Optimising string processing in Rust

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In this article, I'd like to explore how to process strings faster in Rust. I'll take the example of a function to escape the HTML `<`, `>` and `&` characters, starting from a naive implementation and trying to make it faster.

> **Warning**: I'm not an expert in this domain. While I do have a computer science background, I haven't had a job in this domain for nearly ten years, I am not an expert of Rust, and certainly not an expert in optimising stuff, so I'm absolutely not saying that I'm going to show you the fastest way to solve this problem; I mainly wanted to share my experience and what I learned by looking at that.

The problem

The problem is, broadly speaking, the following: we have a string containing some text, we want to do some stuff to it in some circumstances, and return another string. I'll take the specific example of escaping HTML characters: we don't want the text we are displaying to cause problem in our browser, so we escape the following characters:

- `<` to `&lt;`
- `>` to `&gt;`
- `&` to `&amp;`

> We are only escaping those because we assume non-adversarial content (the use case is converting local markdown files to HTML); clearly, more rules would be needed

if we wanted to escape the input of a non trusted user, in which case it might be a good idea to use an existing library that prevents e.g. XSS attacks.

The naive implementation

Let's start with a naive implementation, which is what I began with:

```
pub fn naive(input: &str) -> String {
    let mut output = String::new();
    for c in input.chars() {
        match c {
            '<' => output.push_str("&lt;"),
            '>' => output.push_str("&gt;"),
            '&' => output.push_str("&amp;"),
            _ => output.push(c)
        }
    }
    output
}
```

This function takes a `&str` reference and returns a newly allocated `String`, where the characters are escaped. It proceeds simply: allocate a new `String` at the beginning, walk through each character, escape it if it needs to be, or copy it if it doesn't. It works, but let's test how fast it is.

In order to do so, we'll use the bencher[1] facility of Rust, which unfortunately requires a nightly compiler. We'll test this function on four strings, hoping they reflect the way this function is used in real life:

- two that *don't* contain any characters that needs to be escaped, one being a short paragraph of 60 chars, and the other a longer one of 200 chars;
- two that contain characters that need to be escaped, the first one being a short paragraph of 60 chars with quite a lot of characters to escape, and the other being a longer paragraph of 200 chars with only one character to escape.

[1] `https://doc.rust-lang.org/beta/book/benchmark-tests.html`

In particular, we want to separate the cases where escaping is needed and the ones where it isn't. Indeed, in typical use case, most of the time the escape function won't actually have to do anything.

The results of running `cargo bench` (the source code for these benchmarks is available on Github[2]) is the following:

```
test bench_naive_all        ... bench:  4,551 ns/iter (+/-
103)
test bench_naive_html      ... bench:  2,171 ns/iter (+/- 49)
test bench_naive_no_html   ... bench:  2,155 ns/iter (+/- 26)
```

Unsurprisingly, the results for strings containing characters that need to be escaped and strings that are free of it are similar. Since Rust is a compiled language that *runs blazingly fast*[3], even the naive implementation isn't that bad: it takes around 4.5 microseconds to process a bit more than 500 characters; a novel of 500 thousands characters (not *A Song of Ice and Fire* volume, but not that short either) would thus require around 5 milliseconds. This isn't blocking for my needs, but we can do better, so let's do it.

Using `with_capacity`

So, let's just start by changing one line of code, and instead of writing:

```
let mut output = String::new();
```

which create an empty string, let's allocate upfront roughly enough capacity to store the whole text that we need to store, at least if we don't do any modification on it:

```
let mut output = String::with_capacity(input.len());
```

We now have:

```
test bench_naive_capacity_html    ... bench: 1,698 ns/iter
(+/- 19)
test bench_naive_capacity_no_html ... bench: 1,565 ns/iter
(+/- 21)
test bench_naive_capacity_all     ... bench: 3,243 ns/iter
(+/- 56)
```

[2]https://github.com/lise-henry/bench-escape
[3]https://www.rust-lang.org/

So, our function is now 30% faster, just by changing one line of code, because we avoid multiple allocations of the string when we know it's going to be at least this size.

But we can do better: looking at those results, we see that it takes nearly as much time when the function actually does *nothing* (when there isn't any character to escape). Can't we just avoid the work in that case?

