Project 1: The DEET Debugger

In this project, you'll implement the DEET debugger (Dodgy Eliminator of Errors and Tragedies) to get the deets on those pesky bugs in your code.

This project will give you practice with multiprocessing in Rust, and will give you a better sense of how processes are managed by the operating system as well as how `ptrace` can be used to circumvent process boundaries. While DEET is simpler and less powerful than GDB, you'll experience the mechanics that all debuggers are based on. We welcome you to add your own features to build the debugger that *you* would want to use!

This is a big and complex project that will synthesize everything you've learned so far. Please ask questions on slack if anything is unclear or if you're feeling stuck/confused!

Logistics

This project is due on **Tuesday, May 19 at 11:59PM pacific time**.

You may work with a partner if you would like. You can find partners in the #project-1 partner thread on Slack.

If you would be interested in working on a different project, let us know! This is a small class and we would love to support your individual interests.

Finally, please let us know if you run into any problems. It's still very easy to get tripped up by Rust syntax and mechanics, and there are some nontrivial concepts at play here as well. We are here to help!

Working with a partner

If you work with a partner, only one person should submit. You should add a comment to the top of `main.rs` including both partners' names and sunet IDs (Stanford usernames). Message us on Slack and we can add your partner to your Github repository (or vice versa).

We *strongly, strongly* recommend that you do *not* simply split up the milestones below, but rather work together through all the work. This project is sufficiently complex that both of you need to understand all the parts involved, and we think you will benefit the most if you work closely with your partner to figure out how to solve problems and structure your code instead of working separately. If at all possible, try working together synchronously over an audio or video call.

Git is the industry-standard tool for collaborating on a codebase. Using it to collaborate is more difficult than using it as a sole developer (you'll need to learn how to avoid and resolve merge conflicts when two people edit the same code at the same time). However, if you take time to learn how to use git properly, that experience will benefit you for years to come! Again, message us and we can add your partner to your Github repository (or vice versa).

However, git is mostly oriented for teams where people are working on different parts of a codebase. Using it to collaborate on the same parts of the code at the same time can be difficult, because doing so creates merge conflicts (you edit `Debugger`, your partner edits `Debugger`, and then you try to sync your changes and `git` doesn't know what to do with the two sets of changes). From my experience, the best way to collaborate synchronously is to use an editor plugin that implements Google Docs-style sharing. Here are some that I found from a quick Google search:

- VSCode: Live Share looks really, really awesome.
- Floobits has plugins for IntelliJ, Sublime, Atom, and others. You can get free private workspaces by using an education account.
- CodeTogether is one I haven't heard of before, but they're offering all features for free during the COVID-19 pandemic. May be worth checking out if you don't like the other options.
- TeamHub looks similar, but it looks like it's in beta and you'd need to request an invite.

Tips for working with git

- A merge conflict happens when two people change the same part of a file (e.g. the same function). It won't happen if you make a change at the top of file A and your partner makes a change at the bottom of file A. If possible, coordinate changes with your partner so that you aren't touching the same code at the same time.
  - That said, if a merge conflict happens, it's not the end of the world. Merge conflicts are common, and there are great tools built for resolving them.
- Make frequent, small commits. A gigantic commit is very likely to create merge conflicts! Also, if you break something, it's easier to go back and fix it if you've been making incremental commits along the way. You can always merge small commits into bigger ones, but you can't easily split large commits into smaller ones.
- Write good commit messages. Not only will this help your partner understand the changes you made, but it will also help in resolving merge conflicts, since you can

more quickly understand what changes are conflicting. Here's an article about commit message style.

- Push and pull often. It's always a nightmare when two people independently make a large number of changes, then attempt to push and are forced to resolve a stack of 15 commits.
- Say you have made some commits, and your partner just pushed their commits to the server. You won't be able to push your commits until you pull their commits and reconcile them with your changes. If you run `git pull`, `git` will download their commits and attempt to merge them with yours. If successful, it will commit a new "merge commit" that merges the two sets of changes. However, if you do this often, your git history will end up cluttered with merge commits. I prefer to run `git pull --rebase`, which downloads your partner's changes, then re-commits your changes *on top of them*. It avoids creating merge commits in the history.
- Branches are a useful feature of git that allow contributors to establish separate "threads of development" in a codebase. However, since this project is small and since the milestones should be completed in order, we recommend against using branches here. If you're curious (you will inevitably encounter branches in the future), this article gives a good summary, and this website has a great interactive visualization of how branches work.

Getting set up

The starter code is available on GitHub here.

We recommend using a Linux system for development on this project. Unfortunately, the interface of `ptrace` differs between Linux and BSD (e.g. Mac) systems, and is not available on Windows. Additionally, different systems store debugging symbols in different ways. While it is certainly possible to extend your debugger to work on multiple platforms, we will only target Linux here for simplicity.

