

RustViz: Interactively Visualizing Ownership and Borrowing

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Rust is a systems programming language that guarantees memory safety without the need for a garbage collector by statically tracking ownership and borrowing events. The associated rules are subtle and unique among industry programming languages, which can make learning Rust more challenging. Motivated by the challenges that Rust learners face, we are developing RustViz, a tool that allows teachers to generate an interactive timeline depicting ownership and borrowing events for each variable in a Rust code example. These visualizations are intended to help Rust learners develop an understanding of ownership and borrowing by example. This paper introduces RustViz by example, shows how teachers can use it to generate visualizations, describes learning goals, and proposes a study designed to evaluate RustViz based on these learning goals.

1 INTRODUCTION

Rust is a systems programming language that enforces a set of rules for using resources in memory with the concepts of *ownership* and *borrowing*. These rules are enforced with the compiler’s *borrow checker*, which allows Rust programs to be memory-safe without garbage collection. Instead, resources are deallocated (“dropped”, in Rust parlance) when the static lifetime of the owner ends.

Rust has been gaining traction. For five consecutive years, Rust was the “most loved” programming language in Stack Overflow’s Developer Survey [11]. In industry, Rust has notable users such as Microsoft [15], Amazon [1], Mozilla [6], Cloudflare [9], Dropbox [8], and Discord [7]. With Rust adoption increasing, improvements to Rust’s tooling ecosystem would be beneficial for developers.

While the ownership and borrowing rules ensure memory safety without the performance overhead of garbage collection, these rules also make Rust difficult to learn and Rust code difficult to reason about, even for experienced programmers. A survey of posts on various online forums found that people frequently complained about the borrow checker’s complexity [17]. In one of their interviews of professional programmers, Shrestha et al. [13] found that the borrow checker was an “alien concept” and “the biggest struggle” for an interviewee who was learning Rust. Searches on Rust forums show that “fighting the borrow checker” is a common phrase.

Motivated by the difficulties that Rust learners face, we are developing *RustViz*, a tool for creating visualizations depicting ownership and borrowing events on an interactive timeline for each variable, displayed aligned with the Rust source code. With RustViz, there are two kinds of users: *teachers* use RustViz to generate visualizations and *learners* interact with the visualizations.

We discuss RustViz from the learner’s perspective in Sec. 2. We then discuss how teachers can prepare visualizations in Sec. 3. In Sec. 4, we propose a study that we plan to conduct to evaluate the effectiveness of RustViz based on how well the visualizations help Rust learners accomplish specified learning goals. We conclude after a discussion of future and related work in Secs. 5-7.

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2 RUSTVIZ BY EXAMPLE

RustViz shows ownership and borrowing in Rust with a timeline of memory events for each variable in the source code that the teacher chooses to visualize. This timeline is displayed aligned with the corresponding source code (which itself appears inside educational material generated by the `mdbook` tool, see Sec. 3). When learners hover their cursor over parts of the timeline, Hover Messages are displayed which describe the memory events in more detail. To avoid visual clutter, we describe the key Hover Messages in the text by referring to labels in the figures. These examples are also available as interactive demos at:

<https://web.eecs.umich.edu/~comar/rustviz-hatra20/>

2.1 First Example: Moves, Copies and Drops

Fig. 1 shows a simple example that demonstrates *moves*, *copies*, and *drops*.



Fig. 1. Example visualization in RustViz with moves, copies, and drops (sublabels are only for exposition)

2.1.1 Moves. On Line 2, a `String` resource is created and bound to `s`. In Rust, each resource has a unique *owner*, and when ownership changes, it is called a *move*. In this case, `String::from` heap-allocates and returns a `String`, which moves ownership of that resource to `s` as indicated by the Arrow at (b) pointing from (a) to the Dot at (c). The hollow Line Segment at (d) indicates that `s` cannot be reassigned nor can it be used to mutate the resource (because `let` rather than `let mut` was used to introduce `s`). As learners hover their mouse over these visual elements, they see the following Hover Messages:

- (a) `String::from()` (and the corresponding function in the code is highlighted)
- (b) Move from `String::from()` to `s`
- (c) `s` acquires ownership of a resource
- (d) `s` is the owner of the resource. The binding cannot be reassigned.

