regex engine very fast, but it parallelizes searches and tries to be smart about what it searches too.

Gathering files to search

For an `ack`-like tool, it is important to figure out which files to search in the current directory. This means using a very fast recursive directory iterator, filtering file paths quickly and distributing those file paths to a pool of workers that actually execute the search.

Directory traversal can be tricky because some recursive directory iterators make more stat calls than are strictly necessary, which can have a large impact on performance. It can be terribly difficult to track down these types of performance problems because they tend to be buried in a standard library somewhere. Python only recently fixed this, for example. Rest assured that `ripgrep` uses a recursive directory iterator that makes the minimum number of system calls possible.

Filtering file paths requires not only respecting rules given at the command line (e.g., `grep`'s `--include` or `--exclude`) flags, but also requires reading files like `.gitignore` and applying their rules correctly to all file paths. Even the mere act of looking for a `.gitignore` file in every directory can have measurable overhead! Otherwise, the key performance challenge with this functionality is making sure you don't try to match every ignore rule individually against every file path. Large repositories like the Linux kernel source tree have over a hundred `.gitignore` files with thousands of rules combined.

Finally, distributing work to other threads for searching requires some kind of synchronization. One solution is a mutex protected ring buffer that acts as a sort of queue, but there are lock-free solutions that might be faster. Rust's ecosystem is so great that I was able to reuse a lock-free Chase-Lev work-stealing queue for distributing work to a pool of searchers. Every *other* tool that parallelizes work in this benchmark uses a variant of a mutex protected queue. (`sift` and `pt` might not fit this criteria, since they use Go channels, and I haven't followed any implementation improvements to that code for a few years.)

Searching

Searching is the heart of any of these tools, and we could dig ourselves into a hole on just this section alone and not come out alive for at least 2.5 years. (Welcome to "How Long I've Been Working On Text Search In Rust.") Instead, we will lightly touch on the big points.

Regex engine

First up is the regex engine. Every search tool supports some kind of syntax for regular expressions. Some examples:

- `foo|bar` matches any literal string `foo` or `bar`
- `[a-z]{2}_[a-z]+` matches two lowercase latin letters, followed by an underscore, followed by one or more lowercase latin letters.
- `\bfoo\b` matches the literal `foo` only when it is surrounded by word boundaries. For example, the `foo` in `foobar` won't match but it will in `I love foo.`.
- `(\w+) \1` matches any sequence of word characters followed by a space and followed by exactly the word characters that were matched previously. The `\1` in this example is called a "back-reference." For example, this pattern will match `foo foo` but not `foo bar`.

Regular expression engines themselves tend to be divided into two categories predominantly based on the features they expose. Regex engines that provide support for all of the above tend to use an approach called *backtracking*, which is typically quite fast, but can be very slow on some inputs. “Very slow” in this case means that it might take exponential time to complete a search. For example, try running this Python code:

```
>>> import re
>>> re.search('(a*)*c', 'a' * 30)
```

Even though both the regex and the search string are tiny, it will take a very long time to terminate, and this is because the underlying regex engine uses backtracking, and can therefore take exponential time to answer some queries.

The other type of regex engine generally supports fewer features and is based on finite automata. For example, these kinds of regex engines typically don’t support back-references. Instead, these regex engines will often provide a guarantee that *all searches*, regardless of the regex or the input, will complete in linear time with respect to the search text.

It’s worth pointing out that neither type of engine has a monopoly on average case performance. There are examples of regex engines of both types that are blazing fast. With that said, here’s a breakdown of some search tools and the type of regex engine they use:

- GNU grep and `git grep` each use their own hand-rolled finite automata based engine.
- `ripgrep` uses Rust’s regex library, which uses finite automata.
- The Silver Searcher and Universal Code Grep use PCRE, which uses backtracking.
- Both The Platinum Searcher and sift use Go’s regex library, which uses finite automata.

Both Rust’s regex library and Go’s regex library share Google’s RE2 as a common ancestor.

Finally, both tools that use PCRE (The Silver Searcher and Universal Code Grep) are susceptible to worst case backtracking behavior. For example:

```
$ cat wat
c
aaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
c
$ ucg '(a*)*c' wat
terminate called after throwing an instance of 'FileScannerException'
  what():  PCRE2 match error: match limit exceeded
Aborted (core dumped)
```

The Silver Searcher fails similarly. It reports the first line as a match and neglects the match in the third line. The rest of the search tools benchmarked in this article handle this case without a problem.

Literal optimizations

Picking a fast regex engine is important, because every search tool will need to rely on it sooner or later. Nevertheless, even the performance of the fastest regex engine can be dwarfed by the time it takes to search for a simple literal string. Boyer-Moore is the classical algorithm that is used to find a substring, and even today, it is hard to beat for general purpose searching. One of its defining qualities is its ability to skip some characters in the search text by pre-computing a small skip table at the beginning of the search.

On modern CPUs, the key to making a Boyer-Moore implementation fast is not necessarily the number of characters it can skip, but how fast it can identify a candidate for a match. For example, most Boyer-Moore implementations look for the *last* byte in a literal. Each occurrence of that byte is considered a candidate for a match by Boyer-Moore. It is only at this point that Boyer-Moore can use its precomputed table to skip characters, which means you still need a fast way of identifying the candidate in the first place. Thankfully, specialized routines found in the C standard library, like `memchr`, exist for precisely this purpose. Often, `memchr` implementations are compiled down to SIMD instructions that examine *sixteen* bytes in a single loop iteration. This makes it very fast. On my system, `memchr` often gets throughputs at around several gigabytes a second. (In my own experiments, Boyer-Moore with `memchr` can be just as fast as an explicit SIMD implementation using the PCMPESTRI instruction, but this is something I'd like to revisit.)

For a search tool to compete in most benchmarks, either it or its regex engine needs to use some kind of literal optimizations. For example, Rust's regex library goes to great lengths to extract both prefix and suffix literals from every pattern. The following patterns all have literals extracted from them:

- `foo|bar` detects `foo` and `bar`
- `(a|b)c` detects `ac` and `bc`
- `[ab]foo[yz]` detects `afooy`, `afooz`, `bfooy` and `bfooz`
- `(foo)?bar` detects `foobar` and `bar`
- `(foo)*bar` detects `foo` and `bar`
- `(foo){3,6}` detects `foofoofoo`

If any of these patterns appear at the *beginning* of a regex, Rust's regex library will notice them and use them to find candidate matches very quickly (even when there is more than one literal detected). While Rust's core regex engine is fast, it is still faster to look for literals first, and only drop down into the core regex engine when it's time to verify a match.

The best case happens when an entire regex can be broken down into a single literal or an alternation of literals. In that case, the core regex engine won't be used at all!

A search tool in particular has an additional trick up its sleeve. Namely, since most search tools do line-by-line searching (The Silver Searcher is a notable exception, which does multiline searching by default), they can extract *non-prefix* or "inner" literals from a regex pattern, and search for those to identify candidate *lines* that match. For example, the regex `\w+foo\d+` could have `foo` extracted. Namely, when a candidate line is found, `ripgrep` will find the beginning and end of only that line, and then run the full regex engine on the entire line. This lets `ripgrep` very quickly skip through files by staying out of the regex engine. Most of the search tools we benchmark here don't perform this optimization, which can leave a lot of performance on the table, especially if your core regex engine isn't that fast.

Handling the case of multiple literals (e.g., `foo|bar`) is just as important. GNU grep uses a little known algorithm similar to Commentz-Walter for searching multiple patterns. In short, Commentz-Walter is what you get when you merge Aho-Corasick with Boyer-Moore: a skip table with a *reverse* automaton. Rust's regex library, on the other hand, will either use plain Aho-Corasick, or, when enabled, a special SIMD algorithm called Teddy, which was invented by Geoffrey Langdale as part of the Hyperscan regex library developed by Intel.

This SIMD algorithm will prove to be at least one of the key optimizations that propels `ripgrep` past GNU grep.

The great thing about this is that `ripgrep` doesn't have to do much of this literal optimization work itself. Most of it is done inside Rust's regex library, so every consumer of that library gets all these performance optimizations automatically!

Mechanics

Repeat after me: Thou Shalt Not Search Line By Line.

The naive approach to implementing a search tool is to read a file line by line and apply the search pattern to each line individually. This approach is problematic primarily because, in the common case, finding a match is *rare*. Therefore, you wind up doing a ton of work parsing out each line all for naught, because most files simply aren't going to match at all in a large repository of code.

Not only is finding every line extra work that you don't need to do, but you're also paying a huge price in overhead. Whether you're searching for a literal or a regex, you'll need to start and stop that search for every single line in a file. The overhead of each search will be your undoing.

Instead, all search tools find a way to search a big buffer of bytes all at once. Whether that's memory mapping a file, reading an entire file into memory at once or incrementally searching a file using a constant sized intermediate buffer, they all find a way to do it to some extent. There are some exceptions though. For example, tools that use memory maps or read entire files into memory either can't support `stdin` (like Universal Code Grep), or revert to line-by-line searching (like The Silver Searcher). Tools that support incremental searching (`ripgrep`, GNU grep and `git grep`) can use its incremental approach on any file or stream with no problems.

There's a reason why not every tool implements incremental search: it's *hard*. For example, you need to consider all of the following in a fully featured search tool:

- Line counting, when requested.
- If a read from a file ends in the middle of a line, you need to do the bookkeeping required to make sure the incomplete line isn't searched until more data is read from the file.

- If a line is too long to fit into your buffer, you need to decide to either give up or grow your buffer to fit it.
- Your searcher needs to know how to invert the match.
- Worst of all: your searcher needs to be able to show the context of a match, e.g., the lines before and after a matching line. For example, consider the case of a match that appears at the beginning of your buffer. How do you show the previous lines if they aren't in your buffer? You guessed it: you need to carry over at least as many lines that are required to satisfy a context request from buffer to buffer.

It's a steep price to pay in terms of code complexity, but by golly, is it worth it. You'll need to read on to the benchmarks to discover when it is faster than memory maps!

Printing

It might seem like printing is such a trivial step, but it must be done with at least some care. For example, you can't just print matches from each search thread as you find them, because you really don't want to interleave the search results of one file with the search results of another file. A naive approach to this is to serialize the printer so that only one thread can print to it at a time. This is problematic though, because if a search thread acquires a lock to the printer before starting the search (and not releasing it until it has finished searching one file), you'll end up also serializing every search as well, effectively defeating your entire approach to parallelism.

All code search tools in this benchmark that parallelize search therefore write results to some kind of intermediate buffer *in memory*. This enables all of the search threads to actually perform a search in parallel. The printing still needs to be serialized, but we've reduced that down to simply dumping the contents of the intermediate buffer to `stdout`. Using an in memory buffer might set off alarm bells: what if you search a 2GB file and every line matches? Doesn't that lead to excessive memory usage? The answer is: "Why, yes, indeed it does!" The key insight is that the common case is returning far fewer matches than there are total lines searched. Nevertheless, there are ways to mitigate excessive memory usage. For example, if `ripgrep` is used to search `stdin` or a single file, then it will write search results directly to `stdout` and forgo the intermediate buffer because it just doesn't need it. (`ripgrep` should also do this when asked to *not* do any parallelism, but I haven't gotten to it yet.) In other words, pick two: space, time or correctness.