If you're on Linux, you can stop reading and just use `cargo` as you have in previous exercises. If you're on Mac or Windows, you have two options:

- Use myth, as you did in last week's weekly exercises.
- Use Docker to run your debugger locally. Docker is a popular tool that creates consistent environments to develop/test/deploy software in. (C Playground runs each program in a Docker container!) It may take some more work to get running, but will probably be more smooth in terms of running your code.

Edit: It seems that one of the libraries we're using depends on a newer version of Rust than is installed on the myths. I've filed an IT support ticket, and hopefully Rust will be upgraded within a few days. In the meantime, however, if you would like to use `myth`, you can install a newer version of Rust like so:

```
curl --proto '=https' --tlsv1.2 -sSf https://sh.rustup.rs -o rustup.sh
chmod +x rustup.sh
./rustup.sh -y
echo "source ~/.cargo/env" >> ~/.bash_profile
source ~/.cargo/env
```

If you run `cargo --version`, you should see `cargo 1.43.0 (3532cf738 2020-03-17)` or newer.

Installing Docker

On Mac, you can download and install Docker here. Easy peasy.

On Windows, there are a few ways to install:

- The primary Windows installer is here. However, I've read reports that this will enable HyperV, which will prevent you from using VirtualBox. If that's something you use, then you should not use this option.
- Docker Toolbox is an older version of Docker that runs on VirtualBox (from my understanding). If you use VirtualBox, this may be worth a shot.
- If you use WSL, there is an experimental version of Docker that runs in WSL and will probably be much smoother once stable. You can read about it here.

I'm sorry this is so complicated :(Docker is such a widely-used tool in industry, and it's quite sad to see such poor Windows support. If you're short on time, just run on myth, but if you give this a shot, let me know how it goes.

Building the Docker image

`cd` into the `deet/` directory, and then run `docker build`:

```
docker build -t deet .
```

This will build an `deet` *image* containing dependencies needed to run your program. This might take a while. (In our case, the dependencies are just a barebones version of Ubuntu, `cargo`, and `make`.)

Once you build this image, you won't need to do it again!

Running cargo

Once the image is built, you can run your code. Here's a pretty long incantation that runs `cargo build` in your Docker image:

```
docker run --rm -it \
    -v "${PWD}":/deet -v "${PWD}/.cargo":/.cargo \
    -u $(id -u ${USER}):$(id -g ${USER}) \
    deet \
    cargo build
```

Since this is rather long and complex, we included a mini script that does the `docker run` part for you. You can run it like this:

```
./container cargo build
./container cargo run
```

You can edit code locally on your machine using whatever editor you like and run the `./container` command to run your code. No need to upload or sync your files anywhere.

You can also run other things within the container. For example, you can run make and gdb:

```
./container make
./container gdb samples/function_calls
```

Milestone 0: Read the starter code

This is the first large project in CS 110L, and it may be one of your first times working with a more substantial codebase.

There are a few files you should be aware of:

- `main.rs` is a short file that serves as the entrypoint for the program. You won't need to make any changes here.
- `debugger.rs` contains the code that implements the command-line interface for DEET. You'll be making a lot of changes here.
- `debugger_command.rs` contains some code for parsing commands that are typed into DEET. Any time you add a new command, you'll need to add code here.
- `inferior.rs` contains code to manage child processes being run by the debugger. As you add features that involve controlling the program being debugged, you will need to add code here.
- `dwarf_data.rs` contains a series of helper functions for extracting debugging symbols (e.g. line numbers, variable names, function names) from the executable being debugged. You won't need to make any changes here, but you will need to use these functions in Milestone 3.
- `gimli_wrapper.rs` contains functions that are used to read debugging symbols from a binary file. It is messy code patched together from several Gimli examples; please don't read it :) (unless you plan to do an extension and need to collect more information from the dwarf file)

In addition, we have provided a series of sample programs that you can use to test your debugger. These programs are written in C and are in the `samples/` directory, although we'd like to note that you could use DEET to debug Rust programs as well!

You should run `make` (or `./container make` if you're using Docker) to compile the sample programs before proceeding.

Milestone 1: Run the inferior

In this milestone, you will modify the debugger to start an *inferior*. An inferior is a process that is being traced by the debugger. (Debuggers are apparently just a tad bit narcissistic!)

Currently, code in `debugger_command` and `debugger` extracts arguments from the `r` command and passes them to `Inferior::new`:

```
🍌 ./container cargo run samples/sleepy_print
   Compiling deet v0.1.0 (/deet)
    Finished dev [unoptimized + debuginfo] target(s) in 13.41s
     Running `target/debug/deet samples/sleepy_print`
(deet) r 3
Inferior::new not implemented! target=samples/sleepy_print, args=["3"]
Error starting subprocess
(deet)
```

Your first job is to implement `Inferior::new` to spawn a child process running our target program. This child process should have debugging enabled; similar to what you did in the trace portion of the CS 110 assignment 3, you'll need to call `ptrace` with `PTRACE_TRACEME` after the child process `fork()`s but before `exec` is called.