Using `Cow`

It turns out we can, quite easily, by using Cow[4]. While I like that it bears the name of a pleasant animal, `Cow` actually means `Copy On Write`. As long as you don't need to modify it, it's actually just a pointer to some data, and if you need to modify it and only then, you can allocate an owned object.

So, instead of returning a `String`, we'll return a `Cow<str>`. If we modify the input string, the result will actually be a `String`, but if we do nothing (there are no characters that need to be escaped), we just return what we were given:

```
pub fn naive<'a, S: Into<Cow<'a, str>>>(input: S) -> Cow<'a,
str> {
    let input = input.into();
    fn is_trouble(c: char) -> bool {
        c == '<' || c == '>' || c == '&'
    }

    if input.contains(is_trouble) {
       let mut output = String::with_capacity(input.len());
        for c in input.chars() {
            match c {
                '<' => output.push_str("&lt;"),
                '>' => output.push_str("&gt;"),
                '&' => output.push_str("&amp;"),
                _ => output.push(c)
            }
        }
        Cow::Owned(output)
    } else {
```

[4]https://doc.rust-lang.org/std/borrow/enum.Cow.html

```
        input
    }
}
```

This function might look a bit complicated because of its argument, but it mainly uses the `Into`[5] trait to be able to take a wider varieties of arguments. This way, it is still possible to call this function by passing a `&str` to it, or a `String` if we already have an allocated one.

For a nice introduction on the `Into` trait, see Creating a Rust function that accepts String or &str[6]; you can also read the next article in this series, Creating a Rust function that returns a &str or String[7] that explains `Cow<str>`. These two articles really helped me understand those two powerful concepts of the Rust language, so if you need more explanation on this, I'd rather refer you to them instead of trying to paraphrase them.

Anyway, let's see if this improved our performances:

```
test bench_naive_cow_html     ... bench: 1,959 ns/iter (+/-
36)
test bench_naive_cow_no_html  ... bench:   443 ns/iter (+/-
5)
test bench_naive_cow_all      ... bench: 2,412 ns/iter (+/-
51)
```

Alright, this implementation is actually a tad *slower* when it is working on strings that need to be escaped, but in counterpart, it is now *three times faster* on strings that don't contain any. On a 50/50 mixture of both, it's 25% faster, but I'd think that the global number doesn't really mean anything, at it will depend on the actual content of your file. I'd tend to think, however, that in most cases you *won't* have any characters to escape[8].

The name of this test and function, containing the name `naive`, might be a spoiler alert: if it is naive, can we still do better? Of course we can.

[5]`https://doc.rust-lang.org/std/convert/trait.Into.html`

[6]`http://hermanradtke.com/2015/05/06/creating-a-rust-function-that-accepts-string-o`
`html`

[7]`http://hermanradtke.com/2015/05/29/creating-a-rust-function-that-returns-string-o`
`html`

[8]At least in my use case, where this function is called on any paragraph, title, subsection of text that is emphasised, and so on. Clearly, this would be different if you only ran this function once on the content of a whole document.

Using `find` instead of `contains`

This function is nice when it doesn't need to do anything, but it comes at a cost when it needs to do something: we call `input.contains`, which will walk the string looking for characters that need to be escaped, and then we will walk it *again* to replace those characters.

We can, however, use `find` instead:

```
pub fn find<'a, S: Into<Cow<'a, str>>>(input: S) -> Cow<'a,
str> {
    let input = input.into();
    fn is_trouble(c: char) -> bool {
        c == '<' || c == '>' || c == '&'
    }
    let first = input.find(is_trouble);
    if let Some(first) = first {
        let mut output = String::from(&input[0..first]);
        output.reserve(input.len() - first);
        let rest = input[first..].chars();
        for c in rest {
            match c {
                '<' => output.push_str("&lt;"),
                '>' => output.push_str("&gt;"),
                '&' => output.push_str("&amp;"),
                _ => output.push(c),
            }
        }

        Cow::Owned(output)
    } else {
        input.into()
    }
}
```

Unlike `contains`, `find` also returns the position of the first character that matches its pattern. With that information, we can directly jump to this position knowing that, before it, there was no need for escaping, and create the new string from this substring instead of copying one character at a time.

```
test bench_cow_find_html     ... bench: 1,282 ns/iter (+/-
23)
```

```
test bench_cow_find_no_html ... bench:   613 ns/iter (+/-
4)
test bench_cow_find_all      ... bench: 1,896 ns/iter (+/-
35)
```

This modification has a slight cost when there are no characters to be escaped, as it is 40% slower than the previous `Cow` implementation (but still more than two times faster than the implementation without `Cow`). On the other hand, it's 35% faster when the strings actually needs to be modified. While the percentages might look in favour of the precedent implementation, the absolute values clearly don't.

