
Intro to Rust Lang
The Rust Ecosystem

Today: The Rust Ecosystem

- The Rust Toolchain: `rustup`, `clippy`, `rustfmt`
- Performance and Analysis: Criterion, Flamegraphs
- Reading Documentation
  - `rand`
  - `time` vs `chrono`
  - `anyhow` vs `thiserror`

The Rust Toolchain

Toolchains

- A toolchain is defined as a set of software tools used to build and develop software within a specific ecosystem
- A Rust toolchain is a complete installation of the Rust compiler (rustc) and related tools (like `cargo`)
  - Defined by release channel / version, and the host platform triple
  - `stable-x86_64-pc-windows-msvc`, `beta-aarch64-unknown-linux-gnu`

`rustup`

`rustup`

`rustup` is a *toolchain multiplexer*.

- Rust has several toolchains, which you manage via `rustup`
- `rustup` consolidates them as a single set of tools installed in `~/.cargo/bin`
- Similar to Ruby's `rbenv`, Python's `pyenv`, or Node's `nvm`

`rustup` Channels

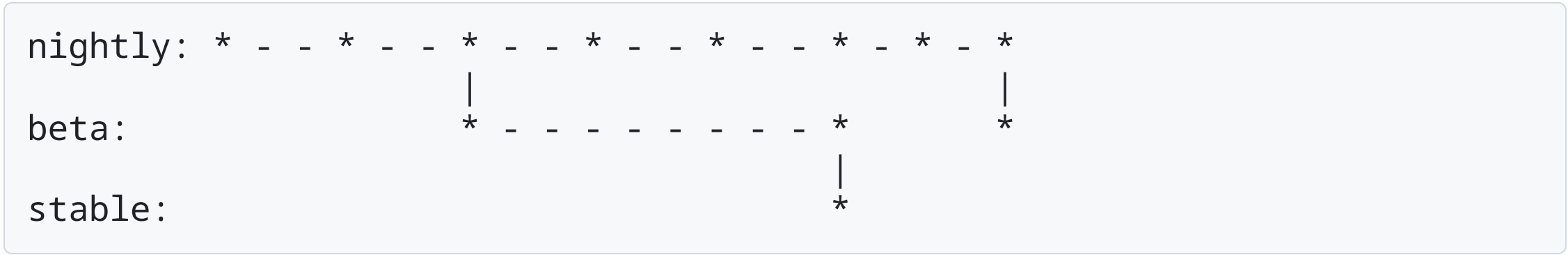
- There are 3 different channels
  - Stable: `rustc` and `cargo` release every 6 weeks
  - Beta: the next stable release
  - Nightly: release made every night, based on the `master` branch

Stability without Stagnation

- Rust cares *a lot* about the stability of your code
- At the same time, we all want to experiment with new features
- You should *never* need to worry about breaking your code after updating Rust
- But you should also be able to opt-in to newer "unstable" features!

The Rust Train

Here is a high-level diagram of Rust's release cycle.



- This is called the “train model”
- Every six weeks, a release “leaves the station”
- Still has to take a "journey" through the beta channel before it "arrives" as a stable release

Unstable Features

We can use features under development by enabling *unstable features*.

- You can only use unstable features on nightly
- Allows you to access cool new things in Rust
  - Example: `try_blocks` with `#![feature(try_blocks)]`
  - Example: `downgrade` on `RwLock` with `#![feature(rwlock_downgrade)]`

`rustup` Usage

Here are some basic `rustup` commands to remember:

- `rustup update`
  - Updates your Rust toolchains to the latest versions
- `rustup default set <stable/beta/nightly>`
  - Sets the default rust toolchain
- `rustup override set <stable/beta/nightly>`
  - Overrides the toolchain for the specific directory

Clippy

Clippy

Clippy is a collection of lints that can catch common mistakes when writing Rust, improving the quality of your code.

- *We have asked you to use clippy for your homeworks!*

Clippy Lint Levels

Clippy offers many different lint levels.

- `clippy::all`: all lints that are on by default
  - `clippy::correctness`: code that is outright wrong or useless
  - `clippy::suspicious`: code that is most likely wrong or useless
  - `clippy::style`: code that should be written in a more idiomatic way
  - `clippy::complexity`: code that does something simple in a complex way
  - `clippy::perf`: code that can be written to run faster
- And more...
- You can even make your own lints!

`clippy` Usage

- Already installed if using `rustup` (default profile)
- To run all lints, run `cargo clippy`
  - To run a specific lint, run `cargo clippy::___`
- To automatically apply suggestions, run `cargo clippy --fix`
- To run lints on tests and other files, run `cargo clippy --all-targets`

Clippy Source Code Usage

You can also configure lint levels directly in your source code.

```
fn main() {
    #[allow(unused_variables)]
    let not_used = 42;

    println!("Hello, World!");
}
```

`rustfmt`

`rustfmt`

`rustfmt` is a formatting tool that checks adherence to Rust's strict formatting standards.

- Already installed if using `rustup` (default profile)
- To format one file: `rustfmt file.rs`
- To format whole project: `cargo fmt`
- To only *check* format: `cargo fmt -- --check`

Configuring `rustfmt`

You can configure format options with a `rustfmt.toml` file

```
indent_style = "Block"
reorder_imports = false
```

- There are many configuration options for `rustfmt`
- **You probably shouldn't create your own unique formatting style**

Consistent Formatting

- The default Rust style is defined in the Rust Style Guide
  - It is **strongly recommended** that developers use this style
- Consistent formatting makes code more readable
  - Also makes it easier to collaborate with others

Performance and Analysis

Performance Profiling

Suppose we want to see how fast or slow our code runs.

```
pub fn fibonacci(n: u64) -> u64 {
    match n {
        0 => 1,
        1 => 1,
        n => fibonacci(n-1) + fibonacci(n-2),
    }
}
```

- How do we test/profile the *performance* of our code?