In `Inferior::new`, you should do the following things:

- Create a Command to `spawn` the target program with the provided arguments.
- Before calling `spawn()` on the command, use `pre_exec` to call `child_traceme` in the child process. See Tuesday's lecture slides for example usage of `pre_exec`. Note that you must `use std::os::unix::process::CommandExt;` in order to use `pre_exec`.
- When a process that has `PTRACE_TRACEME` enabled calls `exec`, the operating system will load the specified program into the process, and then (before the new program starts running) it will pause the process using `SIGTRAP`. You should call `waitpid` on the child process to verify that it stops with signal `SIGTRAP`, in order to verify that everything is in working order (if this check fails, simply return `None`). You are welcome to call `waitpid` directly, or to use the `Inferior::wait` method that we have provided.
- Once you have verified that the child process seems to be in working order, you can construct an `Inferior` and return it!

As mentioned, `PTRACE_TRACEME` causes programs to start in a stopped state. Once you are constructing `Inferior` objects, you'll need a way to start program execution.

We would recommend implementing a "continue" method on `Inferior` (you can't call it `continue`, since that's a reserved keyword) that wakes up the inferior and waits until it stops or terminates. To wake up the inferior, you can use `ptrace::cont` (pass `None` for `sig`), and to wait, you can use `self.wait(None)`. Our continue method returns `Result<Status, nix::Error>` in order to pass on the resulting program status and any errors to the caller. (We use `?` syntax to simplify error handling.)

You'll need to update `Debugger::run` to call this continue method after it constructs an `Inferior`. You should use the status returned from your continue method to print a message about the status of the inferior.

Expected outcomes:

- You can start inferiors and pass arguments using the `run` command
- When an inferior stops or terminates, the debugger should print a message (e.g. *Child exited (status 0)*)
- You can run a program multiple times within a debugging session

Example output:

```
🍌 ./container cargo run samples/sleepy_print
    Finished dev [unoptimized + debuginfo] target(s) in 1.94s
     Running `target/debug/deet samples/sleepy_print`
(deet) r 3
0
1
2
Child exited (status 0)
(deet) r 3
0
1
2
Child exited (status 0)
(deet)
```

Milestone 2: Stopping, resuming, and restarting the inferior

Sometimes, when a process deadlocks, it is helpful to temporarily stop it, poke around (e.g. print a backtrace to see where it is deadlocked), then resume it. In this milestone, we will add the ability to pause and resume an inferior.

As it happens, our debugger already has the ability to pause an inferior. Normally, `SIGINT` will terminate a process, but if a process is being traced under `ptrace`, `SIGINT` will cause it to temporarily stop instead, as if it were sent `SIGSTOP`. (The same is true for all signals that typically terminate a process. This is useful for debugging: if a program segfaults but is being traced under ptrace, the program will stop instead of terminating so that you can get a backtrace and inspect its memory.) You can try this out: run `samples/sleepy_print` under your debugger with the argument `5`. Press `ctrl+c`, and the program will stop.

Now, we need a way to resume a stopped process. Let's add a `continue` command, similar to the one GDB has.

To add a command, you'll need to add an enum variant to `DebuggerCommand` in `debugger_command.rs`, and you'll need to update `DebuggerCommand::from_tokens` to return your new variant when `c`, `cont`, or `continue` are typed in DEET. Then, update `Debugger::run` to continue the inferior when the `continue` command is typed. (You can use your continue method from the previous milestone!) Your `continue` command should print the status of the inferior when it stops or terminates next, similar to the `run` command.

```
🍌 ./container cargo run samples/sleepy_print
    Finished dev [unoptimized + debuginfo] target(s) in 2.56s
     Running `target/debug/deet samples/sleepy_print`
(deet) run 5
0
1
^CChild stopped (signal SIGINT)
(deet) cont
2
3
^CChild stopped (signal SIGINT)
(deet) cont
4
Child exited (status 0)
(deet)
```

Note that there are some edge cases you should handle: What happens if you type `continue` before you type `run`? Your implementation should check whether an inferior is running, and print an error message if there is not one running.

Also, what happens when you pause an inferior using `ctrl+c`, then type `run`? You should take care to kill any existing inferiors before starting new ones, so that there is only one inferior at a time. You can use `Child::kill` to kill a process, and then you'll need to reap the killed process. (We added an `Inferior::kill` method and called this from `Debugger::run`, although you are not required to do so.)