Is it better or worse?

It's hard, in these conditions, to clearly know what of these two implementations is the best, and it shows the limits of such a simple benchmark. The previous implementation was better for texts that contain few characters that needs to be escaped, while this new one is better for texts that contain more. I'd say that the 1300/600ns variant is globally better than the 2000/440ns one, but it really depends on which type of texts you are processing, and if it was really critical, you'd probably want to collect a vast corpus of texts to have more data.

Or... use another implementation anyway?

Using Regex

There's this nice crate, Regex[9], that provides an implementation of regular expressions. Now, clearly, for such a simple case where there are only three characters to be detected, using `find` plus a function (or a closure) seems way simpler, and I really don't see why adding a whole new machinery for such a trivial case would be faster, but let's test it anyway.

Of course, we need to add some dependencies to our `Cargo.toml`, and rewrite our function a little:

```
pub fn find<'a, S: Into<Cow<'a, str>>>(input: S) -> Cow<'a,
str> {
    lazy_static! {
      static ref REGEX: Regex = Regex::new("[<>&]").unwrap();
    }
```

[9] https://crates.io/crates/regex

```
    let input = input.into();
    let first = REGEX.find(&input);
    if let Some((first, _)) = first {
        // The rest is identical to the previous version
        // ...
    } else {
        input.into()
    }
}
```

Alright, so instead of having a function that returns `true` if there is a `<`, a `>` or a `&`, we just have a `Regex` that does the same thing, and instead of using the `find` method of `str` we use the `find` method of `Regex`, which returns a similar result (except it gives us the beginning and the end instead of just the beginning, but we discard this new piece of information anyway).

How good can that be?

```
test bench_regex_html    ... bench: 1,067 ns/iter (+/- 15)
test bench_regex_no_html ... bench:   151 ns/iter (+/- 1)
test bench_regex_all     ... bench: 1,233 ns/iter (+/- 38)
```

Great Scott! This is actually *three times* faster than the fastest implementation when there is no characters to escape, and still 30% faster than the fastest implementation when there are characters to escape. I guess we don't have to choose anymore between the two previous implementations because... *wow*, `Regex` is *fast*.

What's this lazy_static stuff?

Honestly, in this implementation, I just copy/pasted the `lazy_static!` block from the example in Regex documentation[10] (because not only is it fast, it also has a good documentation). `lazy_static!` is a macro that allows to declare a static variable that will only get initialised once, allowing to avoid to recompile the regular expression each time the function is invoked. The regex documentation warns:

> It is an anti-pattern to compile the same regular expression in a loop since compilation is typically expensive.

But what if we are too lazy to use `lazy_static!` and instead simply use the following?

[10] https://doc.rust-lang.org/regex/regex/index.html

```
let regex: Regex = Regex::new("[<>&]").unwrap();
```

Let's see...

```
test bench_regex_no_static_html    ... bench: 38,472 ns/iter
(+/- 773)
test bench_regex_no_static_no_html ... bench: 37,654 ns/iter
(+/- 675)
test bench_regex_no_static_all     ... bench: 76,458 ns/iter
(+/- 1,923)
```

Alright. Let's *not* do that.