On Line 3, `takes_ownership` (not shown) is called with `s` as a parameter, so the `String` resource gets moved from `s` into the function. After this move, `s` is no longer valid for use. This move is shown in RustViz with the Arrow at (f) from (e) to (g). Since `s` is no longer valid for use after the function call, there is no Line Segment in `s`'s timeline after the Dot. Some Hover Messages here are:

- (e) `s`'s resource is moved
- (f) Move from `s` to `takes_ownership()`
- (g) `takes_ownership()` (and the corresponding function in the code is highlighted)

2.1.2 Copies. On Line 4, the (immutable) integer value 5 is bound to `x`. We use `let mut` rather than `let`, so `x` can be reassigned, as indicated by the solid Line Segment at (i). The Hover Messages are:

- (h) `x` acquires ownership of a resource
- (i) `x` is the owner of the resource. The binding can be reassigned.

On Line 5, `y` is initialized with `x`. In Rust, types with stack-only data, like integers, generally have an annotation called the Copy trait. Resources of these types get *copied* rather than moved. The copy is shown in RustViz with the Arrow at **(k)** pointing from **(j)** to **(l)**. Since `x` is still valid for use, the solid Line Segment continues in `x`'s timeline at **(m)**. The Line Segment at **(n)** is hollow because we used `let` rather than `let mut` for `y`. The Hover Messages here are:

- (j)** `x`'s resource is copied
- (k)** Copy from `x` to `y`
- (l)** `y` is initialized by copy from `x`
- (m)** `x` is the owner of the resource. The binding can be reassigned.
- (n)** `y` is the owner of the resource. The binding cannot be reassigned.

On Line 6, we mutate `x`, as indicated by the Dot at **(o)** continuing to solid Line Segment **(p)**:

- (o)** `x` acquires ownership of a resource
- (p)** `x` is the owner of the resource. The binding can be reassigned.

2.1.3 Drops. The variables `s`, `x`, and `y` go out of scope at the end of the function on Line 7, as indicated by Dots **(q)**-**(s)**. Since `x` and `y` were owners, their resources are *dropped*. However, since `s`'s resource was moved earlier, no drop occurs, as indicated in the corresponding Hover Messages:

- (q)** `s` goes out of scope. No resource is dropped.
- (r)** `x` goes out of scope. Its resource is dropped.
- (s)** `y` goes out of scope. Its resource is dropped.

2.2 Second Example: Immutable and Mutable Borrows

Our second example, in Fig. 2, demonstrates *borrowing*, i.e. working with references to resources.

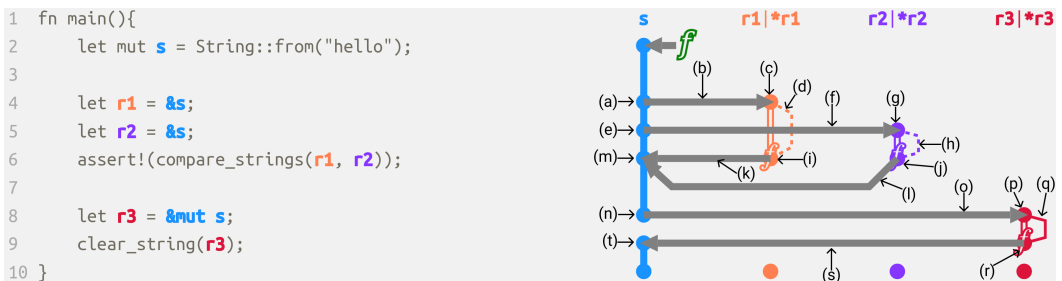


Fig. 2. Example visualization in RustViz with immutable and mutable borrows.