Similarly, what happens if you exit DEET while a process is paused? You should update the handling of `DebuggerCommand::Quit` to terminate the inferior if one is running.

```
(deet) run 5
0
1
^CChild stopped (signal SIGINT)
(deet) quit
Killing running inferior (pid 216)
```

If you want to test your management of child processes, use DEET to start a `sleepy_print` inferior, pause it, start a new inferior, and pause that second inferior. In a separate terminal, run `ps aux | grep sleepy_print` (or `docker exec deet ps aux | grep sleepy_print` if you are using docker). There should only be one `samples/sleepy_print` process. If you see multiple, or you see a `<defunct>` entry, then you are not killing or reaping child processes properly.

```
🍌 ./container cargo run samples/sleepy_print
   Compiling deet v0.1.0 (/deet)
    Finished dev [unoptimized + debuginfo] target(s) in 29.80s
     Running `target/debug/deet samples/sleepy_print`
(deet) run 5
0
1
^CChild stopped (signal SIGINT)
(deet) run 5
Killing running inferior (pid 204)
0
1
^CChild stopped (signal SIGINT)
(deet)
```

```
🍌 docker exec deet ps aux | grep sleepy_print
501          1  0.6  0.2  16292  4448 pts/0    Ss+  10:29   0:00 target/debug/dee
501        210  0.0  0.0   4504   704 pts/0    t+   10:29   0:00 samples/sleepy_p
```

Expected outcomes:

- You can pause an inferior using `ctrl+c`.
- You can resume an inferior using `continue`.
- Inferiors can be paused/resumed several times.
- The status of the inferior is printed whenever it stops/terminates.

- At most one inferior process exists at any time. No zombie processes!
- Any running inferior is terminated when the debugger quits.

Milestone 3: Printing a backtrace

In this milestone, you'll implement code to print a stack trace for a paused program.

Define a new `DebuggerCommand` that is returned when the user types `bt`, `back`, or `backtrace`. For starters, define a method `print_backtrace(&self) -> Result<(), nix::Error>` in `Inferior` that prints "hello world," and call this method when the user types a backtrace command. Test this out to ensure that your debugger is able to read and process the `backtrace` command.

Once you have done this, let's move onto implementing `print_backtrace`.

As a first step, let's print out the value of the `%rip` register. This value is the address of the instruction in the text segment that we are executing. You can use [`ptrace::getregs`] to get the inferior's register values. Use `println!("{:#x}", ...)` to print the register value in hexadecimal. Note that you may see a different value than us depending on the machine you are compiling on.

```
🍌 ./container cargo run samples/segfault
    Finished dev [unoptimized + debuginfo] target(s) in 2.61s
     Running `target/debug/deet samples/segfault`
(deet) run
Calling func2
About to segfault... a=2
Child stopped (signal SIGSEGV)
(deet) back
%rip register: 0x400560
(deet)
```

Great, we're printing something! But this isn't very meaningful. In order to be useful, a backtrace should show function names and line numbers so that a programmer can see which parts of their program is running. However, a running executable is comprised only of assembly instructions and has no awareness of function names or line numbers. In order to print such information, we need to read extra *debugging symbols* that are stored within an executable compiled for debugging. This debugging information stores mappings between addresses and line numbers, functions, variables, and more. With this information, we can find where variables are stored in memory or figure out what line is being executed based on the value of the processor's instruction pointer.

On many platforms, debugging symbols are stored in a format called DWARF and embedded inside the executable file. In developing this assignment, we discovered that

DWARF is extremely complicated, and there are not yet any good high-level DWARF parsers in Rust. In order to avoid subjecting you to the same pain we went through, we have provided you with some functions in `dwarf_data.rs` that you can use in your debugger implementation.

To use these functions, you should first add these two lines to `main.rs`:

```
mod dwarf_data;
mod gimli_wrapper;
```

Then, in `debugger.rs`, `use crate::dwarf_data::{DwarfData, Error as DwarfError}`, and at the beginning of `Debugger::new`, load the target executable file:

```
let debug_data = match DwarfData::from_file(target) {
    Ok(val) => val,
    Err(DwarfError::ErrorOpeningFile) => {
        println!("Could not open file {}", target);
        std::process::exit(1);
    }
    Err(DwarfError::DwarfFormatError(err)) => {
        println!("Could not debugging symbols from {}: {:?}", target, err);
        std::process::exit(1);
    }
};
```

You should store `debug_data` inside the `Debugger` struct. Then, in `Debugger::run`, pass `debug_data` to your `print_backtrace` method.