Note that the details aren't quite the same in every tool. Namely, while The Silver Searcher and Universal Code Grep write matches as structured data to memory (i.e., an array of `match` structs or something similar), both `git grep` and `ripgrep` write the actual output to a dynamically growable string buffer in memory. While either approach does seem to be fast enough, `git grep` and `ripgrep` have to do things this way because they support incremental search where as The Silver Searcher always memory maps the entire file and Universal Code Grep always reads the entire contents of the file into memory. The latter approach can refer back to the file's contents in memory when doing the actual printing, where as neither `git grep` nor `ripgrep` can do that.

Methodology

Overview

Coming up with a good and fair benchmark is *hard*, and I have assuredly made some mistakes in doing so. In particular, there are so many variables to control for that testing every possible permutation isn't feasible. This means that the benchmarks I'm presenting here are *curated*, and, given that I am the author of one of the tools in the benchmark, they are therefore also *biased*. Nevertheless, even if I fail in my effort to provide a fair benchmark suite, I do hope that some of you may find my analysis interesting, which will try to explain the results in each benchmark. The analysis is in turn heavily biased toward explaining my own work, since that is the implementation I'm most familiar with. I have, however, read at least part of the source code of every tool I benchmark, including their underlying regex engines.

In other words, I'm pretty confident that I've gotten the *details* correct, but I could have missed something in the bigger picture. Because of that, let's go over some important insights that guided construction of this benchmark.

- Focus on the problem that an *end user* is trying to solve. For example, we split the entire benchmark in two: one for searching a large directory of files and one for searching a single large file. The former might correspond to an end user searching their code while the latter might correspond to an end user searching logs. As we will see, these two use cases have markedly different performance characteristics. A tool that is good at one isn't necessarily good at the other. (The premise of `ripgrep` is that it is possible to be good at both!)

- Apply *end user* problems more granularly as well. For example, most searches result in few hits relative to the corpus searched, so prefer benchmarks that report few matches. Another example: I hypothesize, based on my own experience, that most searches use patterns that are simple literals, alternations or very light regexes, so bias the benchmarks towards those types of patterns.
- Almost every search tool has slightly different default behavior, and these behavioral changes can have an impact on performance. There is some value in looking at "out-of-the-box" performance, and we therefore do look at a benchmark for that, but stopping there is a bit unsatisfying. If our goal is to do a *fair* comparison, then we need to at least try to convince each tool to do roughly the same work, **from the perspective of an end user**. A good example of this is reporting line numbers. Some tools don't provide a way of disabling line counting, so when doing comparisons between tools that do, we need to explicitly enable line numbers. This is important, because counting lines can be quite costly! A good *non-example* of this is if one tool uses memory maps and another uses an intermediate buffer. This is an implementation choice, and not one that alters what the user actually sees, therefore comparing those two implementation choices in a benchmark is completely fair (assuming an analysis that points it out).

With that out of the way, let's get into the nitty gritty. First and foremost, what tools are we benchmarking?

- `ripgrep` (rg) (v0.1.2) - You've heard enough about this one already.
- GNU grep (v2.25) - Ol' reliable.
- git grep (v2.7.4) - Like `grep`, but built into `git`. Only works well in `git` repositories.
- The Silver Searcher (ag) (commit `cda635`, using PCRE 8.38) - Like `ack`, but written in C and much faster. Reads your `.gitignore` files just like `ripgrep`.
- Universal Code Grep (ucg) (commit `487bfb`, using PCRE 10.21 **with the JIT enabled**) - Also like `ack` but written in C++, and only searches files from a whitelist, and doesn't support reading `.gitignore`.
- The Platinum Searcher (pt) (commit `509368`) - Written in Go and does support `.gitignore` files.
- sift (commit `2d175c`) - Written in Go and supports `.gitignore` files with an optional flag, but generally prefers searching everything (unlike every other tool in this list except for `grep`).

Notably absent from this list is `ack`. I chose not to benchmark it because, at the time of writing, `ack` was much slower than the other tools in this list. However, ack 3 is now in beta and includes some performance improvements, sometimes decreasing search times by half.

Benchmark runner

The benchmark runner is a Python program (requires at least Python 3.5) that you can use to not only run the benchmarks themselves, but download the corpora used in the benchmarks as well. The script is called `benchsuite` and is in the `ripgrep` repository. You can use it like so:

```
$ git clone git://github.com/BurntSushi/ripgrep
$ cd ripgrep/benchsuite
# WARNING! This downloads several GB of data, and builds the Linux kernel.
# This took about 15 minutes on a high speed connection.
# Tip: try `--download subtitles-ru` to grab the smallest corpus, but you'
# be limited to running benchmarks for only that corpus.
$ ./benchsuite --dir /path/to/data/dir --download all
# List benchmarks available.
$ ./benchsuite --dir /path/to/data/dir --list
# Run a benchmark.
# Omit the benchmark name to run all benchmarks. The full suite can take a
# 30 minutes to complete on default settings and 120 minutes to complete w
# --warmup-iter 3 --bench-iter 10.
$ ./benchsuite --dir /path/to/data/dir '^subtitles_ru_literal$'
```

If you don't have all of the code search tools used in the benchmarks, then pass `--allow-missing` to give `benchsuite` permission to skip running them. To save the raw data (the timing for every command run), pass `--raw /path/to/raw.csv`.

The benchmark runner tries to do a few basic things for us to help reduce the chance that we get misleading data:

- Every benchmarked command is run three times before being measured as a "warm up." Specifically, this is to ensure that the corpora being searched is already in the operating system's page cache. If we didn't do this, we might end up benchmarking disk I/O, which is not only uninteresting for our purposes, but is probably not a common end user

scenario. It's more likely that you'll be executing lots of searches against the same corpus (at least, I know I do).
- Every benchmarked command is run ten times, with a timing recorded for each run. The final "result" of that command is its distribution (mean +/- standard deviation). If I were a statistician, I could probably prove that ten samples is insufficient. Nevertheless, getting more samples takes more time, and for the most part, the variance is very low.

Each individual benchmark definition is responsible for making sure each command is trying to do similar work as other commands we're comparing it to. For example, we need to be careful to enable and disable Unicode support in GNU grep where appropriate, because full Unicode handling can make GNU grep run very slowly. Within each benchmark, there are often multiple variables of interest. To account for this, I've added labels like `(ASCII)` or `(whitelist)` where appropriate. We'll dig into those labels in more detail later.

Please also feel encouraged to add your own benchmarks if you'd like to play around. The benchmarks are in the top-half of the file, and it should be fairly straight-forward to copy & paste another benchmark and modify it. Simply defining a new benchmark will make it available. The second half of the script is the runner itself and probably shouldn't need to be modified.

Environment

The actual environment used to run the benchmarks presented in this article was a `c3.2xlarge` instance on Amazon EC2. It ran Ubuntu 16.04, had a Xeon E5-2680 2.8 GHz CPU, 16 GB of memory and an 80 GB SSD (on which the corpora was stored). This was enough memory to fit all of the corpora in memory. The box was specifically provisioned for the purpose of running benchmarks, so it was not doing anything else.

The full log of system setup and commands I used to install each of the search tools and run benchmarks can be found here. I also captured the output of the bench runner (SPOILER ALERT) and the raw output, which includes the timings, full set of command line arguments and any environment variables set for every command run in every benchmark.

Code search benchmarks

This is the first half of our benchmarks, and corresponds to an *end user* trying to search a large repository of code for a particular pattern.

The corpus used for this benchmark is a *built* checkout of the Linux kernel, specifically commit `d0acc7`. We actually build the Linux kernel because the process of building the kernel leaves a lot of garbage in the repository that you probably don't want to search. This can influence not only the relevance of the results returned by a search tool, but the performance as well.

All benchmarks run in this section were run in the root of the repository. Remember, you can see the full raw results of each command if you like. The benchmark names correspond to the headings below.

Note that since these benchmarks were run on an EC2 instance, which uses a VM, which in turn can penalize search tools that use memory maps, I've also recorded benchmarks on my local machine. My local machine is an Intel i7-6900K 3.2 GHz, 16 CPUs, 64 GB memory and an SSD. You'll notice that `ag` does a lot better (but still worse than `rg`) on my machine. Lest you think I've chosen results from the EC2 machine because they paint `rg` more favorably, rest assured that I haven't. Namely, `rg` wins *every single benchmark* on my local machine except for *one*, where as `rg` is beat out just slightly by a few tools on some benchmarks on the EC2 machine.

Without further ado, let's start looking at benchmarks.

`linux_literal_default`

Description: This benchmark compares the time it takes to execute a simple literal search using each tool's default settings. This is an intentionally unfair benchmark meant to highlight the differences between tools and their "out-of-the-box" settings.

Pattern: `PM_RESUME`

```
rg         0.349 +/- 0.104 (lines: 16)
ag         1.589 +/- 0.009 (lines: 16)
ucg        0.218 +/- 0.007 (lines: 16)*+
pt         0.462 +/- 0.012 (lines: 16)
sift       0.352 +/- 0.018 (lines: 16)
git grep   0.342 +/- 0.005 (lines: 16)
```

- `*` - Best mean time.
- `+` - Best sample time.
- `rg == ripgrep`, `ag == The Silver Searcher`, `ucg == Universal Code Grep`, `pt == The Platinum Searcher`

Analysis: We'll first start by actually describing what each tool is doing:

- `rg` respects the Linux repo's `.gitignore` files (of which there are `178`(!) of them), and skips hidden and binary files. `rg` does not count lines.
- `ag` has the same default behavior as `rg`, except it counts lines.
- `ucg` also counts lines, but does not attempt to read `.gitignore` files. Instead, it only searches files from an (extensible) whitelist according to a set of glob rules. For example, both `rg` and `ag` will search `fs/jffs2/README.Locking` while `ucg` won't, because it doesn't recognize the `Locking` extension. (A search tool probably *should* search that file, although it does not impact the results of this specific benchmark.)
- `pt` has the same default behavior as `ag`.
- `sift` searches everything, including binary files and hidden files. It *should* be equivalent to `grep -r`, for example. It also does not count lines.
- `git grep` should have the same behavior at `rg`, and similarly does not count lines. Note though that `git grep` has a special advantage: it does not need to traverse the directory hierarchy. It can discover the set of files to search straight from its git index.

The high-order bit to extract from this benchmark is that a naive comparison between search tools is completely unfair from the perspective of performance, but is really important if you care about the *relevance* of results returned to you. `sift`, like `grep -r`, will throw everything it can back at you, which is totally at odds with the philosophy behind every other tool in this benchmark: only return results that are *probably* relevant. Things inside your `.git` probably aren't, for example. (This isn't to say that `sift`'s philosophy is wrong. The tool is clearly intended to be configured by an end user to their own tastes, which has its own pros and cons.)

