Leveraging Rust in seL4 Userspace

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TCCoE Summit
May 9th, 2024

Rust

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Rust (again)

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Rust

Enforces memory safety using compile-time analysis, without the overhead of a heavyweight language runtime

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Rust

Enforces memory safety, without the overhead of a heavyweight language runtime, using compile-time analysis

```
fn main() {
    let r;

    {
        let x = 5;
        r = &x;
    }

    println!("r: {}", r);
}
```

```
error[E0597]: `x` does not live long enough
 --> src/main.rs:6:13
  |
6 |         r = &x;
  |             ^^ borrowed value does not live long enough
7 |     }
  |     - `x` dropped here while still borrowed
8 |
9 |     println!("r: {}", r);
  |                        - borrow later used here
```


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Rust

Enforces memory safety, without the overhead of a heavyweight language runtime, using compile-time analysis

Aims to provide “zero cost abstractions”

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Rust

Enforces memory safety, without the overhead of a heavyweight language runtime, using compile-time analysis

Aims to provide “zero cost abstractions”

Suitable for use cases from embedded to server, from OS kernel to application

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Rust

Linux now supports Rust in the kernel (merged October 3rd, 2022)[1,2]

[PATCH v9 00/27] Rust support

From: Miguel Ojeda <ojeda-AT-kernel.org>
To: Linus Torvalds <torvalds-AT-linux-foundation.org>, Greg Kroah-Hartman <gregkh-AT-linuxfoundation.org>
Subject: [PATCH v9 00/27] Rust support
Date: Fri, 05 Aug 2022 17:41:45 +0200
Message-ID: <20220805154231.31257-1-ojeda@kernel.org>
Cc: rust-for-linux-AT-vger.kernel.org, linux-kernel-AT-vger.kernel.org, linux-fsdevel-AT-vger.kernel.org, patches-AT-lists.linux.dev, Jarkko Sakkinen <jarkko-AT-kernel.org>, Miguel Ojeda <ojeda-AT-kernel.org>, linux-doc-AT-vger.kernel.org, linux-kbuild-AT-vger.kernel.org, linux-perf-users-AT-vger.kernel.org, live-patching-AT-vger.kernel.org

```
Rust support

This is the patch series (v9) to add support for Rust as a second
language to the Linux kernel.
```

[1]https://lwn.net/ml/linux-kernel/20220805154231.31257-1-ojeda@kernel.org/
[2]https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/commit/?id=8aebac82933ff1a7c8eede18cab11e1115e2062b

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Rust

A Rust compiler toolchain called Ferrocene is ISO 26262 and IEC 61508 qualified[1]

It's official: Ferrocene is ISO 26262 and IEC 61508 qualified!

You can even find the certificate in TÜV SÜDs certificate database.

This means we achieved qualification for the open source Ferrocene toolchain. Ferrocene 23.06.0, based on Rust 1.68, is now fully usable in safety critical environments.

[1]https://ferrous-systems.com/blog/officially-qualified-ferrocene/

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Rust is a good fit for seL4 userspace

A high level language…

- Memory safety
- Abstraction
- Developer productivity

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…even for components without access to OS services

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Rust is a good fit for seL4 userspace

A high level language…

- Memory safety
- Abstraction
- Developer productivity

…even for components without access to OS services

…even for resource-constrained systems

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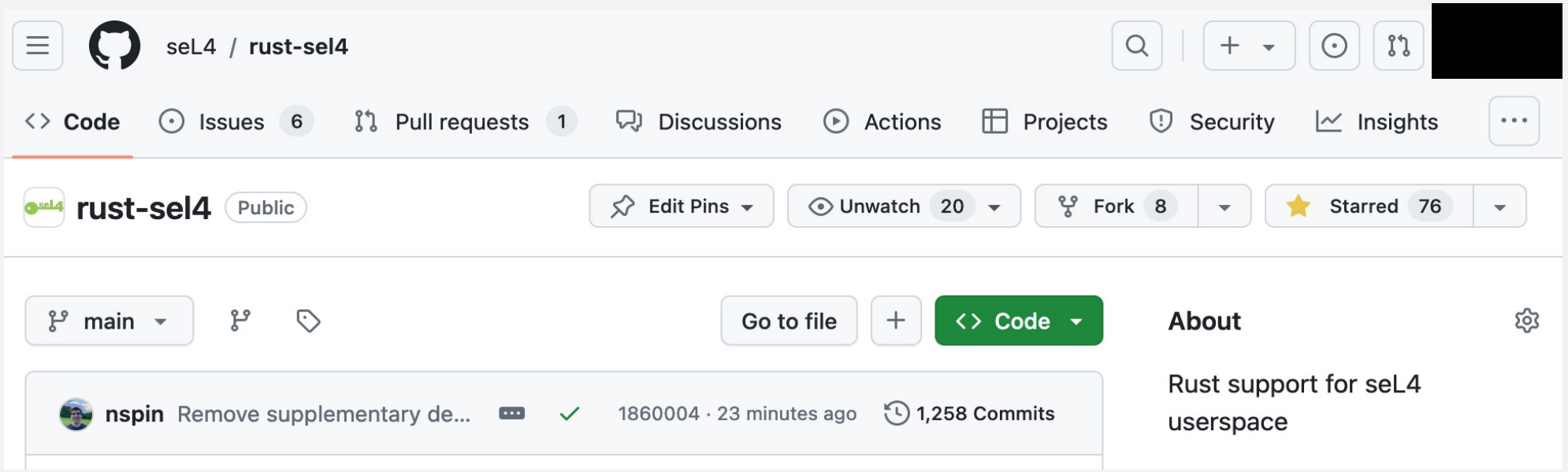
Official Rust support for seL4 userspace