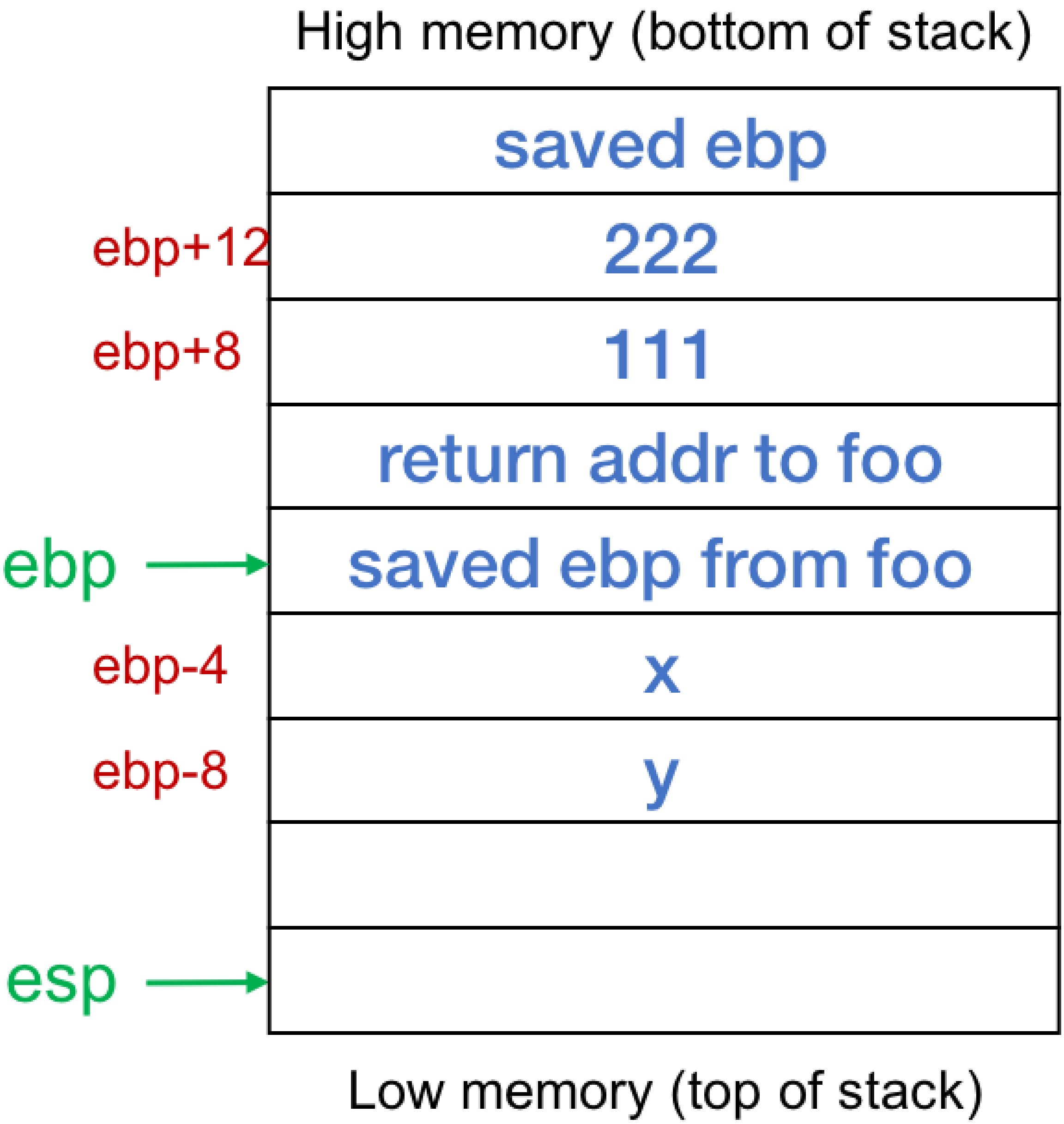
Let's update `print_backtrace` to be more helpful. Armed with your `%rip` value, use `DwarfData::get_line_from_addr` to get the file name and line number corresponding to the current instruction, and use `DwarfData::get_function_from_addr` to get the function name. Print out this information, and you will have the start of something useful:

```
👾 ./container cargo run samples/segfault
    Finished dev [unoptimized + debuginfo] target(s) in 2.43s
     Running `target/debug/deet samples/segfault`
(deet) r
Calling func2
About to segfault... a=2
Child stopped (signal SIGSEGV)
(deet) back
func2 (/deet/samples/segfault.c:5)
(deet)
```

Amazing!

To get the rest of the stack frames in the backtrace, we need to understand a little bit about how the stack is laid out.

This article contains some good explanation of how stack frames work:



A stack frame is bounded by two registers: the value in `%rbp` is the address of the top of the current stack frame, and the value in `%rsp` is the address of the bottom of the current stack frame (`%ebp` and `%esp` refers to the lower 32 bits of the registers but you'll be dealing with `%rbp` and `%rsp` respectively instead).

If we want to get to the previous stack frame, we can read the memory pointed to by `%rbp`, and that will tell us what `%rbp` was for the previous stack frame (i.e. the value we get is the address of the top of the previous stack frame). We could read that address to get the top of the stack frame before that one, and so on.

You may be thinking, *okay, so we can get stack frames, but how does that help us identify which function was running?* Notice that the return address is stored 8 bytes above the saved `%rbp` value. This return address is effectively `%rip` (the instruction pointer) for the previous stack frame.