Using `Regex::replace_all`

But wait a second, if `Regex` is that fast, why not use its `replace_all` method to do all the work, instead of just using `find` and then walking char by char through the rest of the string? Let's try it:

```
pub fn replace(input: &str) -> String {
    lazy_static! {
      static ref REGEX: Regex = Regex::new("[<>&]").unwrap();
    }
    let output = REGEX.replace_all(input, |caps: &Captures|
{
        match caps.at(0).unwrap() {
            "<" => "&lt;".to_owned(),
            ">" => "&gt;".to_owned(),
            "&" => "&amp;".to_owned(),
            _ => unreachable!()
        }
    });
    output
}
```

Here, we use the `replace_all` method, which takes as parameter a closure taking a `Captures` and returning a `String`. The element `0` of `Captures` corresponds to the whole match, so we then insert here the `match` block we previously had in our `for` loop. Also, since we don't differentiate anymore whether we find some characters that must be escaped or not, we removed all the `Cows` (*moo*), so this function goes back to taking a `&str` and returning a `String`.

The results, however, aren't as good as the previous implementation:

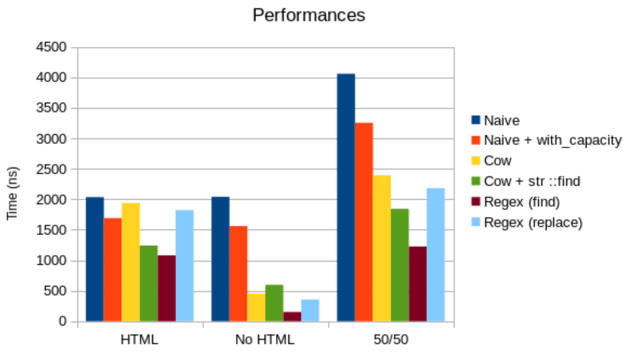
```
test bench_regex_replace_html     ... bench: 1,828 ns/iter
(+/- 36)
test bench_regex_replace_no_html ... bench:    360 ns/iter
(+/- 11)
test bench_regex_replace_all      ... bench: 2,196 ns/iter
(+/- 75)
```

It is two times slower than the implementation only using `find`.

> **Warning**: I don't know a lot about regular expressions, so it is entirely possible that this call to `replace_all` could be optimised and that it is actually worth using this method instead of `find`, but if it is, it requires more competences than I currently have.

Finally, the chart

To sum it up in a picture, here is a chart of the performances of all these implementations (except Regex without lazy static, which clearly is not the way you are supposed to use it). Time is in nanosecond per iteration, and, obviously, the lower the better.



To conclude:

- using a good implementation instead of the naive one actually has huge performances issues, not a mere 10% factor;

- the real improvement is actually when you *don't need to do anything*, and I think this can apply to a broad range of string manipulations (removing unnecessary whitespaces, using typographic quotation marks, replacing `:)` with and so on...);
- *wow*, `Regex` is fast.

Post-scriptum: additional optimisations

Posting this article on the Rust reddit[11] provided a lot of interesting feedback, and many people suggested further optimisations.

Using `u8` instead of `chars`

> While I wasn't initially sure it was safe, and thus avoided doing it, I was told that it's possible to safely search for ASCII characterss in a slice of `u8`, since the leading bit is set to `1` if it isn't the first byte of a character.

It is therefore possible to optimise the algorithm in this current case by looking directly at the bytes (`u8`) of the strings instead of the chars:

```
pub fn find_u8<'a, S: Into<Cow<'a, str>>>(input: S) -> Cow<'a,
str> {
    lazy_static! {
      static ref REGEX: Regex = Regex::new("[<>&]").unwrap();
    }
    let input = input.into();
    let first = REGEX.find(&input);
    if let Some((first, _)) = first {
      let mut output:Vec<u8> = Vec::from(input[0..first].as_bytes());
        output.reserve(input.len() - first);
        let rest = input[first..].bytes();
        for c in rest {
            match c {
                b'<' => output.extend_from_slice(b"&lt;"),
                b'>' => output.extend_from_slice(b"&gt;"),
               b'&' => output.extend_from_slice(b"&amp;"),
                _ => output.push(c),
```

[11] https://www.reddit.com/r/rust/comments/55wpxh/optimising_string_processing_in_rust/

```
            }
        }
        Cow::Owned(String::from_utf8(output).unwrap())
    } else {
        input.into()
    }
}
```

This leads to a significant performance bump when having to escape characters:

```
test bench_regex_u8_html    ... bench: 745 ns/iter (+/- 19)
test bench_regex_u8_no_html ... bench: 147 ns/iter (+/- 0)
test bench_regex_u8_all     ... bench: 894 ns/iter (+/- 19)
```

> Note, however, that this only works because the characters that we want to escape, `<`, `>`, and `&` are ASCII characters. Unlike the other methods described previously, this one cannot be generalized for any UTF-8 character.