With respect to performance, there are two key variables to pay attention to. They will appear again and again throughout our benchmark:

- Counting lines *can be* quite expensive. A naive solution—a loop over every byte and comparing it to a `\n`—will be quite slow for example. Universal Code Grep counts lines using SIMD and `ripgrep` counts lines using packed comparisons (16 bytes at a time). However, in the Linux code search benchmarks, because the size of each individual file is very small and the

number of matches is tiny compared to the corpus size, the time spent counting lines tends to not be so significant. Especially since every tool in this benchmark parallelizes search to some degree. When we get to the single-file benchmarks, this variable will become much more pertinent.
- Respecting `.gitignore` files incurs some amount of overhead. Even though respecting `.gitignore` reduces the number of files searched, it can be slower overall to actually read the patterns, compile them and match them against every path than to just search every file. This is precisely how `ucg` soundly beats `ripgrep` in this benchmark. (We will control for this variable in future benchmarks.) In other words, respecting `.gitignore` is a feature that improves *relevance* first and foremost. It is strictly a bonus if it also happens to improve performance.

The specific reasons why supporting `.gitignore` leads to a slower overall search are:

- Every directory descended requires looking for a corresponding `.gitignore`. Multiply the number of calls if you support additional ignore files, like both The Silver Searcher and `ripgrep` do. The Linux kernel repository has `4,640` directories. `178` of them have `.gitignore` files.
- Each `.gitignore` file needs to be compiled into something that can match file paths. Both The Silver Searcher and `ripgrep` use tricks to make this faster. For example, simple patterns like `/vmlinux` or `*.o` can be matched using simple literal comparisons or by looking at the file extension of a candidate path and comparing it directly. For more complex patterns like `*.c.[012]*.*`, a full glob matcher needs to be used. The Silver Searcher uses `fnmatch` while `ripgrep` translates all such globs into a single regular expression which can be matched against a single path all at once. Doing all this work takes time.
- Unlike `ag`, `rg` will try to support the full semantics of a `.gitignore` file. This means finding *every* ignore pattern that matches a file path and giving precedent to the most recently defined pattern. `ag` will bail on the first match it sees.
- Actually matching a path has non-trivial overhead that must be paid for *every* path searched. The compilation phase described above is complex precisely for making this part faster. We try to stay out of the regex machinery as best we can, but we can’t avoid it completely.

In contrast, a whitelist like the one used by `ucg` is comparatively easy to make fast. The set of globs is known upfront, so no additional checks need to be made while traversing the file tree. Moreover, the globs tend to be of the `*.ext` variety, which fall into the bucket of globs that can be matched efficiently just by looking at the extension of a file path.

The downside of a whitelist is obvious: you might end up missing search results simply because `ucg` didn't know about a particular file extension. You could always teach `ucg` about the file extension, but you're still blind to "unknown unknowns" (i.e., files that you probably want to search but didn't know upfront that you needed to).

`linux_literal`

Description: This benchmark runs the same query as in the `linux_literal_default` benchmark, but we try to do a fair comparison. In particular, we run `ripgrep` in two modes: one where it respects `.gitignore` files (corresponding to the `(ignore)` label) and one where it uses a whitelist and doesn't respect `.gitignore` (corresponding to the `(whitelist)` label). The former mode is comparable to `ag`, `pt`, `sift` and `git grep`, while the latter mode is comparable to `ucg`. We also run `rg` a third time by explicitly telling it to use memory maps for search, which matches the implementation strategy used by `ag`. `sift` is run such that it respects `.gitignore` files and excludes binary, hidden and PDF files. All commands executed here count lines, because some commands (`ag` and `ucg`) don't support disabling line counting.

Pattern: `PM_RESUME`

```
rg (ignore)          0.334 +/- 0.053 (lines: 16)
rg (ignore) (mmap)   1.611 +/- 0.009 (lines: 16)
ag (ignore) (mmap)   1.588 +/- 0.011 (lines: 16)
pt (ignore)          0.456 +/- 0.025 (lines: 16)
sift (ignore)        0.630 +/- 0.004 (lines: 16)
git grep (ignore)    0.345 +/- 0.007 (lines: 16)
rg (whitelist)       0.228 +/- 0.042 (lines: 16)+
ucg (whitelist)      0.218 +/- 0.007 (lines: 16)*
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: We have a ton of ground to cover on this one.

First and foremost, the `(ignore)` vs. `(whitelist)` variables have a clear impact on the performance of `rg`. We won't rehash all the details from the analysis in `linux_literal_default`, but switching `rg` into its whitelist mode brings it into a dead heat with `ucg`.

Secondly, `ucg` is just as fast as `ripgrep` and `git grep (ignore)` is just as fast as `rg (ignore)`, even though I've said that `ripgrep` is the fastest. It turns out that `ucg`, `git grep` and `rg` are pretty evenly matched when searching for plain literals in large repositories. We will see a stronger separation in later benchmarks. Still, what makes `ucg` fast?

- `ucg` reads the entire file into memory before searching it, which means it avoids the memory map problem described below. On a code repository, this approach works well, but it comes with a steep price in the single-file benchmarks.
- It has a fast explicitly SIMD based line counting algorithm. `ripgrep` has something similar, but relies on the compiler for autovectorization.
- `ucg` uses PCRE2's JIT, which is *insanely* fast. In my own very rough benchmarks, PCRE2's JIT is one of the few general purpose regex engines that is competitive with Rust's regex engine (on regexes that don't expose PCRE's exponential behavior due to backtracking, since Rust's regex engine doesn't suffer from that weakness).
- `ucg` parallelizes directory traversal, which is something that `ripgrep` doesn't do. `ucg` has it a bit easier here because it doesn't support `.gitignore` files. Parallelizing directory traversal while maintaining state for `.gitignore` files in a way that scales isn't a problem I've figured out how to cleanly solve yet.

What about `git grep`? A key performance advantage of `git grep` is that it doesn't need to walk the directory tree, which can save it quite a bit of time. Its regex engine is also quite fast, and works similarly to GNU grep's, RE2 and Rust's regex engine (i.e., it uses a DFA).

Both `sift` and `pt` perform almost as well as `ripgrep`. In fact, both `sift` and `pt` do implement a parallel recursive directory traversal while still respecting `.gitignore` files, which is likely one reason for their speed. As we will see in future benchmarks, their speed here is misleading. Namely, they are fast because they stay outside of Go's regexp engine since the pattern is a literal. (There will be more discussion on this point later.)

Finally, what's going on with The Silver Searcher? Is it really that much slower than everything else? The key here is that its use of memory maps is making it *slower*, not faster (in direct contradiction to the claims in its README).

OK, let's pause and pop up a level to talk about what this actually means. First, we need to consider how these search tools fundamentally work. Generally speaking, a search tool like this has two ways of actually searching files on disk:

1. It can memory map the file and search the entire file all at once *as if* it were a single contiguous region of bytes in memory. The operating system does the work behind the scenes to make a file look like a contiguous region of memory. This particular approach is *really* convenient when comparing it to the alternative described next.
2. … or it can allocate an intermediate buffer, read a fixed size block of bytes from the file into it, search the buffer and then repeat the process. This particular approach is absolutely ghoulish to implement, because you need to account for the fact that a buffer may end in the middle of the line. You also need to account for the fact that a single line may exceed the size of your buffer. Finally, if you're going to support showing the lines around a match (its "context") as both `grep` and `ripgrep` do, then you need to do additional bookkeeping to make sure any lines from a previous buffer are printed even if a match occurs at the beginning of the next block read from the file.

Naively, it seems like (1) would be *obviously* faster. Surely, all of the bookkeeping and copying in (2) would make it much slower! In fact, this is not at all true. (1) may not require much bookkeeping from the perspective of the programmer, but there is a lot of bookkeeping going on inside the Linux kernel to maintain the memory map. (That link goes to a mailing list post that is quite old, but it still appears relevant today.)

When I first started writing `ripgrep`, I used the memory map approach. It took me a long time to be convinced enough to start down the second path with an intermediate buffer (because neither a CPU profile nor the output of `strace` ever showed any convincing evidence that memory maps were to blame), but as soon as I had a prototype of (2) working, it was clear that it was much faster than the memory map approach.

With all that said, memory maps aren't all bad. They just happen to be bad for the particular use case of "rapidly open, scan and close memory maps for thousands of small files." For a different use case, like, say, "open this large file and search it once," memory maps turn out to be a boon. We'll see that in action in our single-file benchmarks later.

The key datapoint that supports this conclusion is the comparison between `rg (ignore)` and `rg (ignore) (mmap)`. In particular, this controls for everything *except* for the search strategy and fairly conclusively points right at memory maps as the problem.

With all that said, the performance of memory maps is very dependent on your environment, and the absolute difference between `rg (ignore)` and `ag (ignore) (mmap)` can be misleading. In particular, since these benchmarks were run on an EC2 `c3.2xlarge`, we were probably inside a virtual machine, which could feasibly impact memory map performance. To test this, I ran the same benchmark on my machine under my desk (Intel i7-6900K 3.2 GHz, 16 CPUs, 64 GB memory, SSD) and got these results:

```
rg (ignore)          0.156 +/- 0.006 (lines: 16)
rg (ignore) (mmap)   0.397 +/- 0.013 (lines: 16)
ag (ignore) (mmap)   0.444 +/- 0.016 (lines: 16)
pt (ignore)          0.159 +/- 0.008 (lines: 16)
sift (ignore)        0.344 +/- 0.002 (lines: 16)
git grep (ignore)    0.195 +/- 0.023 (lines: 16)
rg (whitelist)       0.108 +/- 0.005 (lines: 16)*+
ucg (whitelist)      0.165 +/- 0.005 (lines: 16)
```

`rg (ignore)` still soundly beats `ag`, and our memory map conclusions above are still supported by this data, but the difference between `rg (ignore)` and `ag (ignore) (mmap)` has narrowed quite a bit!

`linux_literal_casei`

Description: This benchmark is like `linux_literal`, except it asks the search tool to perform a case insensitive search.

Pattern: `PM_RESUME` (with the `-i` flag set)

```
rg (ignore)          0.345 +/- 0.073 (lines: 370)
rg (ignore) (mmap)   1.612 +/- 0.011 (lines: 370)
ag (ignore) (mmap)   1.609 +/- 0.015 (lines: 370)
pt (ignore)          17.204 +/- 0.126 (lines: 370)
sift (ignore)        0.805 +/- 0.005 (lines: 370)
git grep (ignore)    0.343 +/- 0.007 (lines: 370)
rg (whitelist)       0.222 +/- 0.021 (lines: 370)+
ucg (whitelist)      0.217 +/- 0.006 (lines: 370)*
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: The biggest change from the previous benchmark is that `pt` got an order of magnitude slower than the next slowest tool.