As such, we can implement a backtrace like this:

```
instruction_ptr = %rip
base_ptr = %rbp
while true:
    print function/line number for instruction_ptr
    if function == "main":
        break
    instruction_ptr = read memory at base_ptr + 8
    base_ptr = read memory at base_ptr
}
```

To read memory, you can use `ptrace::read`:

```
rbp = ptrace::read(self.pid(), rbp as ptrace::AddressType)? as usize;
```

When this is done, you should be able to print a full backtrace:

```
👾 ./container cargo run samples/segfault
    Finished dev [unoptimized + debuginfo] target(s) in 2.43s
     Running `target/debug/deet samples/segfault`
(deet) r
Calling func2
About to segfault... a=2
Child stopped (signal SIGSEGV)
Stopped at /deet/samples/segfault.c:5
(deet) back
func2 (/deet/samples/segfault.c:5)
func1 (/deet/samples/segfault.c:12)
main (/deet/samples/segfault.c:15)
(deet)
```

Milestone 4: Print stopped location

When an inferior stops, GDB prints the file/line number that it stopped at. This is extremely helpful when dealing with breakpoints and step debugging, which we will tackle in the next few milestones.

You may have noticed that `Status::Stopped` includes a `usize` containing the value of `%rip` for the stopped process. Modify your `Debugger` implementation such that when the inferior stops, if line number information is available from `DwarfData::get_line_from_addr`, DEET prints the line number where the program stopped. If you're up for it, you can print the function name as well!

```
🍌 ./container cargo run samples/segfault
    Finished dev [unoptimized + debuginfo] target(s) in 2.07s
     Running `target/debug/deet samples/segfault`
(deet) r
Calling func2
About to segfault... a=2
Child stopped (signal SIGSEGV)
Stopped at /deet/samples/segfault.c:5
(deet)
```

Milestone 5: Setting breakpoints

In this milestone, we'll allow a user to set a breakpoint at a specific memory address using a command like `break *0x123456` (or `b *0x123456` for short).

First, update `DebuggerCommand` and `Debugger` to parse a `break` command. We recommend storing a simple `String` target in the `DebuggerCommand` enum variant, and then do more sophisticated parsing (e.g. ensure the target string starts with `*`, and extract the address as a `usize` from the string) in `Debugger`. This is because in Milestone 6, you will be updating this code to take different kinds of breakpoints, e.g. breakpoints on function names or line numbers.

You may use this code to parse a `usize` from a hexadecimal string:

```
fn parse_address(addr: &str) -> Option<usize> {
    let addr_without_0x = if addr.to_lowercase().starts_with("0x") {
        &addr[2..]
    } else {
        &addr
    };
    usize::from_str_radix(addr_without_0x, 16).ok()
}
```

Note that users should be able to set breakpoints before any inferior is running. (If you make them run the inferior first, it will likely exit before they are able to set breakpoints.) As such, you should store set breakpoints in a `Vec<usize>` in the `Debugger` struct. When a user types `break *0x123456`, you should add `0x123456` to the list of set breakpoints.

```
(deet) b *0x123456
Set breakpoint 0 at 0x123456
```

Our implementation prints out a confirmation message along with a breakpoint number, but this is not required.

When creating an `Inferior`, you should pass `Inferior::new` a list of breakpoints. In `Inferior::new`, after you wait for `SIGTRAP` (indicating that the inferior has fully loaded) but before returning, you should install these breakpoints in the child process.

How does one set a breakpoint on a process? The answer is more hacky than you might expect, yet this is exactly how GDB works. To set a breakpoint on the instruction at `0x123456`, simply use ptrace to write to the child process's memory, replacing the byte at `0x123456` with the value `0xcc`. This corresponds to the `INT` ("interrupt") instruction; any process that runs this instruction is temporarily halted.

This is simple in concept but slightly challenging in practice because `ptrace` does not support writing single bytes to a child's memory. In order to write a byte, you must read a full 8 bytes into a `long`, use bitwise arithmetic to substitute the desired byte into that `long`, and then write the full `long` back to the child's memory. Additionally, despite the `nix` crate's `ptrace` having a much nicer interface than the `ptrace` syscall, it's still a bit funky to use (it requires some bizarre type conversions). As such, we would rather you not spend time on trying to figure out how to do this. You may use the following code:

```
use std::mem::size_of;

fn align_addr_to_word(addr: usize) -> usize {
    addr & (-(size_of::<usize>() as isize) as usize)
}

impl Inferior {
    fn write_byte(&mut self, addr: usize, val: u8) -> Result<u8, nix::Error> {
        let aligned_addr = align_addr_to_word(addr);
        let byte_offset = addr - aligned_addr;
        let word = ptrace::read(self.pid(), aligned_addr as ptrace::AddressType)?
        let orig_byte = (word >> 8 * byte_offset) & 0xff;
        let masked_word = word & !(0xff << 8 * byte_offset);
        let updated_word = masked_word | ((val as u64) << 8 * byte_offset);
        ptrace::write(
            self.pid(),
            aligned_addr as ptrace::AddressType,
            updated_word as *mut std::ffi::c_void,
        )?;
```

```
        Ok(orig_byte as u8)
    }
}
```