Rust support for seL4 userspace has been an official seL4 Foundation project since November 2023

https://github.com/seL4/rust-sel4



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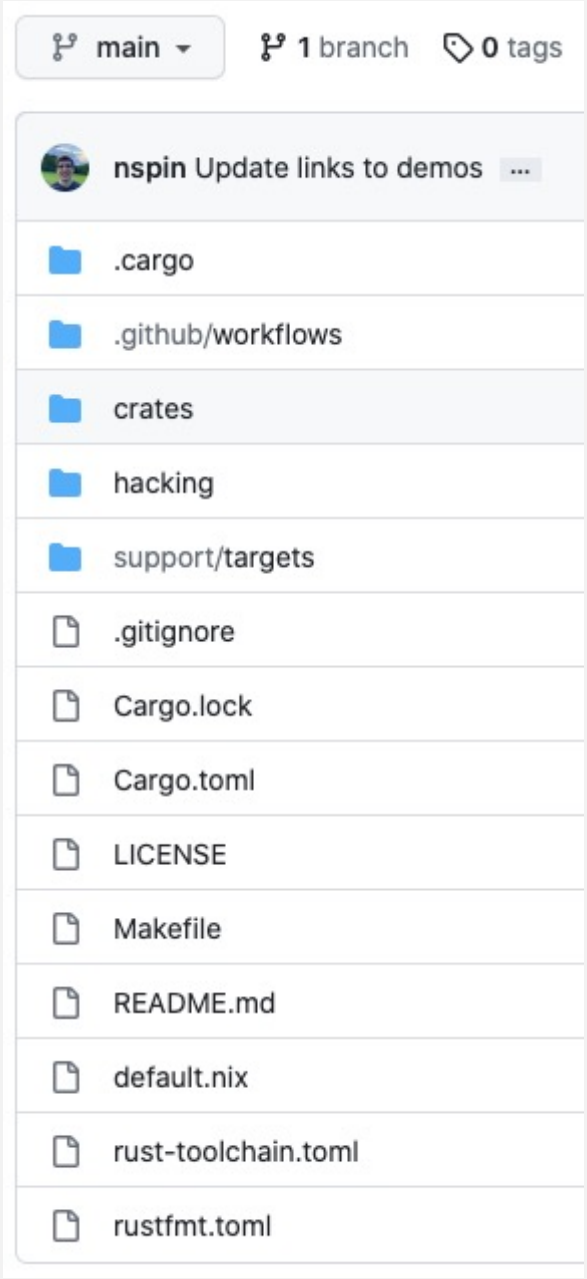
Repository contents

https://github.com/seL4/rust-sel4

- Rust libraries (aka “crates”)
  - Rust bindings for the seL4 API
  - A runtime for root tasks
  - A runtime for seL4 Microkit protection domains
  - …and many more
- General-purpose kernel loader
- CapDL-based system initializer
- Rustc target specs
- Examples
- Tests



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Why this matters

Rust helps you write correct code

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Why this matters

Rust helps you write correct code

…efficiently

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Example: HTTP server using seL4 Microkit

https://github.com/seL4/rust-microkit-http-server-demo

```
LDR|INFO: jumping to kernel
Bootstrapping kernel
Warning: Could not infer GIC interrupt target ID, assuming 0.
available phys memory regions: 1
  [40000000..80000000]
reserved virt address space regions: 3
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  [ffffff8040243000..ffffff8041575000]
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Booting all finished, dropped to user space
MON|INFO: Microkit Bootstrap
MON|INFO: bootinfo untyped list matches expected list
MON|INFO: Number of bootstrap invocations: 0x0000000e
MON|INFO: Number of system invocations:    0x00001373
MON|INFO: completed bootstrap invocations
MON|INFO: completed system invocations
INFO  [sel4_async_network] DHCP config lost
INFO  [sel4_async_network] DHCP config acquired
INFO  [sel4_async_network] IP address: 10.0.2.15/24
INFO  [sel4_async_network] Default gateway: 10.0.2.2
INFO  [sel4_async_network] DNS server 0: 10.0.2.3
```