Performance Profiling: Timer

A simple solution is to just use a timer!

```
use std::time::Instant;
use std::hint::black_box;

fn main() {
    let start_time = Instant::now();

    let _ = black_box(fibonacci(30));

    let elapsed = start_time.elapsed();
    println!("Elapsed: {:.2?}", elapsed);
}
```

```
Elapsed: 14.00ms
```

Problem: Statistical Significance

When we run this code multiple times, we could get different results...

```
Elapsed: 14.30ms
Elapsed: 11.59ms
Elapsed: 8.48ms
Elapsed: 10.35ms
Elapsed: 20.95ms
```

- How do we control our environment?
  - Compiler optimizations can skew results, the OS scheduler and other noise can create performance variations
  - Seeing a number go up/down is one thing, whether it's statistically significant is another

Criterion

Criterion

Criterion is a statistics-driven micro-benchmarking library written in Rust.

- Collects detailed statistics, providing strong confidence that changes to performance are real, not measurement noise
- Produces detailed charts and provides thorough understanding of your code's performance behavior
- Make sure to read the (very well-written) library docs and user guide!

`criterion`

Add `criterion` as a development dependency:

```toml
[dev-dependencies]
criterion = "0.5.0"

[[bench]]
name = "my_benchmark"
harness = false
```

- `name = "my_benchmark"` declares that there is a benchmark file located at `my_crate/benches/my_benchmark.rs` (not in `src/` directory)

Example: Simple `criterion` Benchmark

Create a benchmark file at `my_crate/benches/my_benchmark.rs`:

```
use criterion::{black_box, criterion_group, criterion_main, Criterion};
use my_crate::fibonacci;
```

- Import `criterion` items
- Import the function we want to bench (in this case, `my_crate::fibonacci`)

Example: Simple `criterion` Benchmark

Next, create a benchmark using the `Criterion` object:

```
pub fn criterion_benchmark(c: &mut Criterion) {
    c.bench_function("fib 20", |b| b.iter(|| fibonacci(black_box(20))));
}

criterion_group!(benches, criterion_benchmark);
criterion_main!(benches);
```

Example: Simple `criterion` Benchmark

```
pub fn criterion_benchmark(c: &mut Criterion) {
    c.bench_function("fib 20", |b| b.iter(|| fibonacci(black_box(20))));
}
```

- `black_box` stops the compiler from optimizing away our entire function
  - The compiler is allowed to replace `fibonacci(20)` with a constant

`criterion`

Run the benchmark with `cargo bench`:

```
$ cargo bench

Benchmarking fib 20: Warming up for 3.0000 s
Benchmarking fib 20: Collecting 100 samples in estimated 5.0329 s (475k iterations)
Benchmarking fib 20: Analyzing

fib 20                  time:   [10.404 µs 10.413 µs 10.422 µs]
Found 10 outliers among 100 measurements (10.00%)
  10 (10.00%) high mild
```

Fibonacci Improvements

Our Fibonacci could definitely be improved...

```
pub fn fibonacci(n: u64) -> u64 {
    match n {
        0 => 1,
        1 => 1,
        n => fibonacci(n-1) + fibonacci(n-2),
    }
}
```

- What's the complexity of the algorithm?
  - Exponential!

Fibonacci Improvements

Let's write a second version for comparison:

```
pub fn fibonacci(n: usize) -> usize {

    fn fib_helper(from: (usize, usize), n: usize) -> usize {
        if n == 0 {
            from.0
        } else {
            fib_helper((from.1, from.0 + from.1), n - 1)
        }
    }

    fib_helper((0, 1), n)
}
```

Fibonacci Improvements

Upon rerunning `cargo bench`, `criterion` compares it with our previous run:

```
$ cargo bench

Benchmarking fib 20: Warming up for 3.0000 s
Benchmarking fib 20: Collecting 100 samples in estimated 5.0000 s (2.2B iterations)
Benchmarking fib 20: Analyzing

fib 20                  time:   [2.2469 ns 2.2633 ns 2.2841 ns]
                        change: [-99.978% -99.978% -99.978%] (p = 0.00 < 0.05)
                        Performance has improved.
```

- `change: [-99.978% -99.978% -99.978%] (p = 0.00 < 0.05)`
  - This is a statistically significant improvement!

Flamegraphs

Flamegraphs

Suppose you want to know *where* your program is spending time.

- We want to know which functions take the most time
- We could add timers for every single function call
  - Manually adding timers is error-prone, misses deeper call stacks
- That's why we have `flamegraph`s!