So why did `pt` get so slow? In particular, both `sift` and `pt` use Go's `regexp` package for searching, so why did one perish while the other only got slightly slower? It turns out that when `pt` sees the `-i` flag indicating case insensitive search, it will force itself to use Go's `regexp` engine with the `i` flag set. So for example, given a CLI invocation of `pt -i foo`, it will translate that to a Go regexp of `(?i)foo`, which will handle the case insensitive search.

On the other hand, `sift` will notice the `-i` flag and take a different route. `sift` will lowercase both the pattern and every block of bytes it searches. This filter over all the bytes searched is likely the cause of `sift`'s performance drop from the previous `linux_literal` benchmark. (It's worth pointing out that this optimization is actually incorrect, because it only accounts for ASCII case insensitivity, and not full Unicode case insensitivity, which `pt` gets by virture of Go's regexp engine.)

But still, is Go's regexp engine really that slow? Unfortunately, yes, it is. While Go's regexp engine takes worst case linear time on all searches (and is therefore exponentially faster than even PCRE2 for some set of regexes and corpora), its actual implementation hasn't quite matured yet. Indeed, every *fast* regex engine based on finite automata that I'm aware of implements some kind of DFA engine. For example, GNU grep, Google's RE2 and Rust's regex library all do this. Go's does not (but there is work in progress to make this happen, so perhaps `pt` will get faster on this benchmark without having to do anything at all!).

There is one other thing worth noting here before moving on. Namely, that `rg`, `ag`, `git grep` and `ucg` didn't noticeably change much from the previous benchmark. Shouldn't a case insensitive search incur some kind of overhead? The answer is complicated and actually requires more knowledge of the underlying regex engines than I have. Thankfully, I can at least answer it for Rust's regex engine.

The key insight is that a case insensitive search for `PM_RESUME` is precisely the same as a case sensitive search of the alternation of all possible case agnostic versions of `PM_RESUME`. So for example, it might start like: `PM_RESUME|pM_RESUME|Pm_RESUME|PM_rESUME|...` and so on. Of course, the full alternation, even for a small literal like this, would be *quite* large. The key is that we can extract a small prefix and enumerate all of *its* combinations quite easily. In this case, Rust's regex engine figures out this alternation (which you can see by passing `--debug` to `rg` and examining `stderr`):

```
PM_RE
PM_Re
PM_rE
PM_re
Pm_RE
Pm_Re
Pm_rE
Pm_re
pM_RE
pM_Re
pM_rE
pM_re
pm_RE
pm_Re
pm_rE
pm_re
```

(Rest assured that Unicode support is baked into this process. For example, a case insensitive search for `S` would yield the following literals: `S`, `s` and `ſ`.)

Now that we have this alternation of literals, what do we do with them? The classical answer is to compile them into a DFA (perhaps Aho-Corasick), and use it as a way to quickly skip through the search text. A match of any of the literals would then cause the regex engine to activate and try to verify the match. This way, we aren't actually running the entire search text through the regex engine, which could be quite a bit slower.

But, Rust's regex engine doesn't actually use Aho-Corasick for this. When SIMD acceleration is enabled (and you can be sure it is for these benchmarks, and for the binaries I distribute), a special multiple pattern search algorithm called

Teddy is used. The algorithm is unpublished, but was invented by Geoffrey Langdale as part of Intel's Hyperscan regex library. The algorithm works roughly by using packed comparisons of 16 bytes at a time to find candidate locations where a literal might match. I adapted the algorithm from the Hyperscan project to Rust, and included an extensive write up in the comments if you're interested.

While Teddy doesn't buy us much over other tools in this particular benchmark, we will see much larger wins in later benchmarks.

`linux_word`

Description: This benchmarks the `PM_RESUME` literal again, but adds the `-w` flag to each tool. The `-w` flag has the following behavior: all matches reported must be considered "words." That is, a "word" is something that starts and ends at a word boundary, where a word boundary is defined as a position in the search text that is adjacent to both a word character and a non-word character.

Pattern: `PM_RESUME` (with the `-w` flag set)

```
rg (ignore)         0.362 +/- 0.080 (lines: 6)
ag (ignore)         1.603 +/- 0.009 (lines: 6)
pt (ignore)         14.417 +/- 0.144 (lines: 6)
sift (ignore)       7.840 +/- 0.123 (lines: 6)
git grep (ignore)   0.341 +/- 0.005 (lines: 6)
rg (whitelist)      0.220 +/- 0.026 (lines: 6)*+
ucg (whitelist)     0.221 +/- 0.007 (lines: 6)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: Not much has changed between this benchmark and the previous `linux_literal` or `linux_literal_casei` benchmarks. The most important thing to note is that most search tools handle the `-w` flag just fine without any noticeable drop in performance. There are two additional things I'd like to note.

`rg` is searching with Unicode aware word boundaries where as the rest of the tools are using ASCII only word boundaries. (`git grep` can be made to use

Unicode word boundaries by adjusting your system's locale settings. In this benchmark, we force it to use ASCII word boundaries.)

`sift` and `pt` are the only tools that gets noticeably slower in this benchmark compared to previous benchmarks. The reason is the same as the reason why `pt` got noticeably slower in the `linux_literal_casei` benchmark: both `pt` and `sift` are now also bottlenecked on Go's regexp library. `pt` and `sift` could do a little better here by staying out of Go's regexp library and searching for the `PM_RESUME` literal, and then only confirming whether the match corresponds to a word boundary after it found a hit for `PM_RESUME`. This still might use Go's regexp library, but in a much more limited form.

`linux_unicode_word`

Description: This benchmarks a simple query for all prefixed forms of the "amp-hour" (Ah) unit of measurement. For example, it should show things like `mAh` (for milliamp-hour) and `µAh` (for microamp-hour). It is particularly interesting because the second form starts with `µ`, which is part of a Unicode aware `\w` character class, but not an ASCII-only `\w` character class. We again continue to control for the overhead of respecting `.gitignore` files.

Pattern: `\wAh`

```
rg (ignore)                   0.355 +/- 0.073 (lines: 186)
rg (ignore) (ASCII)           0.329 +/- 0.060 (lines: 174)
ag (ignore) (ASCII)           1.774 +/- 0.011 (lines: 174)
pt (ignore) (ASCII)           14.180 +/- 0.180 (lines: 174)
sift (ignore) (ASCII)         11.087 +/- 0.108 (lines: 174)
git grep (ignore)             13.045 +/- 0.008 (lines: 186)
git grep (ignore) (ASCII)     2.991 +/- 0.004 (lines: 174)
rg (whitelist)                0.235 +/- 0.031 (lines: 180)
rg (whitelist) (ASCII)        0.225 +/- 0.023 (lines: 168)*+
ucg (ASCII)                   0.229 +/- 0.007 (lines: 168)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: In this benchmark, we've introduced a new variable: whether or not to enable Unicode support in each tool. Searches that are Unicode aware report slightly more matches that are missed by the other ASCII only searches.

Of all the tools here, the only ones that support Unicode toggling are `rg` and `git grep`. `rg`'s Unicode support can be toggled by setting a flag in the pattern itself (e.g., `\w` is Unicode aware while `(?-u)\w` is not), and `git grep`'s Unicode suport can be toggled by setting the `LC_ALL` environment variable (where `en_US.UTF-8` is one way to enable Unicode support and `C` forces it to be ASCII). More generally, `git grep`'s Unicode support is supposed to line up with your system's locale settings—setting `LC_ALL` is a bit of a hack.

It gets a little worse than that actually. Not only are `rg` and `git grep` the only ones to support toggling Unicode, but they are the only ones to support Unicode *at all*. `ag`, `pt`, `sift` and `ucg` will all force you to use the ASCII only `\w` character class. (For `pt` and `sift` in particular, Go's `regexp` library doesn't have the ability to treat `\w` as Unicode aware. For `ag` and `ucg`, which use PCRE, `\w` could be made Unicode aware with a flag sent to PCRE. Neither tool exposes that functionality though.)

The key result to note here is that while `git grep` suffers a major performance hit for enabling Unicode support, `ripgrep` hums along just fine with no noticeable loss in performance, even though both `rg (ignore)` and `git grep (ignore)` report the same set of results.

As in the previous benchmark, both `pt` and `sift` could do better here by searching for the `Ah` literal, and only using Go's regexp library to verify a match.)

Looking at the benchmark results, I can think of two important questions to ask:

1. Why is `git grep (ignore) (ASCII)` so much slower than `rg (ignore) (ASCII)`? And while the two aren't directly comparable, it's also a lot slower than `ucg (ASCII)`.
2. How is `rg (ignore)` (which is Unicode aware) just as fast as `rg (ignore) (ASCII)`?

I actually don't have a great answer for (1). In the case of `rg` at least, it will extract the `Ah` literal suffix from the regex and use that to find candidate matches before running the `\w` prefix. While GNU grep has sophisticated literal extraction as well, it looks like `git grep` doesn't go to similar lengths to extract literals. (I'm arriving at this conclusion after skimming the source of `git grep`, so I could be wrong.)

In the case of `ucg`, it's likely that PCRE2 is doing a similar literal optimization that `rg` is doing.

(2) is fortunately much easier to answer. The trick is not inside of `rg`, but inside its regex library. Namely, the regex engine *builds UTF-8 decoding into its finite state machine*. (This is a trick that is originally attributed to Ken Thompson, but was more carefully described by Russ Cox. To read more about how this is achieved in Rust's regex engine, please see the `utf8-ranges` library.) The reason why this is fast is because there is no extra decoding step required. The regex can be matched directly against UTF-8 encoded byte strings one byte at a time. Invalid UTF-8 doesn't pose any problems: the finite automaton simply won't match it because it doesn't recognize it.

In contrast, `git grep` (and GNU grep) have a completely separate path in their core matching code for handling Unicode aware features like this. To be fair, `git grep` can handle text encodings other than UTF-8, where as `rg` is limited to UTF-8 (or otherwise "ASCII compatible" text encodings) at the moment.

`linux_re_literal_suffix`

Description: This benchmarks a simple regex pattern that ends with a literal. We continue to control for the overhead of respecting `.gitignore` files.