It is possible to go a step further, by using the unsafe method `String::from_utf8_un` since we know that the vector of bytes we constructed is valid unicode, replacing

```
Cow::Owned(String::from_utf8(output).unwrap())
```

with

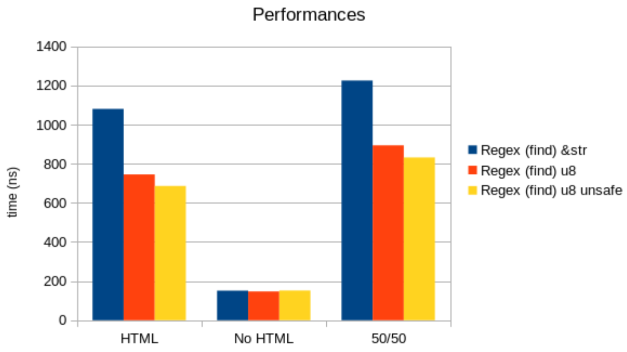
```
Cow::Owned(unsafe { String::from_utf8_unchecked(output) })
```

Since we don't have to check that the vector of `u8` is valid UTF-8, we have a little gain:

```
test bench_regex_u8_unsafe_html     ... bench: 686 ns/iter
(+/- 18)
test bench_regex_u8_unsafe_no_html ... bench: 152 ns/iter
(+/- 2)
test bench_regex_u8_unsafe_all      ... bench: 842 ns/iter
(+/- 29)
```

[12] https://doc.rust-lang.org/std/string/struct.String.html#method.from_utf8_unchecked

This requires using the `unsafe` keyword, which means you need to know what you are doing. While on this particular, this function is small enough to be reasonably certain that nothing is going to go badly, I'd be more reluctant to use this feature in a complex function, or in code that might evolve later on.



Using `Regex::find_iter`

In our main loop, we still walk through each character (or each byte with the version that works on bytes). It is, however, possible to use the `find_iter` method of `Regex` to get a list of matches and insert the substrings between the matches in one step:

```
pub fn find_iter<'a, S: Into<Cow<'a, str>>>(input: S) ->
Cow<'a, str> {
    lazy_static! {
     static ref REGEX: Regex = Regex::new("[<>&]").unwrap();
    }
    let input = input.into();
     let mut last_match = 0;

    if REGEX.is_match(&input)
    {
        let matches = REGEX.find_iter(&input);
       let mut output = String::with_capacity(input.len());
        for (begin, end) in matches {
            output.push_str(&input[last_match..begin]);
            match &input[begin..end] {
                "<" => output.push_str("&lt;"),
                ">" => output.push_str("&gt;"),
                "&" => output.push_str("&amp;"),
                _ => unreachable!()
            }
            last_match = end;
        }
        output.push_str(&input[last_match..]);
        Cow::Owned(output)
    } else {
        input
    }
}
```

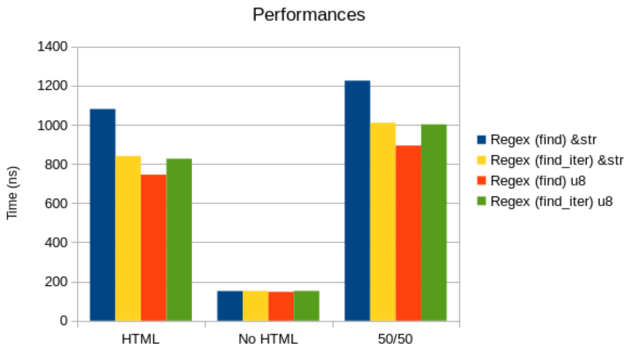
In this case, there is an additional call to `REGEX.is_match` (which returns a boolean) which might not strictly be necessary, but is there to appease the borrow checker (`matches` is returned from `find_iter` which borrows `input`, so the compiler isn't happy with us returning `input` if `matches` is in the same scope). Despite that, it's still a performance gain compared to the implementation only using `find`:

```
test bench_regex_html         ... bench: 1,072 ns/iter (+/-
19)
test bench_regex_iter_html    ... bench:   841 ns/iter (+/-
26)
test bench_regex_no_html      ... bench:   152 ns/iter (+/-
2)
test bench_regex_iter_no_html ... bench:   155 ns/iter (+/-
2)
test bench_regex_all          ... bench: 1,222 ns/iter (+/-
38)
test bench_regex_iter_all     ... bench: 1,010 ns/iter (+/-
19)
```