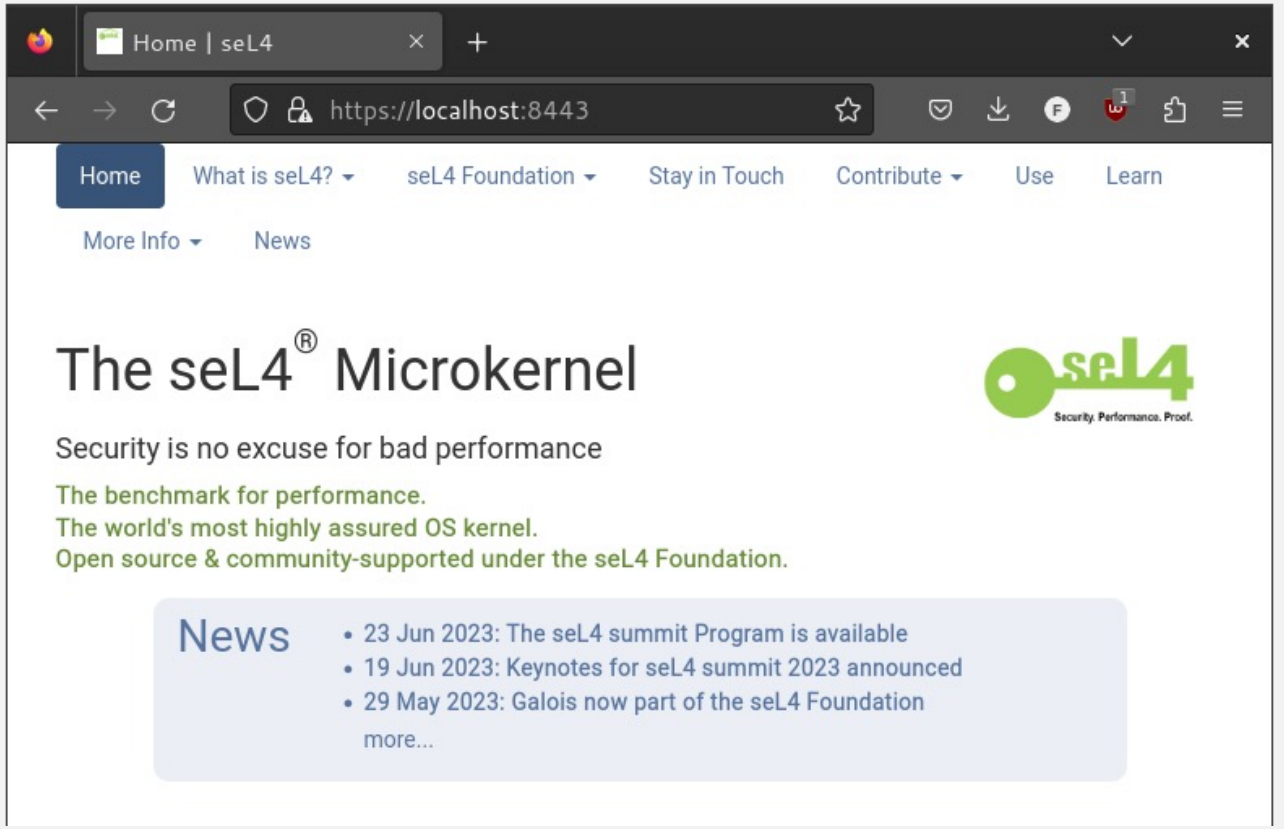

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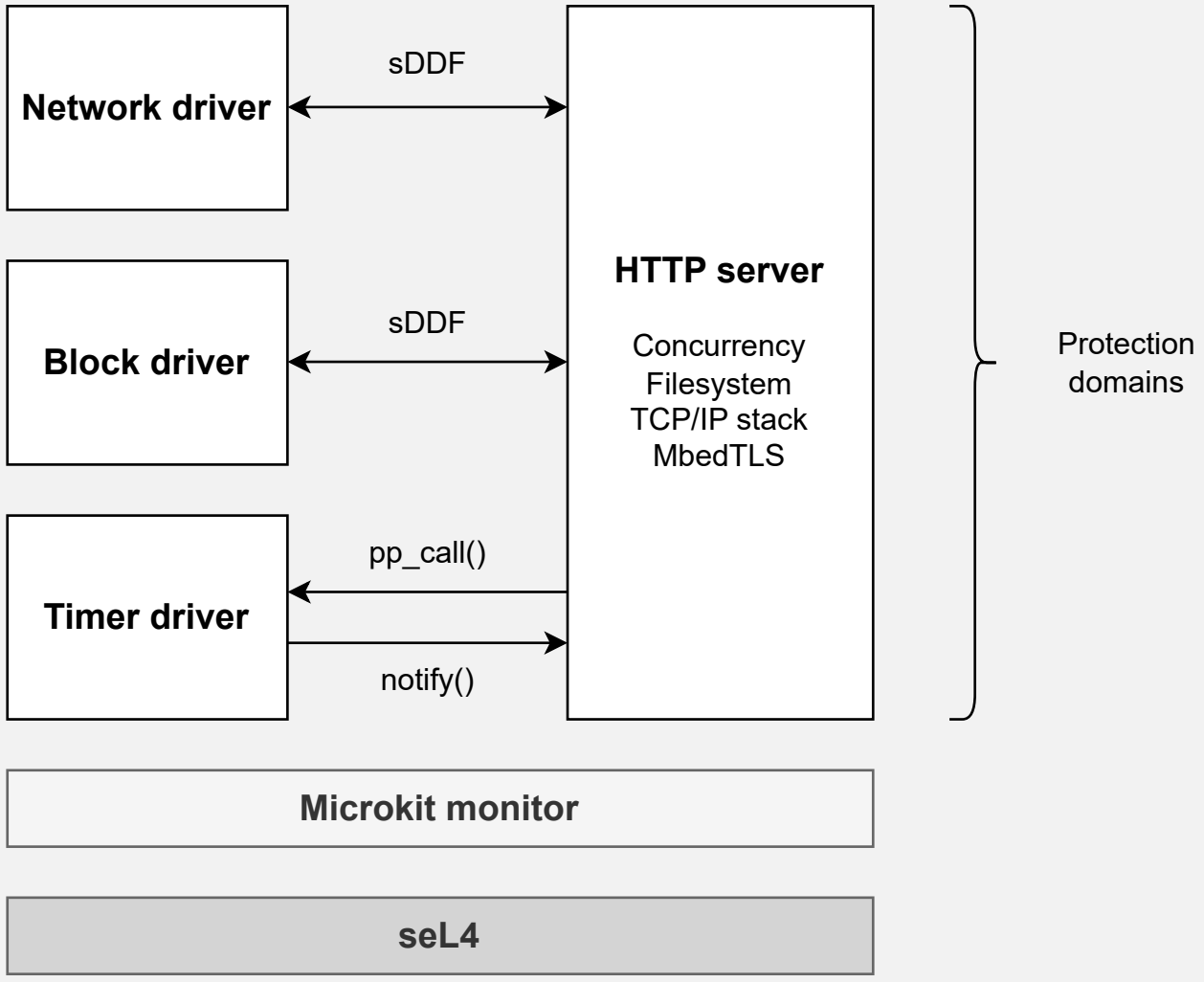

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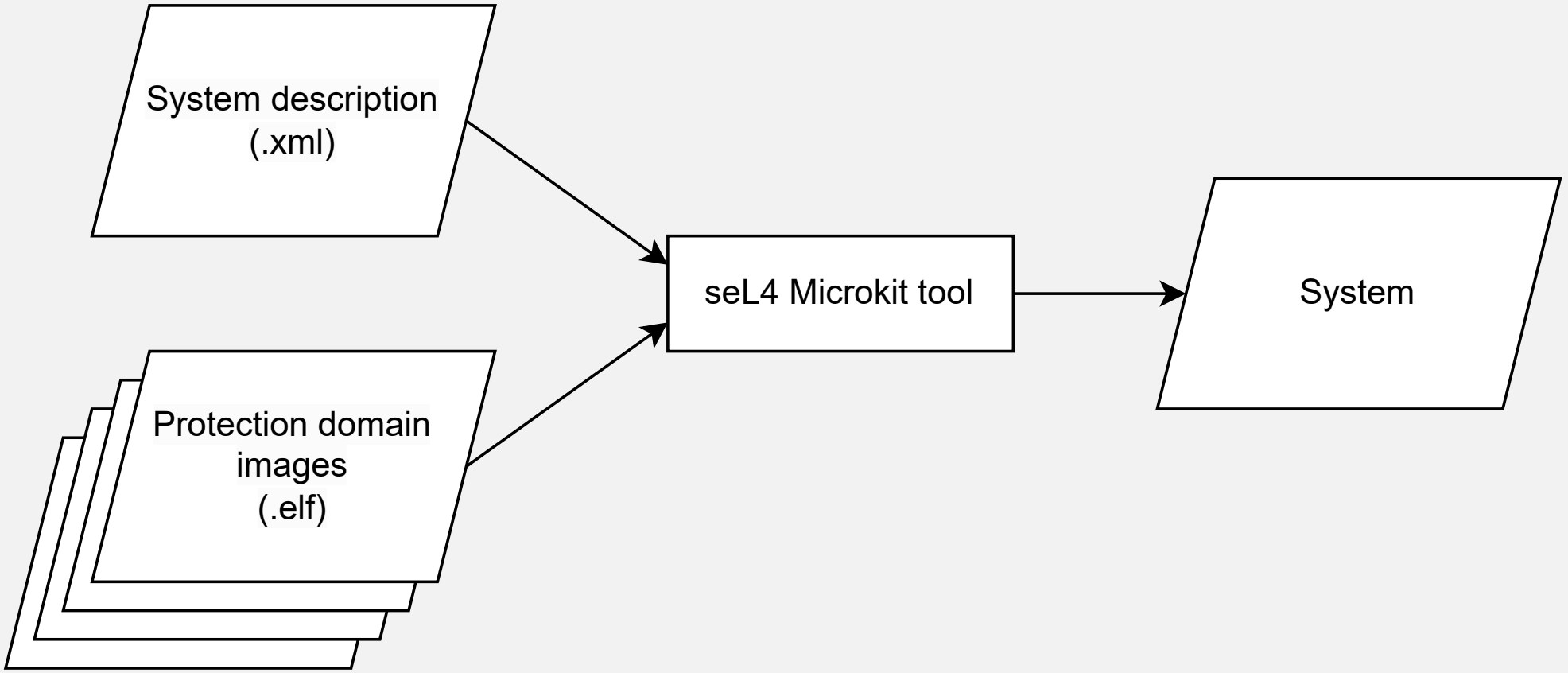