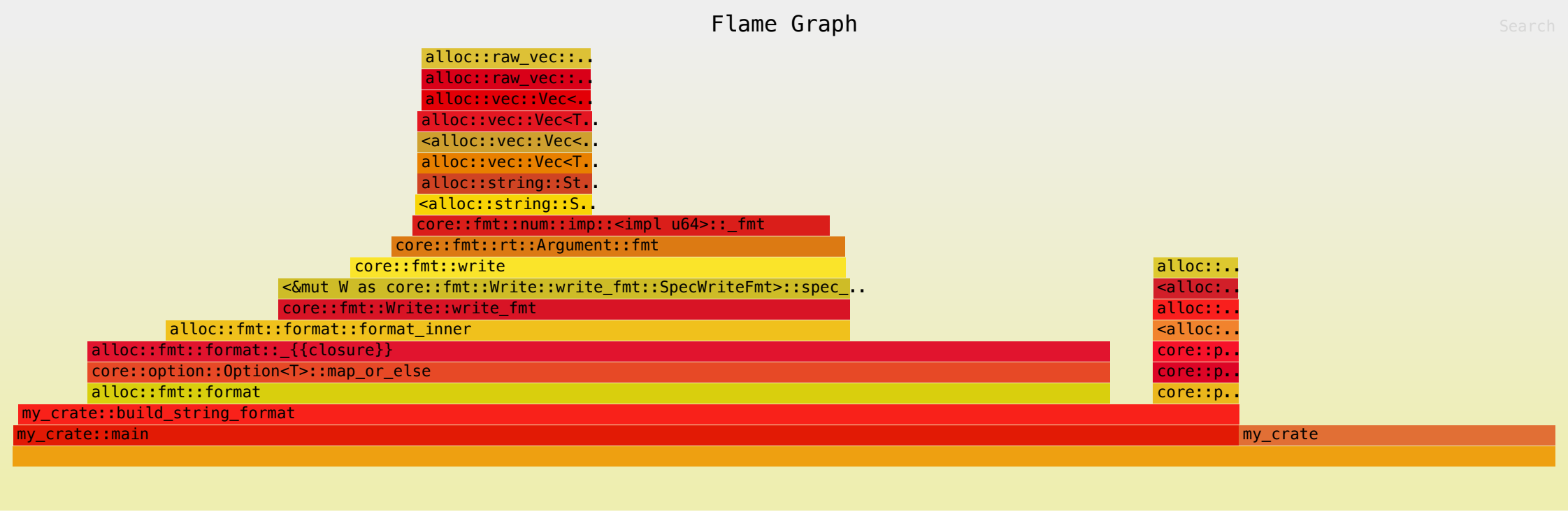
Example: Concatenating Strings

Suppose we have the following function, and we want to know where most of the time is spent:

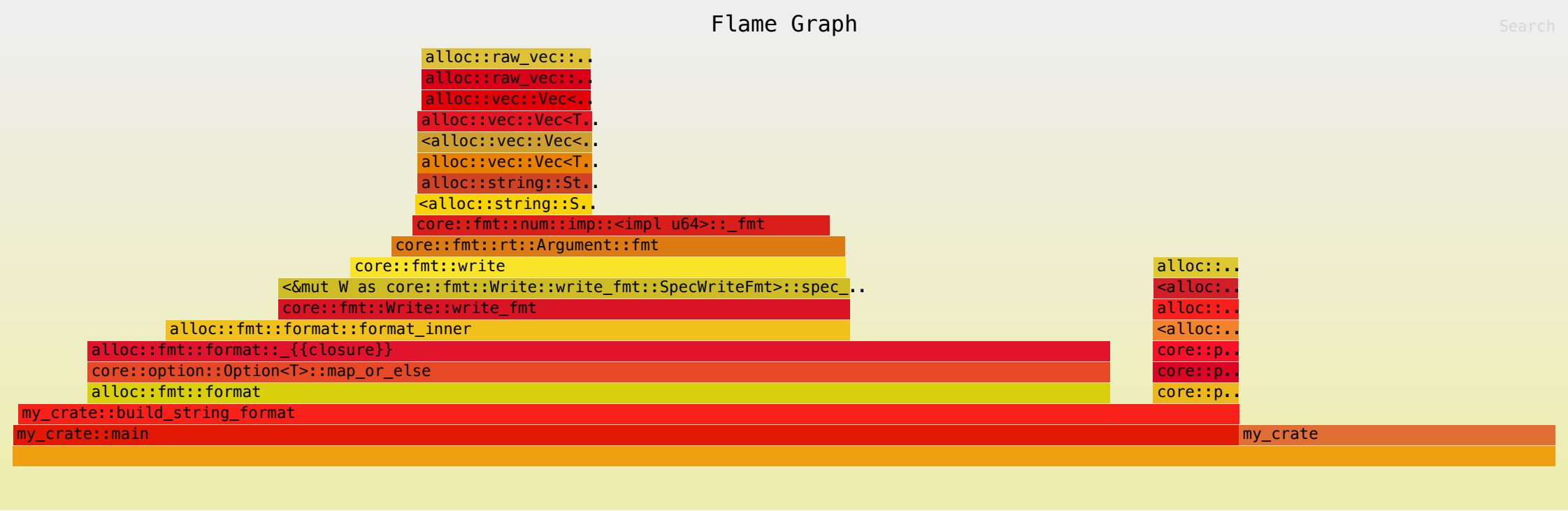
```
fn build_string(n: usize) -> String {
    let mut s = String::new();

    for i in 0..n {
        s += &format!("{}", i);
    }

    s
}

build_string(5); // produces "01234"
build_string(15); // produces "012345678910111213 14"
```

Flamegraph

We can generate flamegraphs for our code with `cargo flamegraph`:



Flamegraph Analysis



- Flamegraphs are generated by *sampling* the call stack many times
- Flamgegraphs display the call stack from bottom to top
  - The width of a block is the relative time spent in that function