Pattern: `[A-Z]+_RESUME`

```
rg (ignore)          0.318 +/- 0.034 (lines: 1652)
ag (ignore)          1.899 +/- 0.008 (lines: 1652)
pt (ignore)          13.713 +/- 0.241 (lines: 1652)
sift (ignore)        10.172 +/- 0.186 (lines: 1652)
git grep (ignore)    1.108 +/- 0.004 (lines: 1652)
rg (whitelist)       0.221 +/- 0.022 (lines: 1630)*+
ucg (whitelist)      0.301 +/- 0.001 (lines: 1630)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: This benchmark doesn't reveal anything particularly new that we haven't already learned from previous benchmarks. In particular, both `rg` and `ucg` continue to be competitive, `pt` and `sift` are getting bottlenecked by Go's regexp library and `git grep` has a slow down similar to the one observed in `linux_unicode_word`. (My hypothesis for that slow down continues to be that `git grep` is missing the literal optimization.) Finally, `ag` continues to be held back by its use of memory maps.

`rg`, and almost assuredly `ucg` (by virtue of PCRE2), are picking on the `_RESUME` literal suffix and searching for that instead of running the regex over the entire search text. This explains why both tools are able to maintain their speed even as the pattern gets slightly more complex. `rg` does seem to slightly edge out `ucg` here, which might be attributable to differences in how each underlying regex library does literal search.

`linux_alternates`

Description: This benchmarks an alternation of four literals. The literals were specifically chosen to start with four distinct bytes to make it harder to optimize.

Pattern: `ERR_SYS|PME_TURN_OFF|LINK_REQ_RST|CFG_BME_EVT`

```
rg (ignore)          0.351 +/- 0.074 (lines: 68)
ag (ignore)          1.747 +/- 0.005 (lines: 68)
git grep (ignore)    0.501 +/- 0.003 (lines: 68)
rg (whitelist)       0.216 +/- 0.031 (lines: 68)+
ucg (whitelist)      0.214 +/- 0.008 (lines: 68)*
```

- `*` - Best mean time.
- `+` - Best sample time.
- We drop `pt` and `sift` from this benchmark and the next one for expediency. In this benchmark and in a few previous benchmarks, they have been hovering around an order of magnitude slower than the next slowest tool. Neither get any better as the complexity of our patterns increase.

Analysis: Yet again, both `rg` and `ucg` maintain high speed even as the pattern grows beyond a simple literal. In this case, there isn't any *one* particular literal that we can search to find match candidates quickly, but a good regular expression engine can still find ways to speed this up.

For `rg` in particular, it sees the four literals and diverts to the Teddy multiple pattern SIMD algorithm (as described in the `linux_literal_casei` benchmark). In fact, for this particular pattern, Rust's core regex engine is never used at all. Namely, it notices that a literal match of any of the alternates corresponds to an overall match of the pattern, so it can completely skip the verification step. This makes searching alternates of literals *very* fast.

`linux_alternates_casei`

Description: This benchmark is precisely the same as the `linux_alternates` benchmark, except we make the search case insensitive by adding the `-i` flag. Note that `git grep` is run under ASCII mode, in order to give it every chance to be fast.

Pattern: `ERR_SYS|PME_TURN_OFF|LINK_REQ_RST|CFG_BME_EVT` (with the `-i` flag set)

```
rg (ignore)          0.391 +/- 0.078 (lines: 160)
ag (ignore)          1.968 +/- 0.009 (lines: 160)
git grep (ignore)    2.018 +/- 0.006 (lines: 160)
rg (whitelist)       0.222 +/- 0.001 (lines: 160)*+
ucg (whitelist)      0.522 +/- 0.002 (lines: 160)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: The case insensitive flag causes quite a bit of separation, relative to the previous `linux_alterates` benchmark. For one, `git grep` gets over 4 times slower. Even `ucg` gets twice as slow. Yet, `rg` continues to maintain its speed!

The secret continues to be the Teddy algorithm, just as in the `linux_alternates` benchmark. The trick lies in how we transform an alternation of *case insensitive* literals into a larger alternation that the Teddy algorithm can actually use. In fact, it works exactly how it was described in the `linux_literal_casei` benchmark: we enumerate all possible alternations of each literal that are required for case insensitive match. Since that can be quite a large number, we limit ourselves to a small number of prefixes from that set that we can enumerate. In this case, we use the following prefixes (which can be seen by running `rg` with the `--debug` flag):

```
CFG_
CFg_
CfG_
Cfg_
ERR_
ERr_
ErR_
Err_
LIN
LIn
LiN
Lin
PME_
PMe_
PmE_
Pme_
cFG_
cFg_
cfG_
cfg_
eRR_
eRr_
erR_
err_
lIN
lIn
liN
lin
pME_
pMe_
pmE_
pme_
```

We feed these literals to the Teddy algorithm, which will quickly identify *candidate* matches in the search text. When a candidate match is found, we need to verify it since a match of a prefix doesn’t necessarily mean the entire pattern matches. It is only at that point that we actually invoke the full regex engine.

`linux_unicode_greek`

Description: This benchmarks usage of a particular Unicode feature that permits one to match a certain class of codepoints defined in Unicode. Both Rust's regex engine and Go's regex engine support this natively, but none of the other tools do.

Pattern: `\p{Greek}` (matches any Greek symbol)

```
rg     0.414 +/- 0.021 (lines: 23)*+
pt     12.745 +/- 0.166 (lines: 23)
sift   7.767 +/- 0.264 (lines: 23)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: This one is pretty simple. `rg` compiles `\p{Greek}` into a deterministic finite state machine while Go (used in `pt` and `sift`) will also use a finite state machine, but it is a *nondeterministic* simulation. The core difference between the two approaches is that the former is only ever in one state at any point in time, while the latter must constantly keep track of all the different states it is in.

`linux_unicode_greek_casei`

Description: This benchmark is just like the `linux_unicode_greek` benchmark, except it makes the search case insensitive. This particular query is a bit idiosyncratic, but it does demonstrate just how well supported Unicode is in `rg`.

Pattern: `\p{Greek}` (with the `-i` flag set, matches any Greek symbol)

```
rg     0.425 +/- 0.027 (lines: 103)
pt     12.612 +/- 0.217 (lines: 23)
sift   0.002 +/- 0.000 (lines: 0)*+
```

- `*` - Best mean time.

- `+` - Best sample time.

Analysis: `sift` doesn't actually beat `rg` here: it just gets so confused by the search request that it gives up and reports no matches. `pt` seems to execute the search, but doesn't handle Unicode case insensitivity correctly. Meanwhile, `rg` handles the request just fine, *and it's still fast*.

In this particular case, the entire `Greek` category, along with all of its case-insensitive variants, are compiled into a single fast deterministic finite state machine.

One interesting thing to note about this search is that if you run it, you'll see a lot more results containing the character `µ`, which looks essentially identical to the character `μ` that also shows up in a case sensitive search. As you might have guessed, even though these two characters look the same, they are in fact distinct Unicode codepoints:

- `µ` is `MICRO SIGN` with codepoint `U+000000B5`.
- `μ` is `GREEK SMALL LETTER MU` with codepoint `U+000003BC`.

The latter codepoint is considered part of the `\p{Greek}` group while the former codepoint is not (the former codepoint appears to be the correct sigil to use in the case of the Linux kernel). However, the Unicode simple case folding tables map `MICRO SIGN` to `GREEK SMALL LETTER MU`, which causes `rg` to pick up on lines containing `MICRO SIGN` even though it strictly isn't part of the `Greek` group.

`linux_no_literal`

Description: This is the last benchmark on the Linux kernel source code and is a bit idiosyncratic like `linux_unicode_greek_casei`. In particular, it looks for lines containing 5 consecutive repetitions of 5 word characters, each separated by one or more space characters. The key distinction of this pattern from every other pattern in this benchmark is that it does not contain any literals. Given the presence of `\w` and `\s`, which have valid Unicode and ASCII interpretations, we attempt to control for the presence of Unicode support.

Pattern: `\w{5}\s+\w{5}\s+\w{5}\s+\w{5}\s+\w{5}`

```
rg (ignore)                 0.577 +/- 0.003 (lines: 490)
rg (ignore) (ASCII)         0.416 +/- 0.025 (lines: 490)
```

```
ag (ignore) (ASCII)        2.339 +/- 0.010 (lines: 766)
pt (ignore) (ASCII)        22.066 +/- 0.057 (lines: 490)
sift (ignore) (ASCII)      25.563 +/- 0.108 (lines: 490)
git grep (ignore)          26.382 +/- 0.044 (lines: 490)
git grep (ignore) (ASCII)  4.153 +/- 0.010 (lines: 490)
rg (whitelist)             0.503 +/- 0.011 (lines: 419)
rg (whitelist) (ASCII)     0.343 +/- 0.038 (lines: 419)*+
ucg (whitelist) (ASCII)    1.130 +/- 0.003 (lines: 416)
```

- `*` - Best mean time.
- `+` - Best sample time.
- `ag` reports many more matches than other tools because it does multiline search where the `\s` can match a `\n`.

Analysis: Since this particular pattern doesn't have any literals in it, it's entirely up to the underlying regex engine to answer this query. It can't be smart and skip through the input—it has to pass it completely through the regex engine. Since non-literal patterns are pretty rare in my experience, this benchmark exists primarily as an engineered way to test how well the underlying regex engines perform.

`rg`, regardless of whether it respects `.gitignore` files or whether it handles Unicode correctly, does quite well here compared to other tools. `git grep` in particular pays a 5x penalty for Unicode support. `rg` on the other hand pays about a 0.3x penalty for Unicode support. Interestingly, even though `ucg` doesn't enable Unicode support, not even PCRE2's JIT can compete with `rg`!

What makes `rg` so fast here? And what actually causes the 0.3x penalty?

`rg` continues to be fast on this benchmark primarily for the same reason why it's fast with other Unicode-centric benchmarks: it compiles the UTF-8 decoding right into its deterministic finite state machine. This means there is no extra step to decode the search text into Unicode codepoints first. We can match directly on the raw bytes.

To a first approximation, the performance penalty comes from compiling the DFA to match the pattern. In particular, the DFA to match the Unicode variant is much much larger than the DFA to match the ASCII variant. To give you a rough idea of the size difference:

- The ASCII DFA has about **250** distinct NFA states.

- The Unicode DFA has about **77,000** distinct NFA states.

(These numbers are produced directly from the compiler in Rust's regex library, and don't necessarily reflect a minimal automaton.)

A DFA produced from these patterns doesn't necessarily have the same number of states, since each DFA state typically corresponds to multiple NFA states. (Check out the Powerset construction Wikipedia article. Although it doesn't correspond to the same implementation strategy used in Rust's regex engine, it should give good intuition.)

However, the first approximation is a bit misleading. While Rust's regex engine does have a preprocessing compilation phase, it does not actually include converting an NFA into a DFA. Indeed, that would be far too slow and could take exponential time! Instead, Rust's regex engine builds the DFA *on the fly* or "lazily," as it searches the text. In the case of the ASCII pattern, this search barely spends any time constructing the DFA states since there are so few of them. However, in the Unicode case, since there are so many NFA states, it winds up spending a lot of time compiling new DFA states. (I've confirmed this by inspecting a profile generated by `perf`.) Digging a bit deeper, the actual story here might be subtler. For example, the Unicode pattern might wind up with the same number of DFA states as the ASCII pattern, primarily because the input its searching is the same and is primarily ASCII. The slow down then must come from the fact that each individual DFA state takes longer to build. This is likely correct since a single Unicode `\w` is over two orders of magnitude larger than a single ASCII `\w`. Therefore, each DFA state probably has a lot more NFA states in it for the Unicode pattern as opposed to the ASCII pattern. It's not clear whether we can do any better here (other than trying to minimize the Unicode `\w`, which would be totally feasible), since we don't actually know the composition of the search text ahead of time.

One idea for improvement is to have multiple types of DFAs. For example, you might imagine trying to match with an ASCII only DFA. If the DFA sees a non-ASCII byte, then it could cause a transition into a Unicode-aware DFA. However, the penalty here is so small that it's hard to justify this kind of implementation complexity!

Single file benchmarks

In the second half of our benchmarks, we will shift gears and look more closely at the performance of search tools on a single large file. Each benchmark will be run on two samples of the OpenSubtitles2016 dataset. One sample will be English and therefore predominantly ASCII, and another sample will be in Russian and therefore predominantly Cyrillic. The patterns for the Russian sample were translated from English using Google Translate. (Sadly, I can't read Russian, but I have tried each search by hand and confirmed that a sample of the results I was looking at were relevant by piping them back through Google Translate.) The English sample is around 1GB and the Russian sample is around 1.6GB, so the benchmark timings aren't directly comparable.

In this benchmark, the performance of the underlying regex engine and various literal optimizations matter a lot more. The two key variables we'll need to control for are line counting and Unicode support. Normally, we'd just not request line counting from any of the tools, but neither of The Silver Searcher or Universal Code Grep support disabling line numbers. Additionally, Unicode support is tricky to control for in some examples because `ripgrep` does not support ASCII only case insensitive semantics when searching with a non-ASCII string. It's Unicode all the way and there's no way to turn it off. As we'll see, at least for `ripgrep`, it's still faster than its ASCII alternatives even when providing case insensitive Unicode support.

As with the Linux benchmark, you can see precisely which command was run and its recorded time in the raw data.

`ripgrep` utterly dominates this round, both in performance *and* correctness.

`subtitles_literal`

Description: This benchmarks the simplest case for any search tool: find all occurrences of a literal string. Tools annotated with `(lines)` were passed the `-n` flag (or equivalent) so that the output reports line numbers.

English pattern: `Sherlock Holmes`