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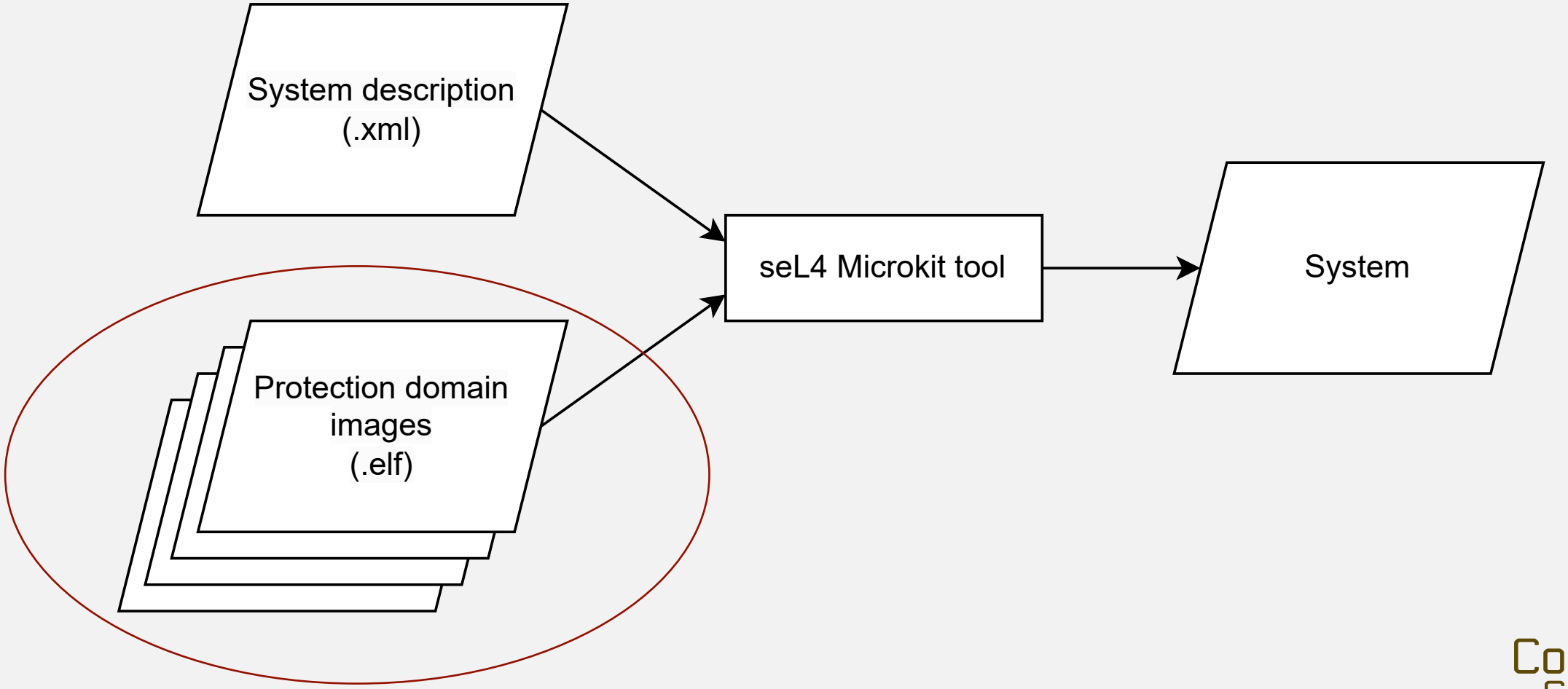