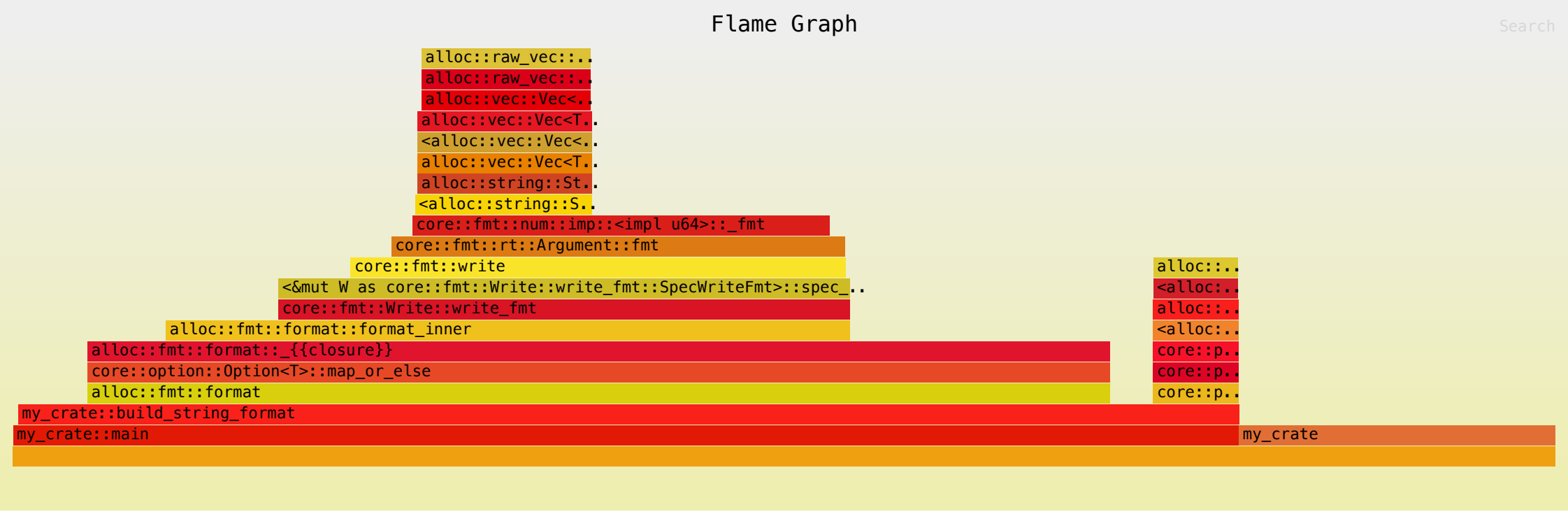
Flamegraph Usage

It's more informative to have a side-by-side comparison:

```
fn build_string_format(n: usize) -> String {
    let mut s = String::new();
    for i in 0..n {
        s += &format!("{}", i);
    }
    s
}

fn build_string_pushstr(n: usize) -> String {
    let mut s = String::with_capacity(n * 2);
    for i in 0..n {
        s.push_str(&i.to_string());
    }
    s
}
```

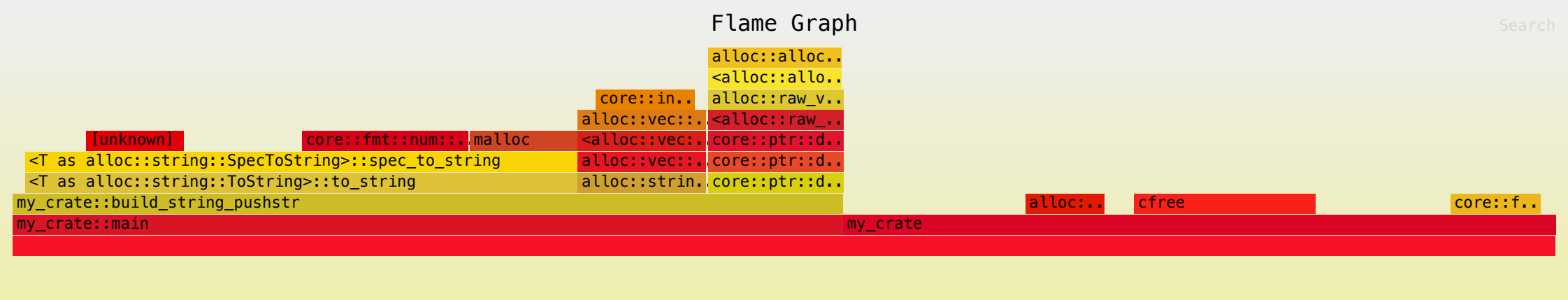
Flamegraph

Here is the flamegraph for `build_string_format`:



Flamegraph

And here is the flamegraph for `build_string_pushstr`:



- This one is faster!

Reading Rust Documentation

Reading Rust Documentation

Reading the documentation of third-party libraries is super important!

- When we are unfamiliar with a tool, the first thing we need to do is read through documentation
- Rust's `rustdoc` tool provides a way for developers to write documentation consistently between packages
    - *All of our homework writeups were generated with `rustdoc`!*

`rustdoc`

Usually, you use `rustdoc` via `cargo doc`. Here are some useful commands:

- `cargo doc --open`: Generates docs and opens it in a browser
- `cargo doc --document-private-items`: Generates documentation for private items like modules and functions
- `cargo doc --no-deps`: Does not generate docs for any dependencies
- `cargo doc --test`: Runs documentation tests

Rust Documentation

All Rust library documentation has the same structure!

- By making documentation consistent, it shortens the time needed to get familiar with a library
- Because Rust has *excellent* first-party tooling for generating documentation, Rust library writers tend to invest in writing *excellent* documentation, guides, and tutorials

`rand`

`rand`

Let's look at an example of a popular third-party crate, `rand`.