The same idea can be applied for the implementation working on bytes but in this case (and on this set of data), it is actually slightly slower, probably because walking through a slice of bytes can be much more optimised than having to find the next unicode character:

```
test bench_regex_u8_html         ... bench:   751 ns/iter
(+/- 46)
test bench_regex_u8_iter_html    ... bench:   827 ns/iter
(+/- 22)
```

```
test bench_regex_u8_no_html       ... bench:   147 ns/iter
(+/- 3)
test bench_regex_u8_iter_no_html ... bench:   152 ns/iter
(+/- 2)
test bench_regex_u8_all           ... bench:   897 ns/iter
(+/- 29)
test bench_regex_u8_iter_all      ... bench: 1,002 ns/iter
(+/- 17)
```



Using `with_capacity` instead of `reserve`

Initially (except in the most naive case), I was initialising the output string with:

```
String::with_capacity(input.len())
```

Later on, on some versions, I initialised this `String` (or this `Vec<u8>`) with the content until the first character to escape, using `reserve` later on:

```
let mut output = String::from(&input[0..first]);
output.reserve(input.len() - first);
```

or

```
let mut output:Vec<u8> = Vec::from(input[0..first].as_bytes());
output.reserve(input.len() - first);
```

Ideally, I would have used something like

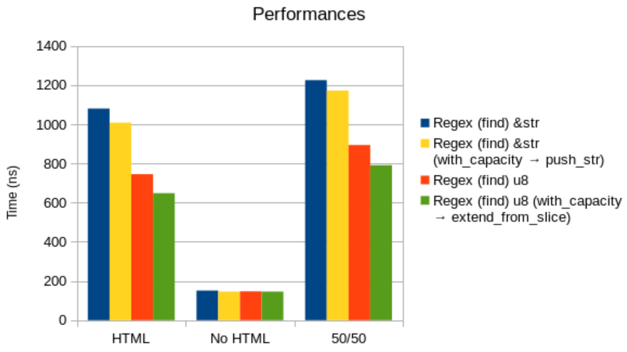
```
let mut output = String::from_with_capacity(&input[0..first],
input.len());
```

But there is no method `from_with_capacity`, so I had to do it in two steps. I was suggested to to it in the opposite order, in order to avoid an unnecessary allocation:

```
let mut output = String::with_capacity(input.len());
output.push_str(&input[0..first]);


let mut output:Vec<u8> = Vec::with_capacity(input.len());
output.extend_from_slice(input[0..first].as_bytes());
```

The results turns out to be slightly faster `String`:



So, the morale seems to be, set capacity first, load content later.

Setting a larger initial capacity

When we create our output string, we use `String::with_capacity(input.len)`. Except... since we are replacing single characters with four of five character strings (`>`-> `&gt;`, `<` -> `&lt;`, `&` -> `&amp;`), the output string will have a bigger length than the initial one. This is bad because we'll need to have one more allocation, and it's possible that, in this process, the compiler will have to copy the entire string we have been building to a new memory location.

So, we should set the initial capacity to a bigger number. Doing this is straightforward, as it just requires to replace:

```
let mut output = String::with_capacity(input.len());
```

by:

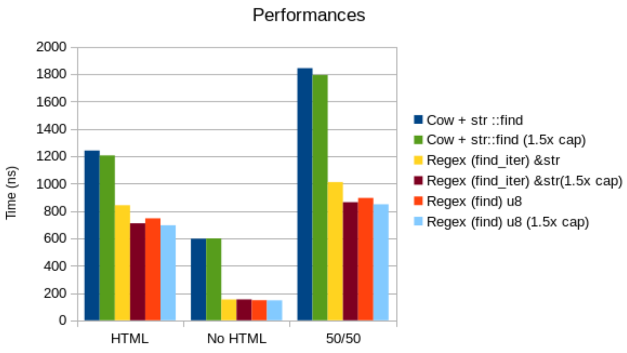
```
let len = input.len();
let mut output = String::with_capacity(len + len/2);
```

(Why add 50%, and not 10%, or double it? Well, I cheated a bit, and looked at the limited strings that I use to bench this function, and the worst case scenario added a bit less than 50% to the string length.)