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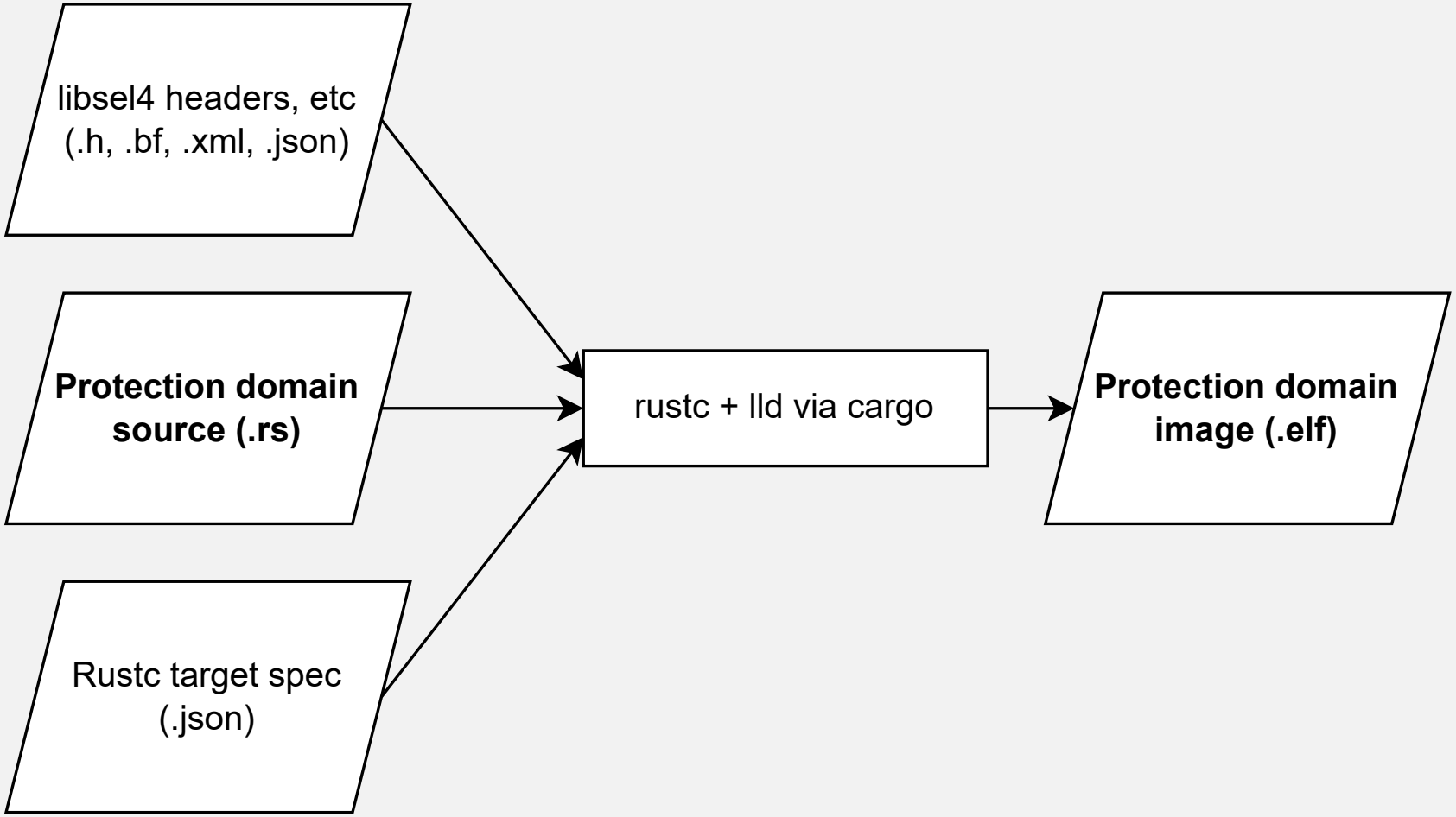

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Example: HTTP server using seL4 Microkit

https://github.com/seL4/rust-microkit-http-server-demo

```
RUST_TARGET_PATH=$(rust_target_dir) \
SEL4_INCLUDE_DIRS=$(microkit_sdk_dir)/include \
    cargo build \
        -Z build-std=core,alloc,compiler_builtins \
        -Z build-std-features=compiler-builtins-mem \
        --target aarch64-sel4
```


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Crate: `sel4-sys`

Low-level libsel4

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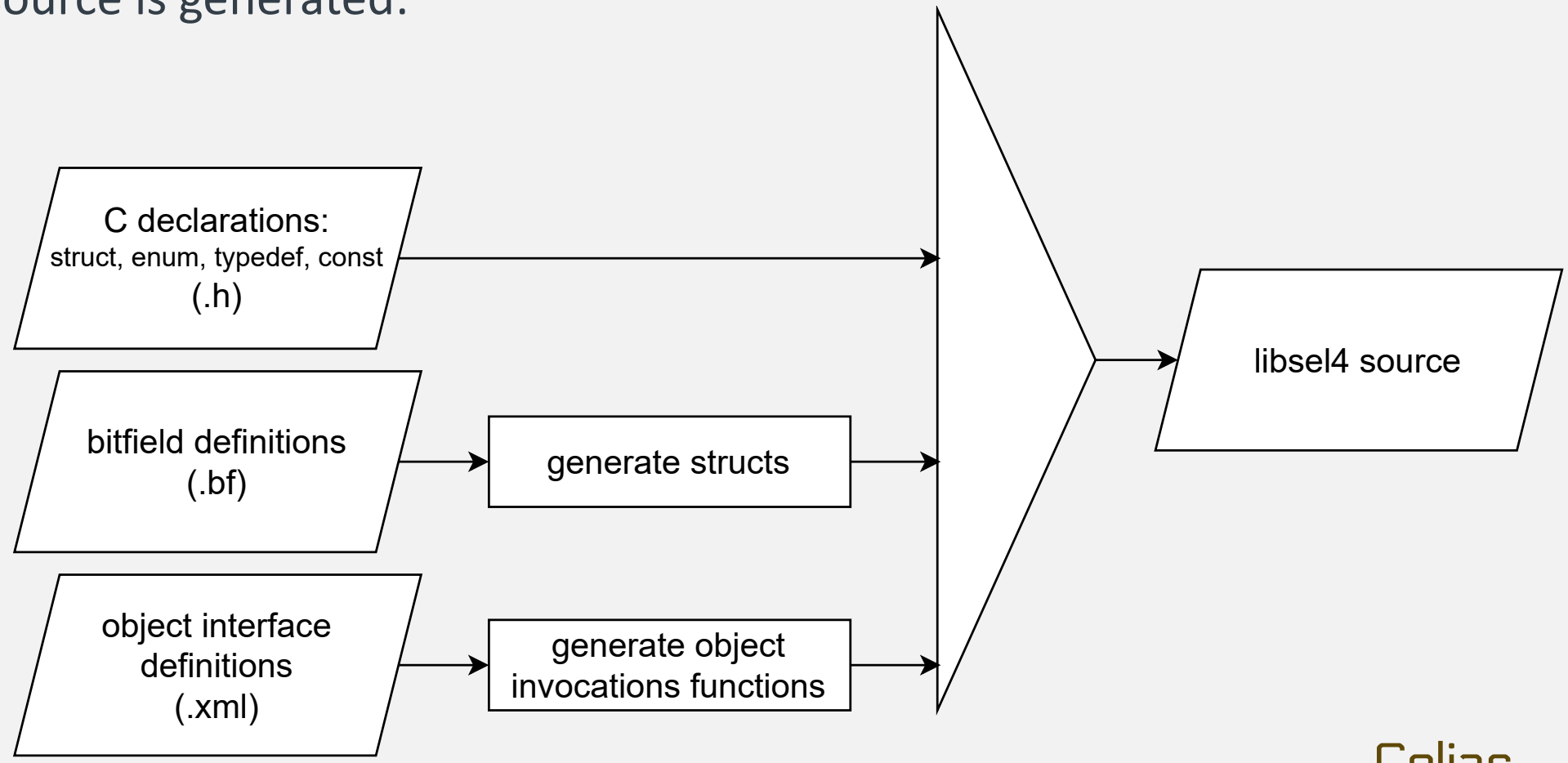
Crate: `sel4-sys`