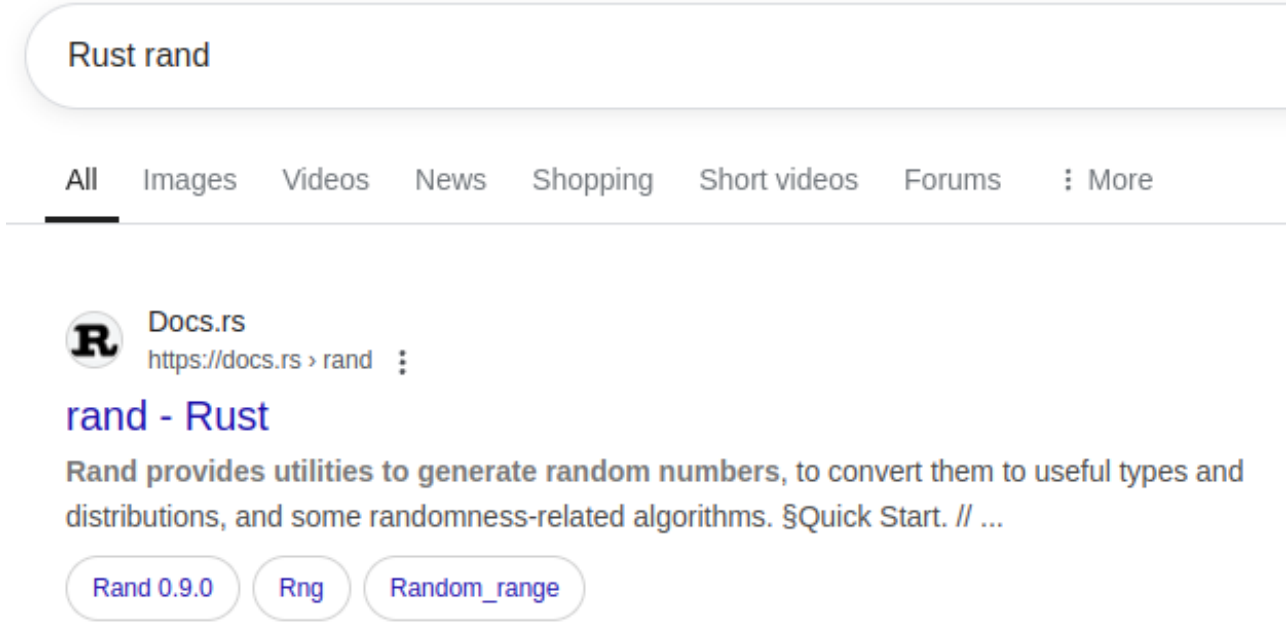
- Rust does not have a random module in the standard library (unlike Python)
- Instead, the de-facto crate for dealing with randomness in Rust is `rand`!
- Use `rand` for:
  - Generating / sampling random numbers
  - Creating probability distributions
  - Providing random algorithms (like vector shuffling)

`rand`?

- How do we use `rand`?
- We should really be asking "how do we learn how to use `rand`"?
- Google is our friend!
    - Search "Rust rand"

Docs.rs

- Docs.rs has documentation for essentially every third-party Rust library
- When publishing your own crate, the documentation gets pushed to Docs.rs



Crate rand

Source

Utilities for random number generation

Rand provides utilities to generate random numbers, to convert them to useful types and distributions, and some randomness-related algorithms.

Quick Start

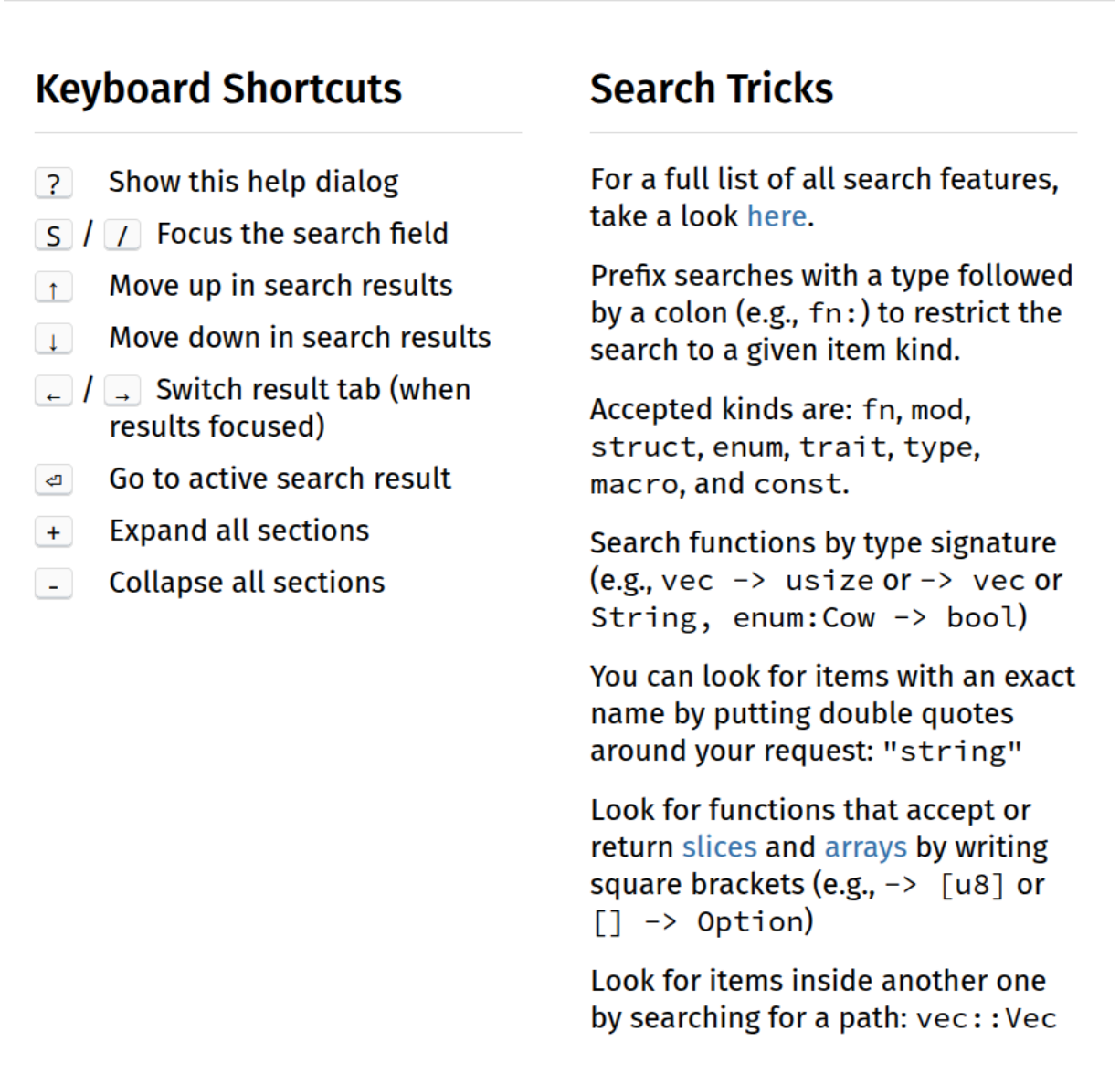
```
// The prelude import enables methods we use below, specifically
// Rng::random, Rng::sample, SliceRandom::shuffle and IndexedRandom::choose.
use rand::prelude::*;

// Get an RNG:
let mut rng = rand::rng();

// Try printing a random unicode code point (probably a bad idea)!
println!("char: '{}'", rng.random::<char>());
// Try printing a random alphanumeric value instead!
println!("alpha: '{}'", rng.sample(rand::distr::Alphanumeric) as char);

// Generate and shuffle a sequence:
let mut nums: Vec<i32> = (1..100).collect();
nums.shuffle(&mut rng);
// And take a random pick (yes, we didn't need to shuffle first!):
let _ = nums.choose(&mut rng);
```