2.2.1 Immutable Borrows. On Line 2, a mutable `String` resource is created as described in Sec. 2.1.

On Lines 4 and 5, *immutable references* to `s` are created and assigned to `r1` and `r2`, respectively. In Rust, immutable references are created with the `&` operator rather than the `&mut` operator, and the creation of an immutable reference is called an *immutable borrow*. Resources cannot be mutated through immutable references, so it is safe for Rust's borrow checker to allow multiple immutable borrows of a resource to be live. The timelines for variables of reference type are split into two parts. The first part is the Line Segment that represents the variable itself, which is displayed in the same way as variables of other types. The second part is the curved line to the right of the Line Segment, here **(d)** and **(h)**, which represents how the borrow allows access to the resource, i.e. how `*r1` and `*r2` work as indicated in the header. The Hover Messages here are:

- (a)** `s`'s resource is immutably borrowed
- (b)** Immutable borrow from `s` to `r1`

- (c) *r1 immutably borrows a resource*
- (d) *Cannot mutate *r1*
- (e) *s's resource is immutably borrowed*
- (f) *Immutable borrow from s to r2*
- (g) *r2 immutably borrows a resource*
- (h) *Cannot mutate *r2*

On Line 6, `r1` and `r2` are passed to `compare_strings`, which is shown in RustViz by the *f* symbol on (i) and (j). `compare_strings` can read the resource through these references, but cannot mutate it. Since `r1` and `r2`'s borrows are no longer used after the function returns, the borrowed resource is returned, despite `r1` and `r2`'s lexical scope not ending. This is due to a feature in Rust called *non-lexical lifetimes*, which allows more programs to pass the borrow checker by disregarding borrows which are no longer live because they are never used again. The return of these borrows are represented by the Arrows at (k) and (l). Some Hover Messages here are:

- (i) *compare_strings() reads from r1*
- (j) *compare_strings() reads from r2*
- (k) *Return immutably borrowed resource from r1 to s*
- (l) *Return immutably borrowed resource from r2 to s*
- (m) *s's resource is no longer immutably borrowed*

2.2.2 Mutable Borrows. On Line 8, a *mutable reference* to `s`'s resource is created and assigned to `r3`. In Rust, mutable references are created with the `&mut` operator rather than the `&` operator, and the creation of a mutable reference to a resource is called a *mutable borrow*. Resources can be mutated through mutable references. To ensure memory safety, if a mutable borrow of a resource is live, no other borrow of that resource, mutable or immutable, may be live. Thanks to non-lexical lifetimes, `r3`'s borrow does not conflict with `r1` or `r2` because `r1` and `r2`'s borrows are not live. We show that `r3`'s borrow is mutable in RustViz with a Solid Line at (q). To ensure memory safety, Rust does not allow a resource to be accessed through its owner if a mutable borrow of that resource is live. Since `r3` mutably borrows `s`'s resource, we cannot access the resource through `s`, so there is no Line Segment between Lines 6 and 7. Some Hover Messages here are:

- (n) *s's resource is mutably borrowed*
- (o) *mutable borrow from s to r3*
- (p) *r3 mutably borrows a resource*
- (q) *Can mutate the resource *r3*

On Line 9, `r3` is passed to `clear_string`, and `clear_string` is able to mutate the `String` through that reference. After the function returns, the borrowed resource is returned to `s`. With the `String` resource no longer being mutably borrowed, `s`'s Line Segment in the timeline resumes. Some Hover Messages here are:

- (r) *clear_string() reads from r3*
- (s) *Return mutably borrowed resource from r3 to s*
- (t) *s's resource is no longer mutably borrowed*

At the end of the function on Line 10, `s`, `r1`, `r2`, and `r3` go out of scope. Since `s` is the owner of a resource, the resource is dropped.

2.2.3 Ownership and Borrowing for Variables of Reference Type. In Rust, variables of reference type follow ownership and borrowing rules that variables of other types do. Ownership of mutable references can be moved, while ownership of immutable references get copied, since immutable references have the `Copy` trait. Variables of reference type can be mutably and immutably borrowed.