You can test this by modifying `Debugger::new` to call `debug_data.print()`. This will print out a list of locations in the loaded binary. You can set a breakpoint on one of these locations, and the program should stop there with a `SIGTRAP`. For example, below, I set a breakpoint at the beginning of `func2` (where the segfault is triggered), which happens to be at `0x400537` for my particular compiler. When I run the program, it does not segfault (since the breakpoint was before the line that causes the segfault), and DEET prints that it stopped on line 3.

```
👾 ./container cargo run samples/segfault
   Compiling deet v0.1.0 (/deet)
    Finished dev [unoptimized + debuginfo] target(s) in 30.75s
     Running `target/debug/deet samples/segfault`
------
samples/segfault.c
------
Global variables:
Functions:
  * main (declared on line 14, located at 0x4005b4, 21 bytes long)
  * func1 (declared on line 9, located at 0x400571, 67 bytes long)
    * Variable: a (int, located at FramePointerOffset(-20), declared at line 9)
  * func2 (declared on line 3, located at 0x400537, 58 bytes long)
    * Variable: a (int, located at FramePointerOffset(-20), declared at line 3)
Line numbers:
  * 3 (at 0x400537)
  * 4 (at 0x400542)
  * 5 (at 0x400558)
  * 6 (at 0x400562)
  * 7 (at 0x40056e)
  * 9 (at 0x400571)
  * 10 (at 0x40057c)
  * 11 (at 0x400588)
  * 12 (at 0x4005b1)
  * 14 (at 0x4005b4)
  * 15 (at 0x4005b8)
  * 16 (at 0x4005c7)
(deet) break *0x400537
Set breakpoint 0 at 0x400537
(deet) r
```

```
Calling func2
Child stopped (signal SIGTRAP)
Stopped at /deet/samples/segfault.c:3
(deet)
```

Expected outcomes:

- Users should be able to use `break *addr` to set breakpoints before an inferior starts running
- When the inferior starts running, `0xcc` should be written to the address of each breakpoint
- Users should be able to use `break *addr` even after an inferior has started running (e.g. you should be able to ctrl+c on a sleeping program and set a breakpoint).

Milestone 6: Continuing from breakpoints

Continuing from a breakpoint is as simple and as hacky as setting a breakpoint was.

When we have "hit a breakpoint," the inferior has executed the `0xcc` INT instruction, causing the inferior to pause (due to `SIGTRAP`). However, the `0xcc` instruction *overwrote* the first byte of a valid instruction in the program. If we continue execution from after `0xcc`, we will have skipped a legitimate instruction. Worse, many instructions are multiple bytes long. If we set a breakpoint on a multi-byte instruction and continue execution as is, the CPU will attempt to interpret the second byte of the instruction as a new, separate instruction. It's likely the program will crash due to a segfault or illegal instruction error.

In order to continue from a breakpoint, we need to replace `0xcc` with the original instruction's value. Then, we need to rewind the instruction pointer (`%rip`) so that it points at the beginning of the original instruction (instead of pointing one byte in).

After doing this, we can resume execution. However, our breakpoint is no longer in the code, since we have swapped `0xcc` for the real instruction. If we had set a breakpoint in a loop or in a function that is called multiple times, this is not ideal!

This problem is addressed with yet another hack. After replacing `0xcc` with the original instruction's first byte, we tell ptrace to continue the inferior to the *next instruction* (instead of completely resuming execution). Then, once the inferior has executed the full instruction, we replace it with `0xcc` again to restore the breakpoint. Finally, we call `ptrace::cont` as usual to resume execution.

Here is pseudocode to implement these strategies in a "continue" method. I have reordered the above to make it slightly easier to implement, but the substance is the same:

```
if inferior is stopped at a breakpoint:
    ptrace::step to go to next instruction
```

```
    wait for inferior to stop due to SIGTRAP
        (if the inferior terminates here, then you should return that status and
        not go any further in this pseudocode)
    restore 0xcc in the breakpoint location

ptrace::cont to resume normal execution
wait for inferior to stop or terminate

if inferior stopped at a breakpoint (i.e. (%rip - 1) matches a breakpoint address
    restore the first byte of the instruction we replaced
    set %rip = %rip - 1 to rewind the instruction pointer
```

Evidently, to do this, you'll need to keep track of the breakpoints that are installed, as well as the instructions they replaced. You can do this however you like. We maintain a `HashMap<usize, Breakpoint>` mapping breakpoint addresses to `Breakpoint` structs:

```
#[derive(Clone)]
struct Breakpoint {
    addr: usize,
    orig_byte: u8,
}
```