```
rg             0.268 +/- 0.000 (lines: 629)*+
rg (no mmap)   0.336 +/- 0.001 (lines: 629)
pt             3.433 +/- 0.002 (lines: 629)
sift           0.326 +/- 0.002 (lines: 629)
grep           0.516 +/- 0.001 (lines: 629)
```

```
rg (lines)     0.595 +/- 0.001 (lines: 629)
ag (lines)     2.730 +/- 0.003 (lines: 629)
ucg (lines)    0.745 +/- 0.001 (lines: 629)
pt (lines)     3.434 +/- 0.005 (lines: 629)
sift (lines)   0.756 +/- 0.002 (lines: 629)
grep (lines)   0.969 +/- 0.001 (lines: 629)
```

Russian pattern: `Шерлок Холмс`

```
rg             0.325 +/- 0.001 (lines: 583)*+
rg (no mmap)   0.452 +/- 0.002 (lines: 583)
pt             12.917 +/- 0.009 (lines: 583)
sift           16.418 +/- 0.008 (lines: 583)
grep           0.780 +/- 0.001 (lines: 583)
rg (lines)     0.926 +/- 0.001 (lines: 583)
ag (lines)     4.481 +/- 0.003 (lines: 583)
ucg (lines)    1.889 +/- 0.004 (lines: 583)
pt (lines)     12.935 +/- 0.011 (lines: 583)
sift (lines)   17.177 +/- 0.010 (lines: 583)
grep (lines)   1.300 +/- 0.003 (lines: 583)
```

- `*` - Best mean time.
- `+` - Best sample time.
- This is the only benchmark that contains `pt` and `sift`, since they become too slow in all future benchmarks.

Analysis: Whether it's part of the underlying regex engine or part of the search tool itself, every search tool in this benchmark does some kind of literal optimization. `ag` will inspect the pattern, and if it doesn't contain any special regex characters, then it will use a Boyer-Moore variant to perform the search instead of PCRE. GNU grep does something similar, although it has clearly been the subject of much optimization.

If that's true, how does `rg` beat GNU grep by almost a factor of 2? Well, first and foremost, we note that both `sift` and `ucg` beat GNU grep as well. I won't be able to go into detail on `ucg`'s speed since PCRE2's JIT isn't something I understand very well, but I can at least tell you that the reasons why `rg` and `sift` are faster than GNU grep are actually distinct:

- `sift` uses Go's regexp library, which will do at least one small literal optimization: if every match of a regex starts with the same byte, the regex engine will scan for that byte before starting a match. If you follow the code that does the scan for the byte all the way back to its source for `x86_64` systems, then you'll find that it is using AVX2 instructions and `ymm` registers, which permit scanning 32 bytes in each iteration. In contrast, GNU grep uses `libc`'s `memchr`, which doesn't use AVX2. However, that C code will be autovectorized to use `xmm` registers and SIMD instructions, which are half the size of `ymm` registers. In other words, by virture of being written in Go, `sift` is making more efficient use of the CPU.
- `rg` also uses `memchr` from `libc`. The `rg` binary that was used in this benchmark was statically linked with `musl`, which provides its own implementation of `memchr`. Despite it being quite a bit terser than GNU's libc implementation used in GNU grep, it appears to be doing roughly the same work. If that's the case, how is `rg` faster? The answer lies not in `memchr` nor in the variant of Boyer-Moore nor in the number characters Boyer-Moore can skip. The answer instead lies in *which byte is given to `memchr`*. `rg` will actually try to guess the "rarest" byte in a literal, and use `memchr` on that. (A standard Boyer-Moore implementation will use `memchr` always on the last byte.) In this particular case, running `memchr` on either `S` or `H` is probably quite a bit better than running it on `s` because `S` and `H` are far less common than `s`. That is, `rg` tries harder than GNU grep to spend more time skipping bytes in a fast SIMD optimized loop. `rg` can get this wrong, but it seems strictly better to at least guess and probably get it right in the common case than to submit to an artifact of common Boyer-Moore implementations.

Now that the secrets of literal search have been revealed, we can better analyze the Russian benchmark. The answer once again lies in *which byte is used* for quick scanning. Both `sift` and `pt` use the same AVX2 routine in Go's runtime, so why did they get so much slower than every other tool in the Russian benchmark? The answer becomes more clear when we look at the actual UTF-8 bytes of the pattern `Шерлок Холмс`:

```
\xd0\xa8\xd0\xb5\xd1\x80\xd0\xbb\xd0\xbe\xd0\xba \xd0\xa5\xd0\xbe\xd0\xbb\
```

There are two key observations to take away from this:

1. Every character in the pattern `Шерлок Холмс` is encoded with two UTF-8 code units, which corresponds to two bytes.
2. Every character starts with either the byte `\xD0` or `\xD1`.

If we looked at the UTF-8 bytes of the Russian subtitles we're searching, we'd end up seeing exactly the same pattern. This pattern occurs because the contents of the file are mostly Cyrllic, which are all mostly part of a couple small ranges in Unicode. This means that the `\xD0` and `\xD1` bytes occur *a lot*.

If you recall from above, Go's regex engine will scan for occurrences of the first byte. But if that first byte happens as frequently as it does here, the overall search will wind up going slower because there is overhead associated with doing that scan. This is *precisely* the trade off one is exposed to whenever `memchr` is used.

As you might have guessed, `rg` works around this issue by trying to guess the rarest byte. `rg` specifically draws from a pre-computed frequency table of all 256 bytes. Bytes like `\xD0` and `\xD1` are considered to be among the most frequent while bytes like `\xA8` and `\x81` are considered more rare. Therefore, `rg` will prefer bytes other than `\xD0` and `\xD1` for use with `memchr`.

GNU grep continues to do well on this benchmark mostly because of blind luck: Boyer-Moore uses the last byte, which will correspond to `\x81`, which is much rarer than `\xD0` or `\xD1`.

Switching gears, we should briefly discuss memory maps. In this benchmark, `rg` beats out `rg (no mmap)` by about 25%. The only difference between the two is that the former memory maps the file into memory while the latter incrementally reads bytes from the file into an intermediate buffer, and searches it. In this case, the overhead of the memory map is very small because we only need to create one of them. This is the *opposite* result from our Linux benchmark above, where memory maps proved to be worse than searching with an intermediate buffer since we needed to create a new memory map for every file we searched, which ends up incurring quite a bit of overhead. `rg` takes an empirical approach here and enables memory map searching when it knows it only needs to search a few files, and otherwise searches using an intermediate buffer.

One last note: I've neglected to talk about `(lines)` because there's really not much to say here: counting lines takes work, and if you don't need to report line numbers, you can avoid doing that work. `ucg` has a rather cool SIMD algorithm to count lines and `rg` also has a packed counting algorithm that works similarly to the `memchr` implementations we talked about.

If it were up to me, I'd probably remove benchmarks with line numbers altogether, since most tools tend to reliably pay just a little bit extra for them. However, neither `ag` nor `ucg` allow turning them off, so we need to turn them on in other tools in order to make a fair comparison.

`subtitles_literal_casei`

Description: This benchmark is just like `subtitles_literal`, except it does case insensitive search. Tools annotated with `(lines)` show line numbers in their output, and tools annotated with `(ASCII)` are doing an ASCII-only search. Correspondingly, tools *not* labeled with `(ASCII)` are doing a proper Unicode search.

English pattern: `Sherlock Holmes` (with the `-i` flag set)

```
rg                      0.366 +/- 0.001 (lines: 642)*+
grep                    4.084 +/- 0.005 (lines: 642)
grep (ASCII)            0.614 +/- 0.001 (lines: 642)
rg (lines)              0.696 +/- 0.002 (lines: 642)
ag (lines) (ASCII)      2.775 +/- 0.004 (lines: 642)
ucg (lines) (ASCII)     0.841 +/- 0.002 (lines: 642)
```

Russian pattern: `Шерлок Холмс`

```
rg                      1.131 +/- 0.001 (lines: 604)
grep                    8.187 +/- 0.006 (lines: 604)
grep (ASCII)            0.785 +/- 0.001 (lines: 583)
rg (lines)              1.733 +/- 0.002 (lines: 604)
ag (lines) (ASCII)      0.729 +/- 0.001 (lines: 0)*+
ucg (lines) (ASCII)     1.896 +/- 0.005 (lines: 583)
```

- `*` - Best mean time.
- `+` - Best sample time.
- There is no `rg (ASCII)` because `rg` can't do ASCII-only case insensitive search.

Analysis: This is a fun benchmark, because we start to see just how awesome `rg`'s support for Unicode is. Namely, that it not only gets it correct, but it's also *fast*. It’s fast enough that it beats the competition even when the competition is using ASCII-only rules.

Right off the bat, GNU grep pays dearly for doing a case insensitive search with Unicode support. The problem it faces is that it can no longer do a straight-forward Boyer-Moore search, so it either needs to fall back to some alternative literal search or its full regex engine. Even though GNU grep is much faster at ASCII-only case sensitive search than its Unicode aware variant, `rg`’s Unicode case insensitive search still handedly beats GNU grep’s ASCII-only case insensitive search.

The reason why `rg` is so fast on this benchmark is the same reason why it’s fast in the `linux_literal_casei` benchmark: it turns the pattern `Sherlock Holmes` into an alternation of all possible literals according to Unicode’s simple case folding rules. It then takes a small prefix from each alternate so that our set of literals looks like this:

```
SHER
SHEr
SHeR
SHer
ShER
ShEr
SheR
Sher
sHER
sHEr
sHeR
sHer
shER
shEr
sheR
sher
ſHER
ſHEr
ſHeR
ſHer
ſhER
ſhEr
```

```
ſheR
ſher
```

(Notice that we get Unicode right by including `ſ` as a case variant of `S`.)

It then feeds these literals to the Teddy SIMD multiple pattern algorithm. The algorithm is unpublished, but was invented by Geoffrey Langdale as part of Intel's Hyperscan regex library. The algorithm works roughly by using packed comparisons of 16 bytes at a time to find candidate locations where a literal might match. I adapted the algorithm from the Hyperscan project to Rust, and included an extensive write up in the comments if you're interested.

While essentially the same analysis applies to the Russian benchmark, there are a few interesting things to note. Namely, while the results show `grep (ASCII)` as being very fast, it seems clear that it's completely ignoring the `-i` flag in this case since the pattern is not an ASCII string. Notably, its timing is essentially identical to its timing on the previous `subtitles_literal` benchmark. The other interesting thing to note is that `ag` reports `0` matches. This isn't entirely unreasonable, if it somehow knows that it can't satisfy the request (case insensitive search of a non-ASCII string when Unicode support isn't enabled). If I had to guess, I'd say PCRE is returning an error (possibly from `pcre_exec`) and it isn't being forwarded to the end user, but that's just a shot in the dark.

`subtitles_alternate`

Description: This benchmarks an alternation of literals, where there are several distinct leading bytes from each literal. We control for line counting.

English pattern: `Sherlock Holmes|John Watson|Irene Adler|Inspector Lestrade|Professor Moriarty`

```
rg              0.294 +/- 0.001 (lines: 848)*+
grep            2.955 +/- 0.003 (lines: 848)
rg (lines)      0.619 +/- 0.001 (lines: 848)
ag (lines)      3.757 +/- 0.001 (lines: 848)
ucg (lines)     1.479 +/- 0.002 (lines: 848)
grep (lines)    3.412 +/- 0.004 (lines: 848)
```

Russian pattern: `Шерлок Холмс|Джон Уотсон|Ирен Адлер|инспектор Лестрейд|профессор Мориарти`

```
rg              1.300 +/- 0.002 (lines: 691)*+
grep            7.994 +/- 0.017 (lines: 691)
rg (lines)      1.902 +/- 0.002 (lines: 691)
ag (lines)      5.892 +/- 0.003 (lines: 691)
ucg (lines)     2.864 +/- 0.006 (lines: 691)
grep (lines)    8.511 +/- 0.005 (lines: 691)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: `rg` does really well here, on both the English and Russian patterns, primarily thanks to Teddy as described in the analysis for `subtitles_literal_casei`. On the English pattern, `rg` is around an *order of magnitude* faster than GNU grep.

The performance cost of counting lines is on full display here. For `rg` at least, it makes returning search results take twice as long.

Note that the benchmark description mentions picking literals with distinct leading bytes. This is to avoid measuring an optimization where the regex engine detects the leading byte and runs `memchr` on it. Of course, this optimization is important (and `rg` will of course do it), but it's far more interesting to benchmark what happens in a slightly trickier case.

`subtitles_alternate_casei`

Description: This benchmark is just like `subtitles_alternate`, except it searches case insensitively. In this benchmark, instead of controlling for line counting (all commands count lines), we control for Unicode support.

English pattern: `Sherlock Holmes|John Watson|Irene Adler|Inspector Lestrade|Professor Moriarty` (with the `-i` flag set)

```
rg              2.724 +/- 0.002 (lines: 862)*+
grep            5.125 +/- 0.006 (lines: 862)
ag (ASCII)      5.170 +/- 0.004 (lines: 862)
```

```
ucg (ASCII)    3.453 +/- 0.005 (lines: 862)
grep (ASCII)   4.537 +/- 0.025 (lines: 862)
```

Russian pattern: `Шерлок Холмс|Джон Уотсон|Ирен Адлер|инспектор Лестрейд|профессор Мориарти`

```
rg             4.834 +/- 0.004 (lines: 735)
grep           8.729 +/- 0.004 (lines: 735)
ag (ASCII)     5.891 +/- 0.001 (lines: 691)
ucg (ASCII)    2.868 +/- 0.005 (lines: 691)*+
grep (ASCII)   8.572 +/- 0.009 (lines: 691)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: While `rg` gets an *order of magnitude* slower on this benchmark compared to `subtitles_alternate`, it still comfortably beats out the rest of the search tools, even when other tools don't support Unicode. A key thing this benchmark demonstrates are the limits of the Teddy algorithm. In fact, `rg` opts to not use Teddy in this benchmark because it predicts it won't perform well.

Why doesn't Teddy perform well here? Well, the answer is in how we generate literals for this pattern. Namely, `rg` will try to generate all possible literals that satisfy Unicode simple case folding rules, and then will take a short prefix of that set to cut the number of literals down to reasonable size. In this particular case, we wind up with 48 literals:

```
INS
INs
INſ
IRE
IRe
InS
Ins
Inſ
IrE
Ire
JOH
JOh
```

```
JoH
Joh
PRO
PRo
PrO
Pro
SHE
SHe
ShE
She
iNS
iNs
iNſ
iRE
iRe
inS
ins
inſ
irE
ire
jOH
jOh
joH
joh
pRO
pRo
prO
pro
sHE
sHe
shE
she
ſHE
ſHe
ſhE
ſhe
```

If we passed all of those to Teddy, it would become overwhelmed. In particular, Teddy works by finding candidates for matches very quickly. When there are roughly the same number of candidates as there are matches, Teddy performs exceedingly well. But, if we give it more literals, then it's more likely to find candidates that don't match, and will therefore have to spend a lot more time verifying the match, which can be costly.

(A more subtle aspect of the Teddy implementation is that a larger number of literals increases the cost of every verification, even if the number of candidates produced doesn't increase. As I've mentioned before, if you want the full scoop on Teddy, see its well commented implementation. Going into more detail on Teddy would require a whole blog post on its own!)

When `rg` sees that there are a large number of literals, it could do one of two things:

1. Try to cut down the set even more. For example, in this case, we could strip the last character from each prefix off and end up with a much smaller set. Unfortunately, even though we have fewer literals, we wind up with a still not-so-small set of two-character literals, which will also tend to produce a lot more false positive candidates just because of their length.
2. Move to a different multiple pattern algorithm, such as Aho-Corasick.

I have tried to implement (1) in the past, but I've always wound up in a game of whack-a-mole. I might make one common case faster, but another common case a lot slower. In those types of cases, it's usually better to try and achieve good average case performance. Luckily for us, Aho-Corasick does *exactly* that.

We do still have a few tricks up our sleeve though. For example, many Aho-Corasick implementations are built as-if they were tries with back-pointers for their failure transitions. We can actually do better than that. We can compile all of its failure transitions into a DFA with a transition table contiguous in memory. This means that every byte of input corresponds to a single lookup in the transition table to find the next state. We never have to waste time chasing pointers or walking more than one failure transition for any byte in the search text.

Of course, this transition table based approach is memory intensive, since you need space for `number_of_literals * number_of_states`, where `number_of_states` is roughly capped at the total number of bytes in all of the literals. While 48 literals of length 3 is too much for Teddy to handle, it's barely a blip when it comes to Aho-Corasick, even with its memory expensive transition table based approach. (N.B. In the literature, this particular implementation of Aho-Corasick is often called “Advanced” Aho-Corasick.)

`subtitles_surrounding_words`

Description: This benchmarks a pattern that searches for words surrounding the literal string `Holmes`. This pattern was specifically constructed to defeat both prefix and suffix literal optimizations.

English pattern: `\w+\s+Holmes\s+\w+`

```
rg              0.605 +/- 0.000 (lines: 317)
grep            1.286 +/- 0.002 (lines: 317)
rg (ASCII)      0.602 +/- 0.000 (lines: 317)*+
ag (ASCII)      11.663 +/- 0.008 (lines: 323)
ucg (ASCII)     4.690 +/- 0.002 (lines: 317)
grep (ASCII)    1.276 +/- 0.002 (lines: 317)
```

Russian pattern: `\w+\s+Холмс\s+\w+`

```
rg              0.957 +/- 0.001 (lines: 278)*+
grep            1.660 +/- 0.002 (lines: 278)
ag (ASCII)      2.411 +/- 0.001 (lines: 0)
ucg (ASCII)     2.980 +/- 0.002 (lines: 0)
grep (ASCII)    1.596 +/- 0.003 (lines: 0)
```

- `*` - Best mean time.
- `+` - Best sample time.

Analysis: In order to compete on this benchmark, a search tool will need to implement a so-called “inner literal” optimization. You can probably guess what that means: it is an optimization that looks for literal strings that appear *anywhere* in the pattern, and if a literal is found that must appear in every match, then a search tool can quickly scan for that literal instead of applying the full regex to the search text.

The key thing that permits this optimization to work is the fact that most search tools report results *per line*. For example, in this case, if a line contains the literal `Holmes`, then the search tool can find the beginning and ending of that line and run the full pattern on *just that line*. If the literal is relatively rare, this keeps us out of the regex engine for most of the search. And of course, if the literal doesn't appear at all in the corpus, then we will have never touched the regex engine at all.

To achieve the full optimization, you probably need to parse your pattern into its abstract syntax (abbreviated "AST" for abstract syntax tree) to extract the literal. It is worth pointing out however that one can probably get a lot of mileage with simpler heuristics, but a real pattern parser is the only way to do this optimization robustly. The problem here is that for most regex engines, parsing the pattern is an unexposed implementation detail, so it can be hard for search tools to extract literals in a robust way without writing their own parser, and a modern regex parser is no easy task! Thankfully, Rust's regex library exposes an additional library, `regex-syntax`, which provides a full parser. `rg` implements this optimization relatively easily with the help of `regex-syntax`, while GNU grep implements this optimization because the search tool and the underlying regex engine are coupled together.

Why does the search tool need to perform this optimization? Why can't the underlying regex engine do it? I personally have thought long and hard about this particular problem and haven't been able to come up with an elegant solution. The core problem is that once you find an occurrence of the literal, you *don't know where to start searching the full regex*. In a general purpose regex engine, a pattern could match an arbitrarily long string. For example, `\w+\s+Holmes\s+\w+` mightly only match at the very end of a gigabyte sized document. There are ways to work around this. For example, you could split the regex into three pieces: `\w+\s+`, `Holmes` and `\s+\w+`. On every occurrence of the `Holmes` literal, you could search for the beginning of the match by executing `\w+\s+` in reverse starting just before the literal, and executing `\s+\w+` forwards starting just after the literal. The key problem with this approach is that it exposes you to quadratic behavior in the worst case (since `\w+\s+` or `\s+\w+` could cause you to re-scan text you've already seen). While I believe there is a general purpose way to solve this and still guarantee linear time searching, a good solution hasn't revealed itself yet.

Based on the data in this benchmark, only `rg` and GNU grep perform this optimization. Neither `ag` nor `ucg` attempt to extract any inner literals from the pattern, and it looks like PCRE doesn't try to do anything too clever. (Of course, Rust's regex library doesn't either, this optimization is done in `rg` proper.)

As for the Russian pattern, we see that only tools with proper Unicode support can execute the query successfully. The reason is because `\w` is ASCII only in `ucg` and `ag`, so it can't match the vast majority of word characters (which are Cyrllic) in our sample. Otherwise, both `rg` and GNU grep remain fast, primarily because of the inner literal optimization.

`subtitles_no_literal`

Description: This benchmark purposefully has no literals in it, which makes it a bit idiosyncratic, since most searches done by end users probably have at least some literal in them. However, it is a useful benchmark to gauge the general performance of the underlying regex engine.

English pattern: `\w{5}\s+\w{5}\s+\w{5}\s+\w{5}\s+\w{5}\s+\w{5}\s+\w{5}`