In the above visualization, some of these subtleties are not shown. For example, on Line 6, the references of `r1` and `r2` are copied into `compare_strings` since immutable references have the Copy trait. However, we choose not to show these copies in the visualization. On Line 9, the reference of `r3` is moved into `clear_string`. Again, we choose not to show this.

The reason for this is to focus on showing the ownership and borrowing of the String resource, which is most pertinent to a learner who is just being introduced to the ownership and borrowing system. If we show every single memory event, the visualization would become too noisy and potentially distract the learner from the focus of the example. One advantage of our approach of using manually-determined memory events rather than automatic generation from source code is that the teacher can choose precisely which memory events to focus on.

3 GENERATING VISUALIZATIONS

With RustViz, teachers generate visualizations using our Rust library. The library is still a work in progress, and there are certainly improvements that can be made to the workflow of generating a visualization. In this section, we walk through a simple example of how a teacher would currently use our tool to generate the following very simple visualization:

```
fn main() {
    let s = String::from("hello");
}
```



First, the teacher creates an annotated version of the code marking variables and functions with unique hashes (the data hash is always 0 for functions). Each use of the same variable uses the same hash.

```
fn main() {
    let <tspan data-hash="1">s</tspan> =
    <tspan class="fn" data-hash="0" hash="2">String::from</tspan>("hello");
}
```

Once the annotated version of the source code is created, teachers write a visualization specification that calls RustViz library functions. In this case, the code to generate the visualization is as follows:

```
//variable s
let s = ResourceAccessPoint::Owner(Owner {
    hash: 1, name: String::from("s"), is_mut: false, lifetime_trait: LifetimeTrait::None });
//function String::from()
let from_func = ResourceAccessPoint::Function(Function {
    hash: 2, name: String::from("String::from()") });
//data structure that will contain our specified memory events
let mut vd = VisualizationData {
    timelines: BTreeMap::new(), external_events: Vec::new() };
//specify the memory events
vd.append_external_event(ExternalEvent::Move{
    from: Some(from_func), to: Some(s.clone())}, &(2 as usize));
vd.append_external_event(ExternalEvent::GoOutOfScope{ ro: s.clone() }, &(3 as usize));
//render the visualization
svg_generation::render_svg(&"04_01_01".to_owned(), &"one_var".to_owned(), &vd);
```

We first describe the variable `s`. The hash and name matches what was seen in the annotated source code. We set `is_mut` as `false` because `let` was used rather than `let mut` in the source code. We set `lifetime_trait` as `LifetimeTrait::None` because there are no moves or copies from `s` that we want to show in the visualization. If we wanted to show any moves from `s`, we would set this to `LifetimeTrait::Move`. If we wanted to show any copies from `s`, we would set this to `LifetimeTrait::Copy`. We then describe the function `String::from()`. For functions, we only need to specify the hash and name.

After the variables are described, we create the data structure that will hold the specified memory events. The first event is a move from `String::from()` to `s`, which we specify by giving where the move is from, where the move is to, and on what line the move occurs. The second event is `s` going out of scope.

Finally, we call `render_svg` which renders the visualization as an SVG. The first two arguments tell the library where to find the annotated source code and the last argument is the data structure that we added our specified memory events to. This SVG can be included in a book generated using the `mdbook` system, which is used for generating the Rust Book [10] and other Rust documentation. The SVG can be tweaked after it is generated in situations where the teacher wants more fine-grained control over the visualization.

Although somewhat complex, it is reasonably straightforward to create new visualizations given examples of existing visualizations. The benefit of manual construction is that the teacher can omit events that may not be relevant to the learning goal of the example.