The Book

For the user guide and further documentation, please read The Rust Rand Book.

Anatomy of `rustdoc`

- Navigation Bar (on the left)
- Search Bar (at the top)
  - Press "s" to search
- Settings (at the top right)
- Help menu (at the top right)
  - Press "?" for pop-up
  - Lots of cool tricks!



Keyboard Shortcuts

? Show this help dialog
S / / Focus the search field
↑ Move up in search results
↓ Move down in search results
← / → Switch result tab (when results focused)
⏎ Go to active search result
+ Expand all sections
- Collapse all sections

Search Tricks

For a full list of all search features, take a look here.

Prefix searches with a type followed by a colon (e.g., `fn:`) to restrict the search to a given item kind.

Accepted kinds are: `fn`, `mod`, `struct`, `enum`, `trait`, `type`, `macro`, and `const`.

Search functions by type signature (e.g., `vec -> usize` or `-> vec` or `String, enum:Cow -> bool`)

You can look for items with an exact name by putting double quotes around your request: `"string"`

Look for functions that accept or return slices and arrays by writing square brackets (e.g., `-> [u8]` or `[] -> Option`)

Look for items inside another one by searching for a path: `vec::Vec`

`rand` Docs

Let's take a quick look at the actual documentation!

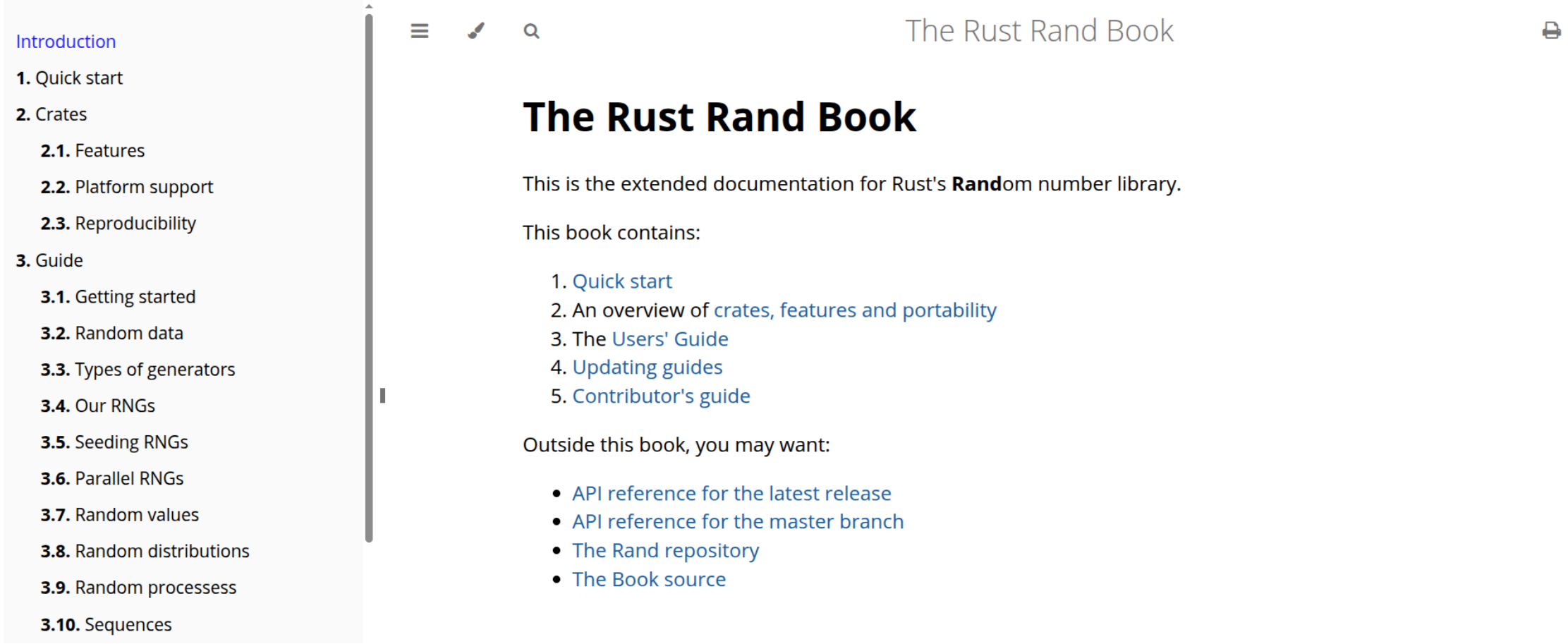
https://docs.rs/rand/latest/rand/

`rand` : Quick Start

```
// The prelude import enables methods we use below...
use rand::prelude::*;

// Get an RNG:
let mut rng = rand::rng();

println!("char: '{}'", rng.random::<char>());
println!("alpha: '{}'", rng.sample(rand::distr::Alphanumeric) as char);

// Generate and shuffle a sequence:
let mut nums: Vec<i32> = (1..100).collect();
nums.shuffle(&mut rng);
// And take a random pick (yes, we didn't need to shuffle first!):
let _ = nums.choose(&mut rng);
```

The Rust Rand Book

If we click on the link under the Quick Start, we are taken to The Rust Rand Book.