Low-level libsel4

How the C libsel4 source is generated:



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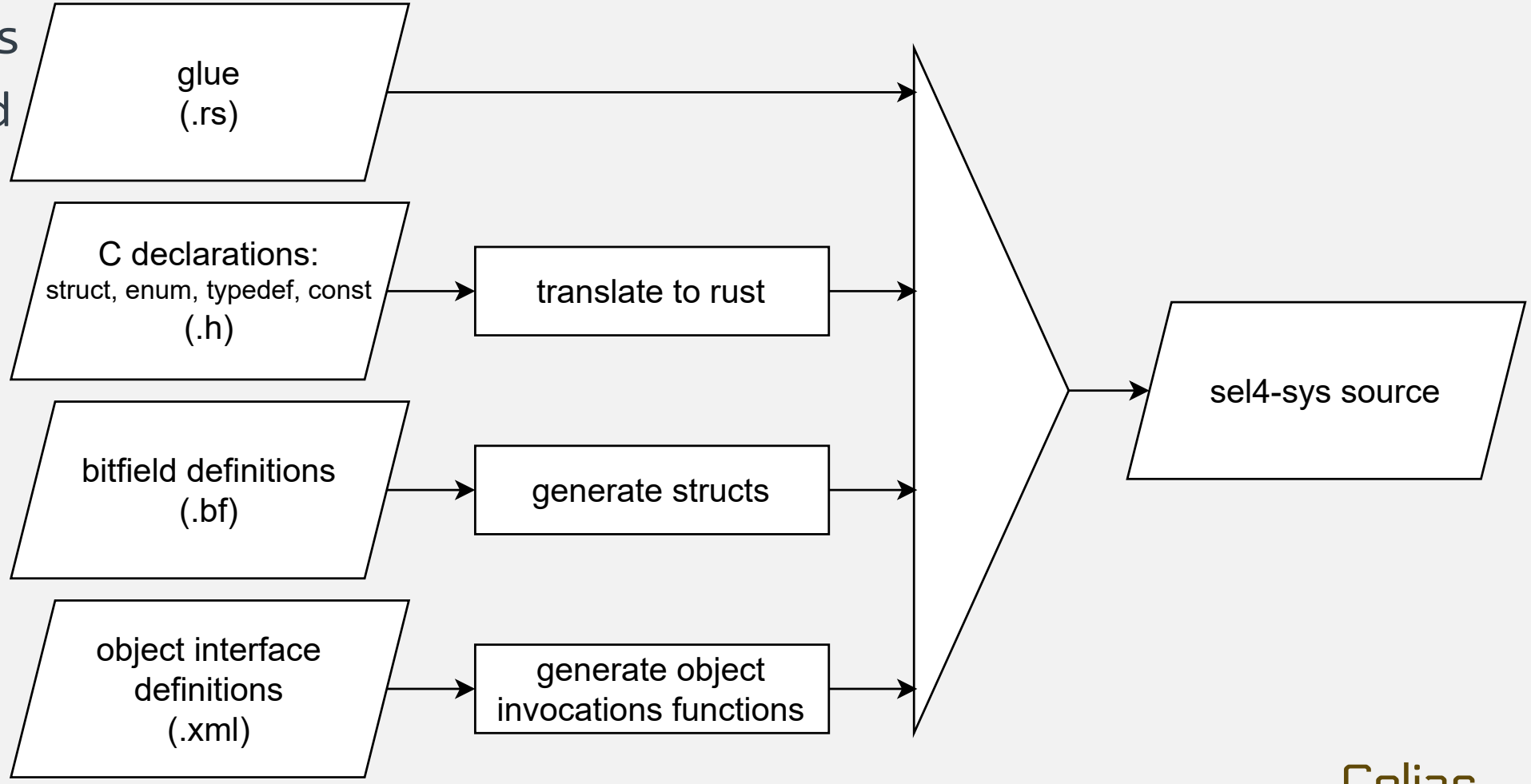
Crate: `sel4-sys`

Low-level libsel4

How the `sel4-sys` source is generated



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Crate: `sel4-sys`

Low-level libsel4

- Pure Rust
- The only build-time dependency outside of Rust and libsel4 headers is libclang
- Simple to build:
  - Supply libsel4 headers (including .bf and .xml) via `$SEL4_INCLUDE_DIRS`
  - Crate `build.rs` takes care of code generation
- Does not use thread-local storage (TLS)
- Testing: masquerade as `libsel4.a` and link against `sel4test`

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Crate: `sel4`

Higher-level libsel4

The “real” Rust libsel4: wraps `sel4-sys`, leveraging the Rust type system and idioms to present a cleaner and more ergonomic API

- No additional dependencies
- TLS is optional
- Plays nicely with C libsel4

Rustdoc:

https://sel4.github.io/rust-sel4/views/aarch64-root-task/aarch64-sel4/doc/sel4/index.html

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Crate: sel4

Higher-level libsel4

```
// implicit (TLS, or global in single-threaded case)

untyped_cap.untyped_retype(
    &blueprint,
    &cnode,
    slot,
    1,
);

// explicit

untyped_cap.with(&mut ipc_buffer).untyped_retype(
    &blueprint,
    &cnode,
    slot,
    1,
);
```


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Crate: `sel4`

Higher-level libsel4

LoC for a minimal cross-platform root task with no dependencies beyond the `sel4` crate that…