Expected outcomes:

- Users should be able to set breakpoints at instructions and continue onwards from them

As an example, here I run `samples/segfault`, setting initial breakpoints on lines 15 and 10, then (after running the inferior and hitting the first breakpoint) adding another breakpoint at line 5. You can see that I hit each of the three breakpoints before the program eventually segfaults.

```
🍌 ./container cargo run samples/segfault
    Finished dev [unoptimized + debuginfo] target(s) in 2.04s
     Running `target/debug/deet samples/segfault`
------
samples/segfault.c
------
Global variables:
Functions:
  * main (declared on line 14, located at 0x4005b4, 21 bytes long)
  * func1 (declared on line 9, located at 0x400571, 67 bytes long)
    * Variable: a (int, located at FramePointerOffset(-20), declared at line 9)
```

```
  * func2 (declared on line 3, located at 0x400537, 58 bytes long)
    * Variable: a (int, located at FramePointerOffset(-20), declared at line 3)
Line numbers:
  * 3 (at 0x400537)
  * 4 (at 0x400542)
  * 5 (at 0x400558)
  * 6 (at 0x400562)
  * 7 (at 0x40056e)
  * 9 (at 0x400571)
  * 10 (at 0x40057c)
  * 11 (at 0x400588)
  * 12 (at 0x4005b1)
  * 14 (at 0x4005b4)
  * 15 (at 0x4005b8)
  * 16 (at 0x4005c7)
(deet) break *0x4005b8
Set breakpoint 0 at 0x4005b8
(deet) break *0x40057c
Set breakpoint 1 at 0x40057c
(deet) r
Child stopped (signal SIGTRAP)
Stopped at /deet/samples/segfault.c:15
(deet) break *0x400558
Set breakpoint 2 at 0x400558
(deet) cont
Child stopped (signal SIGTRAP)
Stopped at /deet/samples/segfault.c:10
(deet) cont
Calling func2
About to segfault... a=2
Child stopped (signal SIGTRAP)
Stopped at /deet/samples/segfault.c:5
(deet) cont
Child stopped (signal SIGSEGV)
Stopped at /deet/samples/segfault.c:5
(deet)
```

Milestone 7: Setting breakpoints on symbols

As a finishing touch, modify your implementation of `Debugger` to allow setting breakpoints on line numbers and functions in addition to raw addresses.

If the specified breakpoint target starts with `*`, set a breakpoint on a raw address as you did in the previous two milestones. If the target parses as a `usize` without error, treat it as a line number. Finally, if a function exists whose name matches the specified target, set a breakpoint at that function. You should print an error message if none of these cases succeed.

You can use `DwarfData::get_addr_for_line` and `DwarfData::get_addr_for_function` to translate a line number or function name into an address. (You can pass `None` as the first argument to each function, unless you feel like supporting GDB's syntax that allows for setting a breakpoint on a line in a specific file.) Then, you can simply use your code from the previous milestones to set a breakpoint at an address.

```
🍌 ./container cargo run samples/segfault
   Compiling deet v0.1.0 (/deet)
    Finished dev [unoptimized + debuginfo] target(s) in 26.91s
     Running `target/debug/deet samples/segfault`
(deet) break 15
Set breakpoint 0 at 0x4005b8
(deet) break func1
Set breakpoint 1 at 0x400575
(deet) break func2
Set breakpoint 2 at 0x40053b
(deet) r
Child stopped (signal SIGTRAP)
Stopped at /deet/samples/segfault.c:15
(deet) c
Child stopped (signal SIGTRAP)
Stopped at /deet/samples/segfault.c:9
(deet) c
Calling func2
Child stopped (signal SIGTRAP)
Stopped at /deet/samples/segfault.c:3
(deet) c
About to segfault... a=2
Child stopped (signal SIGSEGV)
Stopped at /deet/samples/segfault.c:5
(deet)
```

Voilà! You have a functional debugger ready to knock the socks off of any GDB user!

We hope you enjoyed the process of working through this and are proud of what you've built! It may not be the fanciest debugger in town, but you've implemented the foundation that all debuggers are built on. Hopefully this also gives you some respect for systems tooling – this was a lot of work, and there's a lot going on here!

Optional extensions

Next line

To implement something like GDB's "next" command, you can add a single-step method to `Inferior` that steps forward by one instruction (being careful to manage breakpoints properly). Then, you can call this method in a loop until you end up on a different line, or until the inferior terminates.

Print source code on stop

Each time the inferior stops, in addition to showing a line number, GDB prints the line of source code that the inferior stopped on. This is extremely helpful when step debugging. It's not too difficult to implement: since you know the file path and line number, you can read the file and print the appropriate text from it.

Print variables

You may have noticed that we populated `DwarfData` with a list of variables in each function. Using this information, you can implement something like GDB's `print` command to inspect the contents of variables.