```
rg              2.777 +/- 0.003 (lines: 13)
rg (ASCII)      2.541 +/- 0.005 (lines: 13)*+
ag (ASCII)      10.076 +/- 0.005 (lines: 48)
ucg (ASCII)     7.771 +/- 0.004 (lines: 13)
grep (ASCII)    4.411 +/- 0.004 (lines: 13)
```

Russian pattern: `\w{5}\s+\w{5}\s+\w{5}\s+\w{5}\s+\w{5}\s+\w{5}\s+\w{5}`

```
rg              4.905 +/- 0.003 (lines: 41)
rg (ASCII)      3.973 +/- 0.002 (lines: 0)
ag (ASCII)      2.395 +/- 0.004 (lines: 0)*+
ucg (ASCII)     3.006 +/- 0.005 (lines: 0)
grep (ASCII)    2.483 +/- 0.005 (lines: 0)
```

- `*` - Best mean time.
- `+` - Best sample time.
- `ag` gets more matches on the English pattern since it does multiline search. Namely, the `\s` can match a `\n`.
- `grep` with Unicode support was dropped from this benchmark because it takes over 90 seconds on the English pattern and over 4 **minutes** on the Russian pattern. In both cases, GNU grep and `rg` report the same results.

Analysis: Once again, no other search tool performs as well as `rg`. For the English pattern, both `rg` and `rg (ASCII)` have very similar performance, despite `rg` supporting Unicode.

What specifically makes `rg` faster than GNU grep in this case? Both search tools ultimately use a DFA to execute this pattern, so their performance should be roughly the same. I don't actually have a particularly good answer for this. Both GNU grep and Rust's regex library unroll the DFA's inner loop, and both implementations compute states on the fly. I can make a guess though.

Rust's regex library avoids a single pointer dereference when following a transition. How it achieves this is complicated, but it's done by representing states as indices into the transition table rather than simple incremental ids. This permits the generated code to use simple addition to address the location of the next transition, which can be done with addressing modes in a single instruction. (Specifically, this optimization means we don't need to do any multiplication to find the state transition.) A single pointer dereference might not seem like much, but when it's done for every state transition over a large corpus such as this, it can have an impact.

When it comes to the Russian pattern, such details are far less important because GNU grep takes *minutes* to run. This suggests that it isn't building UTF-8 decoding into its DFA, and is instead doing something like decoding a character at a time, which can have a lot of overhead associated with it. I admit that I don't quite grok this aspect of GNU grep though, so I could have its cost model wrong. Now, in all fairness, GNU grep's locale and encoding support far exceeds what `rg` supports. However, in today's world, UTF-8 is quite prevalent, so supporting that alone is often enough. More to the point, given how common UTF-8 is, it's important to remain fast while supporting Unicode, which GNU grep isn't able to do.

Unfortunately, the other tools don't support Unicode, so they can't be meaningfully benchmarked on the Russian pattern.

Bonus benchmarks

In this section, we'll take a look at a few crazier benchmarks that aren't actually part of the suite I've published. Indeed, the performance differences between tools are often so large that a fastidious analysis isn't really necessary. More to the point, these usage patterns aren't necessarily representative of common usage (not that these usages aren't important, they're just niche), so the performance differences are less important. Nevertheless, it is fun to see how well `rg` and the other tools hold up under these requests.

`everything`

Description: In this benchmark, we compare how long it takes for each tool to report every line as a match. This benchmark was run in the root of the Linux repository.

Pattern: `.*`

```
rg                    1.081 (lines: 22065361)
ag                    1.660 (lines: 55939)
git grep              3.448 (lines: 22066395)
sift                110.018 (lines: 22190112)
pt                    0.245 (lines: 3027)
rg (whitelist)        0.987 (lines: 20936584)
ucg (whitelist)       5.558 (lines: 23163359)
```

Analysis: This benchmark is somewhat silly since it's something you probably never want a search tool to do. Nevertheless, it is useful to know that `rg` scales quite well to a huge number of matches.

One of the key tricks that a good regex engine will do in this case is stop searching text as soon as it knows it has a match if all the caller cares about is "is there a match or not?" In this case, we will find a match at the beginning of every line, immediately quit, find the line boundaries and then repeat the process. There is no particular special cased optimization for `.*` in either `rg` or Rust's regex library (although there could be).

Interestingly, neither `ag` nor `pt` actually report every line. They appear to have some kind of match limit. Which isn't altogether unreasonable. This is a search tool after all, and some might consider that returning every result isn't useful.

`nothing`

Description: This is just like the `everything` benchmark, except it inverts the results. The correct result is for a search tool to report no lines as matching.

This benchmark also searches the Linux kernel source code, from the root of repository.

Pattern: `.*` (with the `-v` or `--invert-match` flag set)

```
rg                  0.302 (lines: 0)
ag                  takes minutes
git grep            0.905 (lines: 0)
sift               12.804 (lines: 0)
pt                  -----
rg (whitelist)      0.251 (lines: 0)
ucg (whitelist)     -----
```

Analysis: While this benchmark is even more ridiculous than the previous one ("give me nothing of everything"), it does expose a few warts and omissions in other tools. Namely, `ag` seems to slow way down when reporting inverted matches. Neither `pt` nor `ucg` support inverted searching at all. `sift` redeems itself from the previous benchmark (perhaps it has a lot of overhead associated with printing matches that it doesn't hit here). Neither `rg` nor `git grep` have any problems satisfying the request.

`context`

Description: This benchmarks how well a search tool can show the context around each match. Specifically, in this case, we ask for the two lines preceding and succeeding every match. We run this benchmark on the English subtitle corpus. Note that all tools are asked to count lines.

Pattern: `Sherlock Holmes` (with `--context 2`)

```
rg        0.612 (lines: 3533)
ag        3.530 (lines: 3533)
grep      1.075 (lines: 3533)
sift      0.717 (lines: 3533)
pt       17.331 (lines: 2981)
ucg       -----
```

Analysis: `rg` continues to do well here, but beats `sift` by only a hair. In general, computing the context shouldn't be that expensive since it is done rarely (only for each match). Nevertheless, both `ag` and `pt` seem to take a pretty big hit for it. `pt` also seems to have a bug. (Which is understandable, getting contexts right is tricky.) Finally, `ucg` doesn't support this feature, so we can't benchmark it.

`huge`

Description: This benchmark runs a simple literal search on a file that is `9.3GB`. In fact, this is the original English subtitle corpus in its entirety. (In the benchmark suite, we take a 1GB sample.)

Pattern: `Sherlock Holmes`

```
rg                  1.786 (lines: 5107)
grep                5.119 (lines: 5107)
sift                3.047 (lines: 5107)
pt                 14.966 (lines: 5107)
rg (lines)          4.467 (lines: 5107)
ag (lines)         19.132 (lines: 5107)
grep (lines)        9.213 (lines: 5107)
sift (lines)        6.303 (lines: 5107)
pt (lines)         15.485 (lines: 5107)
ucg (lines)         4.843 (lines: 1543)
```

Analysis: At first glance, it appears `ucg` competes with `rg` when counting lines (being only slightly slower), but in fact, `ucg` reports the wrong number of results! My suspicion is that `ucg` gets into trouble when trying to search files over 2GB.

The other intesting bit here is how slow `pt` is, even when not counting lines, despite the fact that `sift` is fast. They both use Go's regexp engine and should be able to be fast in the case of a simple literal. It's not clear what `pt`'s slow down here is. One hypothesis is that even though I'm asking it to not count lines, it's still counting them but simply not showing them.

Conclusions

I started this blog post by claiming that I could support the following claims with evidence:

- For both searching single files *and* huge directories of files, no other tool obviously stands above `ripgrep` in either performance or correctness.
- `ripgrep` is the only tool with proper Unicode support that doesn't make you pay dearly for it.
- Tools that search many files at once are generally *slower* if they use memory maps, not faster.

I attempted to substantiate the first claim by picking a popular repository (Linux kernel) and a variety of patterns that an end user might search for. While `rg` doesn't quite come out on top on every benchmark, no other tool can claim superiority. In particular, `git grep` edges out `rg` on occasion by a few milliseconds, but `rg` in turn will beat `git grep` handedly (sometimes by an order of magnitude, as in the case of `linux_unicode_word`) as the patterns grow more complex, especially when the search tool is asked to support Unicode. `rg` manages to compete with `git grep` and beat other tools like The Silver Searcher by:

- Implementing fast directory traversal with a minimal number of stat calls.
- Applying `.gitignore` filters with a `RegexSet`, which enables matching multiple globs against a single path all at once.
- Distributing work quickly to multiple threads with a Chase-Lev work stealing queue.
- Explicitly *not* using memory maps.
- Using an overall very fast regex engine.

I also attempted to substantiate the first claim by showing benchmarks of `rg` against other tools on a single file. In this benchmark, `rg` comes out on top in every single one, often by a large margin. Some of those results are a result of the following optimizations:

- Attempting to pick a "rare" byte to use `memchr` with for fast skipping.
- Using a special SIMD algorithm called Teddy for fast multiple pattern search.
- When Teddy isn't usable, fallback to an "advanced" form of Aho-Corasick that never moves through more than one transition on each byte of input.
- Building UTF-8 decoding into a finite state machine.

For the second claim, I provided benchmarks that attempt to use Unicode features such as conforming to Unicode's simple case folding rules and

Unicode aware character classes such as `\w`. The only tools capable of handling Unicode are `rg`, GNU grep and `git grep`. The latter two tend to get much slower when supporting the full gamut of Unicode while `rg` mostly maintains its performance.

For the third claim, I showed multiple benchmarks of `rg` controlling for memory maps. Namely, we measured how fast `rg` was both with and without memory maps, and showed that memory maps perform worse when searching many small files in parallel, but perform better on searching single large files. (At least, on `Linux x86_64`.) We also learned that memory maps probably pay an additional penalty inside a VM.

My hope is that this article not only convinced you that `rg` is quite fast, but more importantly, that you found my analysis of each benchmark educational. String searching is an old problem in computer science, but there is still plenty of work left to do to advance the state of the art.