…spawns a thread: <300 LoC

...spawns a task: <400 LoC

…maps and drives a serial device: <300 LoC

https://github.com/seL4/rust-sel4/tree/main/crates/examples/root-task

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The Rust Standard Library

Layer	Provides	Requires

`libstd`	`std::fs`
	`std::net`
	`std::thread`
	`std::process`
	Language runtime
		OS services

`liballoc`	`alloc::vec`
	`alloc::collections`
	`alloc::string`
		heap allocator

`libcore`	`core::mem`
	`core::num`
	`core::iter`
	`core::ffi`
		nothing!
		(except panic handler)

depends on

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The Rust Standard Library

Layer	Provides	Requires
#![no_std]	~~libstd~~	

	`std::fs`
	`std::net`
	`std::thread`
	`std::process`
	Language runtime
		OS services

	`liballoc`	`alloc::vec`
		`alloc::collections`
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			heap allocator

	`libcore`	`core::mem`
		`core::num`
		`core::iter`
		`core::ffi`
			nothing!
			(except panic handler)

depends on

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Language runtime

- Entrypoint: `_start` *(required)*
- Stack *(required)*
- Thread local storage *(optional)*
- Heap allocator: `#[global_allocator]` *(optional)*
- Panic handler: : `#[panic_handler]` *(required)*
- Exception handling *(optional)*

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Crate: `sel4-panicking`

Internal language runtime building block

Configurable exception handling (±TLS, ±heap)

Heavy lifting done by external dependency: `unwinding` crate

```
use sel4_panicking::catch_unwind;

let result = catch_unwind(|| {
    debug_println!("hello!");
});
assert!(result.is_ok());

let result = catch_unwind(|| {
    panic!("oh no!");
});
assert!(result.is_err())
```


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Crate: `sel4-backtrace`

Internal language runtime building block

Flexible backtrace collection for debugging

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Crate: `sel4-backtrace`

Internal language runtime building block

Defer symbolization:

```
Bootstrapping kernel
available phys memory regions: 1
  [60000000..80000000]
reserved virt address space regions: 3
  [8060000000..8060246000]
  [807e157000..807e1590a6]
  [807e15a000..8080000000]
Booting all finished, dropped to user space
collecting stack backtrace
sending stack backtrace
    0001b09a910101f0f88a0101d4d6900101a09f8b0101bce5900101a0e8900101e8e7900101c0f1900101a8ee90010180c0a9100000
```


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Crate: `sel4-backtrace`

Internal language runtime building block

Defer symbolization:

```
$ cargo run -p sel4-backtrace-cli -- -f ./result/root-task.elf
0001b09a910101f0f88a0101d4d6900101a09f8b0101bce5900101a0e8900101e8e7900101c0f1900101a8ee90010180c0a9100000
    Finished dev [unoptimized + debuginfo] target(s) in 0.15s
     Running `target/debug/sel4-symbolize-backtrace -f ./result/root-task.elf
0001b09a910101f0f88a0101d4d6900101a09f8b0101bce5900101a0e8900101e8e7900101c0f1900101a8ee90010180c0a9100000
backtrace: ./result/root-task.elf
    0:            0x244d30 - sel4_backtrace::collect
                             sel4_backtrace::BacktraceSendWithToken::collect
                             sel4_backtrace_simple::SimpleBacktracing::collect
                               at /nix/store/chv0yzjhbrih0ghvfr420qi2bph9d7pw-workspace/src/sel4-backtrace/
    1:            0x22bc70 - tests_root_task_backtrace::g
                             core::ops::function::FnMut::call_mut
                             <core::slice::iter::Iter<T> as core::iter::traits::iterator::Iterator>::for_ea
                             tests_root_task_backtrace::f
                             tests_root_task_backtrace::main::{{closure}}
                             sel4_panicking::catch_unwind::do_call
                             sel4_panicking::catch_unwind
                               at /nix/store/chv0yzjhbrih0ghvfr420qi2bph9d7pw-workspace/src/tests-root-task
    2:            0x242b54 - tests_root_task_backtrace::main
```

Crate: `sel4-backtrace`

Internal language runtime building block

Symbolize on-device:

```
Bootstrapping kernel
available phys memory regions: 1
  [60000000..80000000]
reserved virt address space regions: 3
  [8060000000..8060246000]
  [807e184000..807e1860a6]
  [807e187000..8080000000]
Booting all finished, dropped to user space
printing backtrace:
    0:            0x22b7cc - sel4_backtrace::collect_with
                             sel4_backtrace::collect
                             tests_root_task_backtrace::g
                             core::ops::function::FnMut::call_mut
                             <core::slice::iter::Iter<T> as core::iter::traits::iterator::Iterator>::for_
                             tests_root_task_backtrace::f
                             tests_root_task_backtrace::main::{{closure}}
                             sel4_panicking::catch_unwind::do_call
                             sel4_panicking::catch_unwind
```

Crate: `sel4-root-task`

Language runtime #1

Configurable (±TLS, ±heap, ±unwinding)

Glues together:

- `sel4`
- `sel4-initialize-tls`
- `sel4-panicking`
- `sel4-dlmalloc`
- …and more

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Crate: `sel4-root-task`

Language runtime #1

```rust
#![no_std]
#![no_main]
#![feature(never_type)]

use sel4_root_task::root_task;

#[root_task]
fn main(_bootinfo: &sel4::BootInfo) -> ! {
    sel4::debug_println!("Hello, World!");

    sel4::BootInfo::init_thread_tcb().tcb_suspend().unwrap();

    unreachable!()
}
```


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Crate: `sel4-microkit`

Language runtime #2

Configurable (±TLS, ±heap, ±unwinding)

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Crate: sel4-microkit

Language runtime #2

```rust
#![no_std]
#![no_main]

use sel4_microkit::{debug_println, protection_domain, Channel, Handler, MessageInfo};

#[protection_domain(stack_size = 4096 * 4, heap_size = 4096 * 12)]
fn init() -> HandlerImpl {
    debug_println!("Hello, World!");
    HandlerImpl {}
}

struct HandlerImpl {}

impl Handler for HandlerImpl {
    fn notified(&mut self, channel: Channel) -> Result<(), Self::Error> {
        todo!()
    }

    fn protected(
        &mut self,
        channel: Channel,
        msg_info: MessageInfo,
    ) -> Result<MessageInfo, Self::Error> {
        todo!()
    }
}
```