The performance gain is significant, e.g. for the implementation using `Regex::find_iter`:

```
test bench_regex_iter_html           ... bench: 832 ns/iter
(+/- 24)
test bench_regex_iter_morecap_html    ... bench: 702 ns/iter
(+/- 16)
test bench_regex_iter_no_html        ... bench: 150 ns/iter
(+/- 5)
test bench_regex_iter_morecap_no_html ... bench: 150 ns/iter
(+/- 1)
test bench_regex_iter_all            ... bench: 995 ns/iter
(+/- 29)
test bench_regex_iter_morecap_all     ... bench: 846 ns/iter
(+/- 11)
```

A similar modification on other implementation yields similar results:



And the winner is...

So, with all those options, what is the fastest? Currently, at least on my computer, the fastest was the following, using `Regex`, then walking through the slice of bytes, using an initial capacity of 1.5 the length of the input string, and using `String::from_utf8_unchecked` to generate the output string:

```
pub fn find_u8_unsafe_morecap<'a, S: Into<Cow<'a, str>>>(input:
S) -> Cow<'a, str> {
    lazy_static! {
     static ref REGEX: Regex = Regex::new("[<>&]").unwrap();
    }
    let input = input.into();
    let first = REGEX.find(&input);
    if let Some((first, _)) = first {
        let len = input.len();
         let mut output:Vec<u8> = Vec::with_capacity(len +
len/2);
      output.extend_from_slice(input[0..first].as_bytes());
        let rest = input[first..].bytes();
        for c in rest {
            match c {
                b'<' => output.extend_from_slice(b"&lt;"),
                b'>' => output.extend_from_slice(b"&gt;"),
               b'&' => output.extend_from_slice(b"&amp;"),
                _ => output.push(c),
            }
        }
     Cow::Owned(unsafe { String::from_utf8_unchecked(output)
})
    } else {
        input
    }
}
```

Getting the following results:

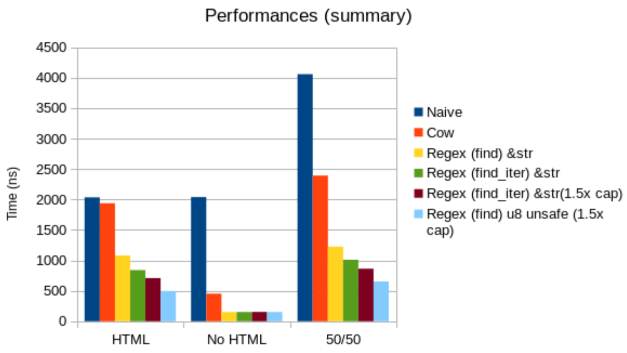
```
test bench_regex_u8_unsafe_morecap_html     ... bench: 497
ns/iter (+/- 14)
test bench_regex_u8_unsafe_morecap_no_html ... bench: 152
ns/iter (+/- 2)
```

```
test bench_regex_u8_unsafe_morecap_all      ... bench: 653
ns/iter (+/- 13)
```

While these results are nice, they require the use of `unsafe` and working on bytes (which might not be possible for more generic string processing).

Post-scriptum conclusion

We have gone a long way from our naive approach. But looking at the results:



I'd argue that the major performance improvements were:

- avoid doing work when there is no work to do (using `Cow`);
- using `Regex::find` instead of the standard library method on `str`, which, at least currently, isn't as fast.

There was room for more improvement after that (either using `Regex::find_iter`, tweaking the initial capacity, or working on bytes instead of chars) but it wasn't by the same order of magnitude.

Thanks

I'd like to thank everyone who commented on the Rust reddit thread on this article[13] and `burntsushi`, `TaslemGuy`, `tspiteri`, `LEmp_Evrey`, and I'm probably forgetting a lot of people.

[13]`https://www.reddit.com/r/rust/comments/55wpxh/optimising_string_processing_in_rust/`