4 LEARNING GOALS AND PROPOSED STUDY DESIGN

4.1 Learning Goals

To evaluate the effectiveness of RustViz as a learning tool, we plan to conduct human studies to see if RustViz measurably helps learners develop a mental model for reasoning about Rust code. To that end, we determined a set of learning goals that RustViz is intended to help learners accomplish and will be used as the evaluation criteria:

- (1) Understand concepts related to ownership in Rust
 - (a) Understand that each resource has a unique identifier called its owner
 - (b) Identify when resources are dropped
 - (c) Understand the different ways that ownership can be moved
 - (d) Understand the difference between move and copy
- (2) Understand Rust's borrowing rules
 - (a) Understand the difference between mutable and immutable borrows
 - (b) Understand how ownership and borrowing interact with each other
- (3) Understand the difference between lexical scope and non-lexical lifetimes

Notably, we avoid certain concepts such as lifetime annotations, compound data types (e.g., structs and array slices), reborrowing, and the `unsafe` keyword. The focus of RustViz is to provide learners a good introduction to the *basics* of Rust's ownership and borrowing system.

4.2 Study Format

The participants in our study will be adults who are proficient in C or C++ but have no prior exposure to Rust, screened out through self-reporting. During the study, participants will be asked to complete three tasks: the pre-survey, the interactive tutorial, and the post-survey.

In the pre-survey, participants will answer questions about their experience and familiarity with various programming languages and programming concepts.

In the interactive tutorial, participants will view a series of short readings that introduce basic Rust concepts. Following each reading, participants will answer questions related to the reading's topic, with the ability to refer back to the reading if desired. Questions may draw on concepts from a prior section. We will impose a time limit for each section that participants should be able to comfortably stay within. To measure the effect of RustViz, some participants will view readings without visualizations (the control group), while others will view readings with visualizations accompanying any example code (the treatment group). The readings will provide sufficient information to answer the questions even without visualizations.

After the interactive tutorial, participants will be prompted to complete a post-survey asking about their perceptions regarding the tool.

Due to the time constraints of a study, this setting is likely not the most conducive to learning the material. However, we would still like to conduct the study to see if there are measurable differences between those who view the visualizations and those who do not. The qualitative feedback we receive from the study may also be helpful in finding possible improvements to RustViz. Later, we plan to conduct similar studies in a longer-term classroom setting.

4.3 Interactive Tutorial

As the participants go through the interactive tutorial, we will record the time it takes for them to complete each section as well as the accuracy of their responses to the questions. By classifying questions and sections by the Rust concepts they cover (e.g., mutability, borrowing, ownership) we will be able to evaluate whether the visualization helps participants achieve the identified learning goals. In particular, we believe that decreased completion time and increased accuracy in the treatment group for questions and sections related to a specific learning goal is evidence that RustViz helps learners achieve that learning goal. One example of a question we might ask in the interactive tutorial is as follows:

Consider the following Rust program.

```
fn id(y : String) -> String {y}
fn f(x : String) -> i32 {
  println!("Hello, {}!", x);
  let z = id(x);
  println!("Goodbye, {}!", z);
  42
}
fn main() {
  println!("Welcome!");
  {
    let a = String::from("world");
    println!("Thinking...");
    let q = f(a);
    println!("The meaning of life is: {}.", q);
  }
  println!("Done.");
}
```

We would then provide the participant with the text sent to standard out and ask “*The string resource that a initially owns is dropped between which two adjacent lines of output above?*”.

As a follow up, we could ask the participant “*Describe how ownership of the string resource is moved. Your answer should take the form of a sequence of events chosen from the drop-down list. You do not need to account for calls to println! (it is a macro and does not cause a move).*”

4.4 Other Collected Data

We will also record the cursor movements of the participants, which will allow us to measure usage of the interactive features in RustViz. This data will be used to evaluate whether increased usage of the interactive features helps participants achieve the identified learning goals.

We will use the post-survey to get qualitative feedback on RustViz. One example of a question would be to ask them to rate their agreement with the statement “*The visualizations helped me develop an understanding of Rust’s borrowing rules*”, which would help us further evaluate RustViz against learning goal 2. We will also use the post-survey to collect feedback on both the visualization and the study design, so we can improve them in the future.