Aside: mdBook

- **mdBook** is a command line tool to create books with Markdown
- Used to make the official Rust Book
- Commonly used to make higher-level tutorials
    - Rust documentation structure can't cover everything

The Rust Rand Book

The Rust Rand Book covers the higher-level concepts that might not be easily understandable in the `rustdoc` format.

- Core concepts of randomness
- Kinds of RNGs
- Seeding strategies
- Cryptographic vs non-cryptographic randomness
- Performance considerations
- Understanding the design and architecture of `rand`

`rand` Lower-level Documentation

If we want to know the lower-level specific details about `rand`, then we need to read through the actual documentation.

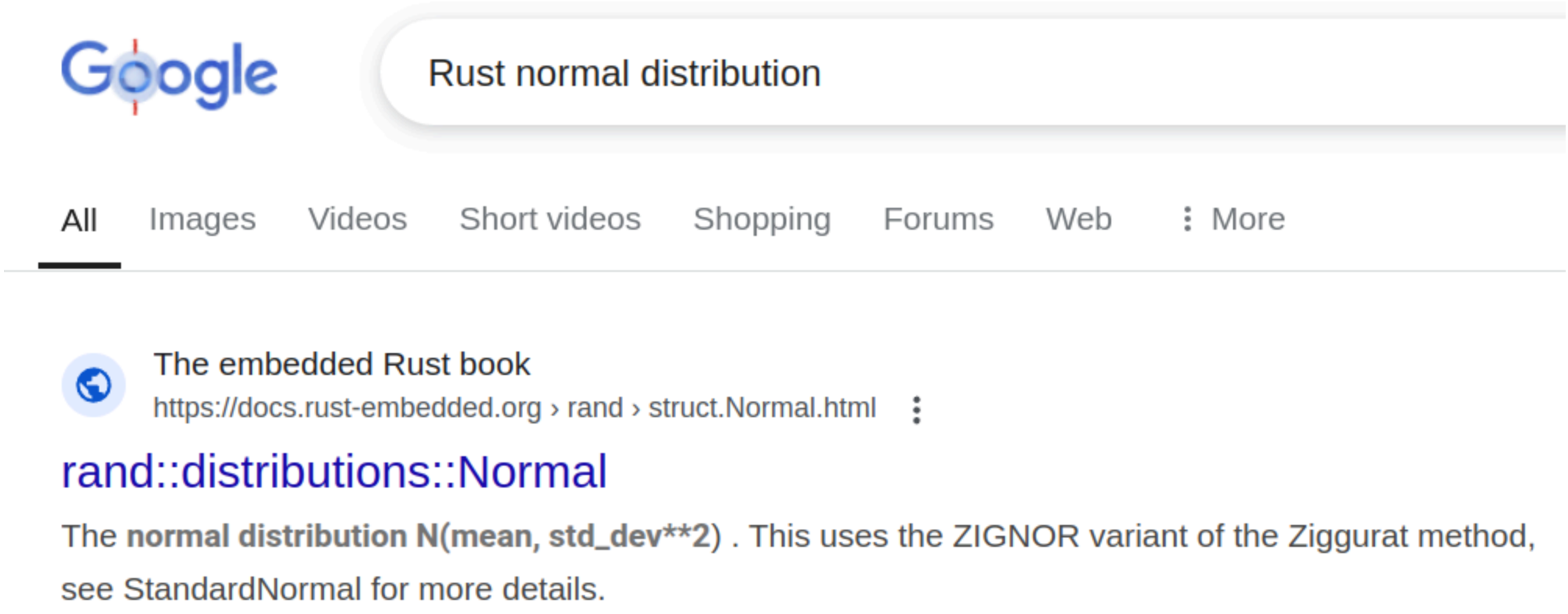
- Specific RNG implementations and their guarantees
  - `ThreadRng`, `StdRng`, `SmallRng`, etc.
  - Security properties
  - Performance characteristics
- Detailed distribution implementations
  - `Uniform`, `Bernoulli`, `Alphanumeric`
  - Parameter configurations / constructors
  - Sampling methods

Normal Distribution?

`rand` provides some basic probability distributions for us.

- `Uniform`, `Bernoulli`, `Alphanumeric`
- Where are the others?
- What about a Normal / Gaussian distribution?

Google is not your friend?



- This is actually not correct...
  - Make sure you are looking at Docs.rs!

Google can *help*!

GitHub Pages

https://rust-random.github.io › book › guide-dist

Random distributions - The Rust Rand Book

The Normal distribution (also known as Gaussian) **simulates sampling from the Normal distribution** ("Bell curve") with the given mean and standard deviation.

Docs.rs

https://docs.rs › rand_distr

rand_distr - Rust

This crate provides the following probability **distributions**: Related to real-valued quantities that grow linearly (e.g. errors, offsets):. Normal distribution, ...

`rand_distr`

`rust-random` breaks functionality into multiple crates. `rand_distr` is one of them!

```
use rand_distr::Normal;

let normal = Normal::new(2.0, 3.0).unwrap(); // mean 2, standard deviation 3
let v = normal.sample(&mut rand::rng());
println!("{} is from a N(2, 9) distribution", v)
```

`rand_distr`

```
use rand_distr::Normal;

let normal = Normal::new(2.0, 3.0).unwrap(); // mean 2, standard deviation 3
let v = normal.sample(&mut rand::rng());
println!("{} is from a N(2, 9) distribution", v)
```

- `rand_distr` complements `rand` by providing more probability distributions
- Crates that you use will often depend on each other
- Anyone can create a type that implements `Distribution`, integrating it into the `rand` "ecosystem"
  - Example: `zipf` distribution

Aside: Large Language Models

Large Language Models have proven that they can boost developer productivity.