Higher-level crates

- `sel4-logging`
- `sel4-sync`
- `sel4-externally-shared`
- `sel4-shared-ring-buffer`
- `sel4-microkit-message`
- `sel4-async-*`

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Asynchronous programming in Rust

Concurrent programming model for lightweight green threads at the library level

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Asynchronous programming in Rust

Futures:

```
pub trait Future {
    type Output;

    fn poll(self: Pin<&mut Self>, cx: &mut Context<'_>) -> Poll<Self::Output>;
}

pub enum Poll<T> {
    Ready(T),
    Pending,
}
```


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Asynchronous programming in Rust

Composing futures

```
fn recv_request() -> impl Future<Request>;

fn send_response(req: &Request) -> impl Future<()>;

fn serve() -> impl Future<()> {
    recv_request.then(|req| {
        send_response(&req)
    })
}
```


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Asynchronous programming in Rust

Composing futures

```rust
fn recv_request() -> impl Future<Request>;

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fn serve() -> impl Future<()> {
    recv_request.then(|req| {
        send_response(&req)
    })
}
```

async/await

```rust
async fn recv_request() -> Request;

async fn send_response(req: &Request);

async fn serve() {
    let req = recv_request().await;
    send_response(req)
}
```


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Asynchronous programming in Rust on seL4

```rust
async fn send_response_header<U: AsyncIo>(
    &self,
    conn: &mut U,
    name: &str,
    value: &[u8],
) -> Result<(), U::Error> {
    conn.send_all(name.as_bytes()).await?;
    conn.send_all(b": ").await?;
    conn.send_all(value).await?;
    conn.send_all(b"\r\n").await?;
    Ok(())
}
```


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Asynchronous programming in Rust on seL4

```
for f in [use_socket_for_http, use_socket_for_https].map(Rc::new) {
    for _ in 0..MAX_NUM_SIMULTANEOUS_CONNECTIONS {
        spawner
            .spawn_local({
                let network_ctx = network_ctx.clone();
                let f = f.clone();
                async move {
                    loop {
                        let socket = network_ctx.new_tcp_socket();
                        f(TcpSocketWrapper::new(socket)).await;
                    }
                }
            })
            .unwrap()
    }
}
```


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Asynchronous programming in Rust on seL4

PD event handler is centered around an “executor”:

- Maintains pool of futures (i.e. green threads)
- Responds to external events by polling futures which have been woken up

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Asynchronous programming in Rust on seL4

Crates:

- `sel4-async-timer`
- `sel4-async-network`
- `sel4-async-block-io`
- `sel4-async-single-threaded-executor`

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Example: HTTP server using seL4 Microkit

https://github.com/seL4/rust-microkit-http-server-demo

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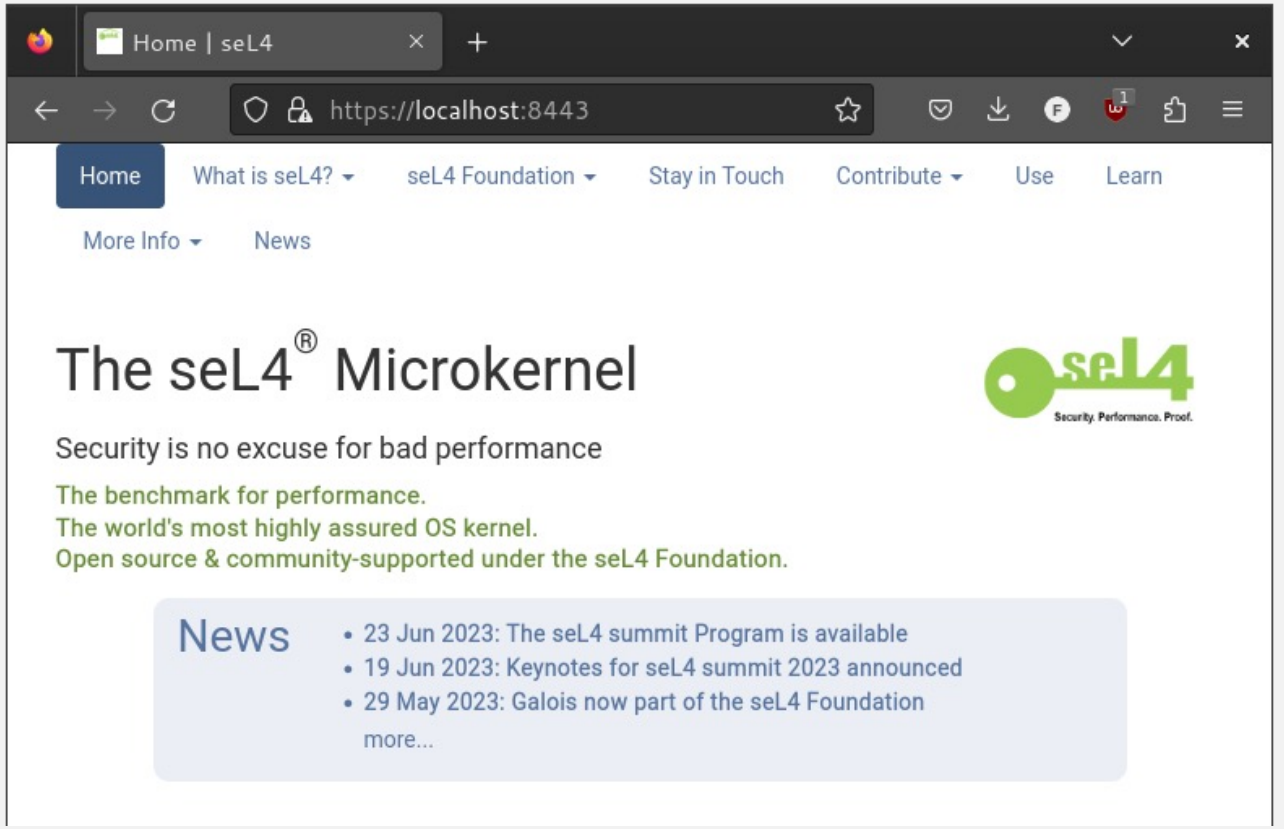

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Support

- GitHub issue tracker: https://github.com/seL4/rust-sel4/issues
- seL4 mailing list
- Me: mailto:nick@nickspinale.com or @nspin on the seL4 Mattermost

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Discussion

https://github.com/seL4/rust-sel4