5 FUTURE WORK

The next step would be to conduct a pilot study as described in Sec. 4 to better understand the effectiveness of RustViz as a learning tool. If the study reveals possible improvements to RustViz, we may implement them and conduct further studies. We also plan to use RustViz in an undergraduate programming languages course during a unit on Rust. This will provide us with more data and feedback on the effectiveness of our tool.

With our current design, we did not put thought toward visualizing code that fails the borrow checker or has branch points. It may be useful to generate a visualization that shows violations of ownership and borrowing rules, as example erroneous code can be useful to learners. Furthermore, it may be useful to show learners to see how ownership and borrowing rules manifest in code with branch points. In future revisions, we may improve our design to show these situations.

Currently, RustViz generates visualizations from manually-determined memory events rather than from the source code directly. We could explore the possibility of automatic generation from source code. However, there will be challenges with scaling up the visualization for complex code with more variables, branches, moves, and borrows. Moreover, the teacher may not want to visualize everything. For these reasons, it may not be worth pursuing fully automatic generation. Instead, creating a simplified domain-specific language for manually generating the visualizations may be more helpful for teachers. Automatic generation would be most useful for practitioners who want to generate visualizations for their own code.

6 RELATED WORK

We find that there is little peer-reviewed research on visualizations to assist in reasoning about Rust’s unconventional rules despite interest in the Rust community for such tools. There do exist blog posts that mock up ideas for visualizations of Rust code. One post showcases a vertical timeline of ownership and borrowing events [12]—this design is visually similar to RustViz, except without interactivity. This blog post simply provides a mock-up of an idea, while our contribution includes a tool for creating visualizations. A different mock-up in another blog post shows a possible approach for visualizing Rust code in an editor rather than for documentation [16].

On the Rust Internals Forum, Faria [5] (username *Nashenas88*) started a thread to discuss ideas for visualizing ownership and borrowing within an editor. The thread contains various ideas for such a visualization from Faria and others. Notably, Faria was able to create a working prototype of lifetime visualization in Atom that is generated directly from Rust source code. This approach works automatically from source code for use in an editor, while our tool works from manually-determined memory events for use in documentation. Furthermore, this prototype shows the information by highlighting or outlining relevant source code, rather than using a timeline approach. The prototype is no longer being maintained, and it is unclear what the direction of the project is.

For their bachelor thesis, Dominik [4] created an algorithm that identifies lifetime constraints and the code that generates the constraints from information extracted from the Rust compiler, including the Polonius borrow checker. Dominik also shows a visualization of the lifetime constraints as a directed graph, though it is quite complex. Blaser [2] builds on this work for their bachelor thesis by developing a tool that can explain lifetime errors in code given the lifetime constraints. Blaser also created an extension for Visual Studio Code that can show a graph-based visualization of the lifetime constraints that is simpler than Dominik’s. As an alternative to the graph-based visualization, Blaser’s Visual Studio Code extension can show a text-based explanation of lifetime errors in Rust code. The focus of Blaser’s tool seems to be to help programmers reason about lifetime-related errors in their code through editor integrations, while our focus is on generating visualizations in documentation for use in a teaching setting.

Outside of Rust, there are many visualization systems developed to teach beginners about program behavior, and Sorva et al. [14] published an extensive review of such systems. There are also tutoring systems for teaching programming, some of which include visualizations. Crow et al. [3] created a review of a number of these systems and identified those that have visualizations.

7 CONCLUSION

In this paper, we introduced RustViz, the tool we are developing to generate visualizations of ownership and borrowing in Rust programs from manually-provided memory events. These visualizations are designed to be displayed alongside example code in documentation to help Rust learners develop a basic understanding of Rust's ownership and borrowing rules. We showcased our current visual design by walking through a couple of examples, showed how RustViz is used to generate the visualizations, described learning goals that RustViz is being designed to help learners accomplish, and described the design of the pilot study we plan to conduct as an initial evaluation of our tool. Our belief is that RustViz can improve the learning outcomes of Rust learners, and the next step is to conduct a pilot study to better understand the effectiveness of the tool.

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