- Due to Rust's strict guardrails and a "if it compiles it works" mentality, LLMs are actually quite good at helping with small amounts of Rust code
- However, LLMs are generally quite bad at the types of hard problems that Rust aims to solve
  - Complex software systems, concurrent and parallel programs, etc.
- Generally not that much training data (compared to Python or Javascript)
- Leverage LLMs for basic syntax and boilerplate!

Rust Time

- Time for Rust!

Time?

How do we keep time in Rust? There are several options:

- `std::time` : Basic system time functionality
- `time` : Some more time functionality (dates, months, parsing, formatting)
- `chrono` : Even more functionality (UTC time zones, Gregorian calendar)

How do you choose which `time` to use?

- Google is your friend!

Google is your friend!

https://www.google.com/search?q=Rust+chrono+vs+time

Answer: It Depends!

You should read through the documentation of each to figure out which is the best for you.

- `std::time` : https://doc.rust-lang.org/std/time
- `time` : https://docs.rs/time/latest/time/
- `chrono` : https://docs.rs/chrono/latest/chrono/

Error Handling

Error Handling

- In lecture 5, we talked about how to handle errors on your own
  - Hopefully you know what `Result<T, E>` is...
- Creating `MyError` types for `Result<T, MyError>` everywhere can create a lot of boilerplate and become cumbersome
- It is usually easier and faster to use a third-party library that can help you manage errors better!

Error Handling Libraries

- `anyhow`
  - "I don't want to care about error types"
- `thiserror`
  - "I want to easily define errors for my library"
- `snafu`
  - "I want BOTH!"

anyhow

You can think about `anyhow` as a library that provides type-erased errors.

```
use anyhow::Result;

fn get_cluster_info() -> Result<ClusterMap> {
    let config = std::fs::read_to_string("cluster.json")?;
    let map: ClusterMap = serde_json::from_str(&config)?;
    Ok(map)
}
```

- Remember how painful it was to define a proper error type?
- `anyhow` provides `anyhow::Error`, a trait object based error type for easy idiomatic error handling in Rust applications
- Allows you to use `?` wherever you want (a better `Box<dyn Error>`)

`anyhow`: Attach context

You can add a `with_context` to attach a context to any errors.

```
use anyhow::{Context, Result};

fn main() -> Result<()> {
    // <-- snip -->
    it.detach().context("Failed to detach the important thing")?;

    let content = std::fs::read(path)
        .with_context(|| format!("Failed to read instrs from {}", path))?;
    // <-- snip -->
}
```

```
Error: Failed to read instrs from ./path/to/instrs.json
Caused by:
    No such file or directory (os error 2)
```

Summary: `anyhow`

- `anyhow` is good for type erasure in binaries
- `anyhow` is also good for attaching dynamic context to errors

`thiserror`

`thiserror` provides a single, convenient derive macro for the standard library's `std::error::Error` trait.

```
use thiserror::Error;

#[derive(Error, Debug)]
pub enum DataStoreError {
    #[error("data store disconnected")]
    Disconnect(#[from] io::Error),
    #[error("the data for key `{0}` is not available")]
    Redaction(String),
    #[error("unknown data store error")]
    Unknown,
}
```

`thiserror`: Format Strings

```
#[derive(Error, Debug)]
pub enum Error {
    #[error("invalid rdo_lookahead_frames {0} (expected < {max})", max = i32::MAX)]
    InvalidLookahead(u32),
}
```

```
#[derive(Error, Debug)]
pub enum Error {
    #[error("first letter must be lowercase but was {:?}", first_char(.0))]
    WrongCase(String),

    #[error("invalid index {idx}, expected at least {} and at most {}",
                                                .limits.lo, .limits.hi)]
    OutOfBounds { idx: usize, limits: Limits },
}
```

`thiserror`: To and `From`

You can use `thiserror` to unify different error types!

```
#[derive(Error, Debug)]
pub enum MyError {
    Io(#[from] io::Error),
    Glob(#[from] globset::Error),
}
```

```
#[derive(Error, Debug)]
pub struct MyError {
    msg: String,
    #[source]  // optional if field name is `source`
    source: anyhow::Error,
}
```

Summary: `thiserror`

- `thiserror` is good for creating error types in libraries
- Use `thiserror` for libraries and `anyhow` for binaries
- Use `snafu` when you need both!

Aside: `snafu`

`snafu` is like a combination of both `anyhow` and `thiserror`.

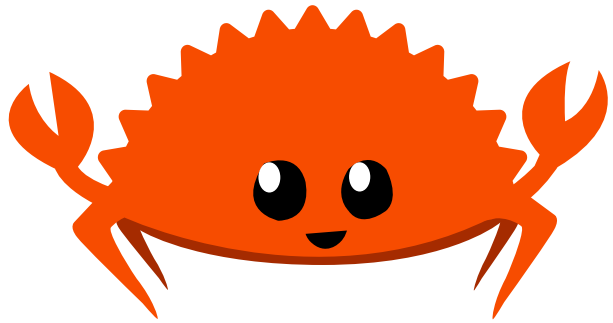
- Less mature, but picking up a lot of traction
- Look at the docs if you are interested!

Homework - Ownership Quiz

- This homework is a Gradescope Quiz!
- 30 questions from the Brown Rust Book
- Read through chapter 4 on ownership
  - Answer the quiz questions on the web page as you go through it
  - All answers will be revealed after you attempt!
- Each question is worth 5 points, so you don't need to do everything
- Focus on *understanding* rather than the questions themselves

Next Lecture: Closures and Iterators

Thanks for coming!



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