cFS Applications in Rust with n2o4

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Notice

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The team:

- Abe Falcone, Principal Investigator
- Michael Betts
- Jacob Buffington
- Zachary Catlin
- Joseph Colosimo
- Timothy Emeigh
- Derek Fox
- Hannah Grzybowski
- Fredric Hancock
- Evan Jennerjahn
- Jordan Josties
- David Palmer (LANL)
- Lukas Stone
- Ian Thornton
- Mitchell Wages
- Daniel Washington
- Michael Zugger
- *and several alumni*

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- *and several alumni*

Presenting Thursday morning!

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The team:

(Note: latest available group photo, with a slightly different set of people)

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Context: the BlackCAT mission

Astronomy... *IN SPACE!*

BlackCAT

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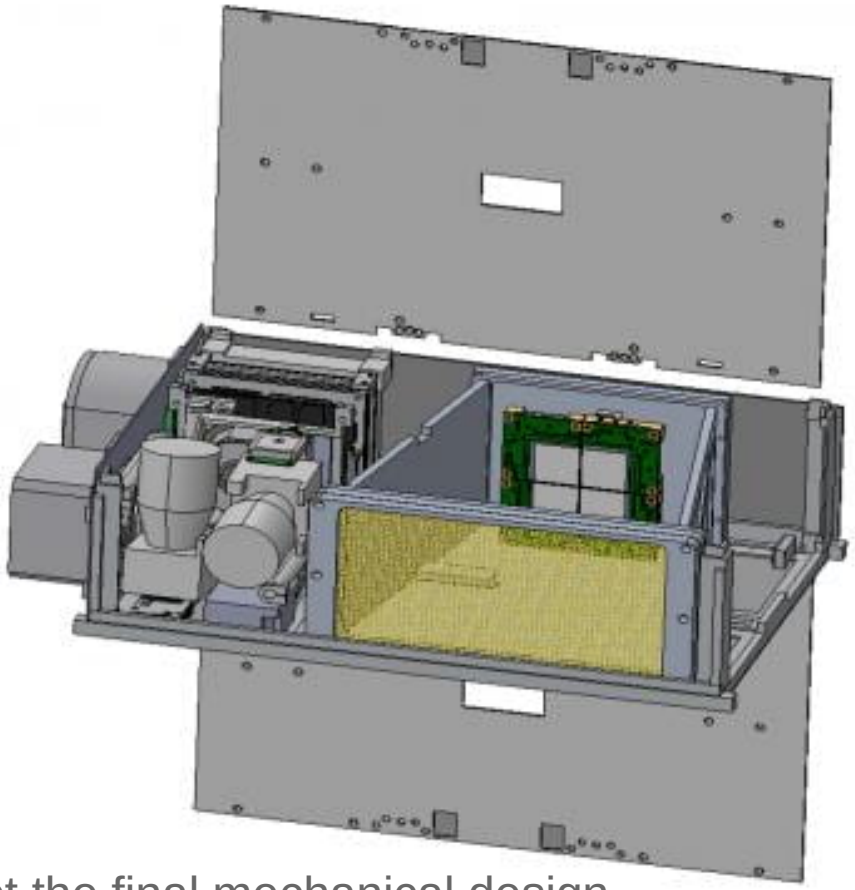
BlackCAT

- Soft X-ray coded aperture telescope using novel hybrid CMOS detectors
- Detects and localizes astronomical transients in the ~0.3–20 keV band for rapid follow-up by other facilities
- ~1 sr field of view, pointed anti-sun
- Sole payload on a 6U CubeSat in a ~550-km sun-synchronous orbit
- Expected launch date: late 2024



Note: not the final mechanical design, but should be close

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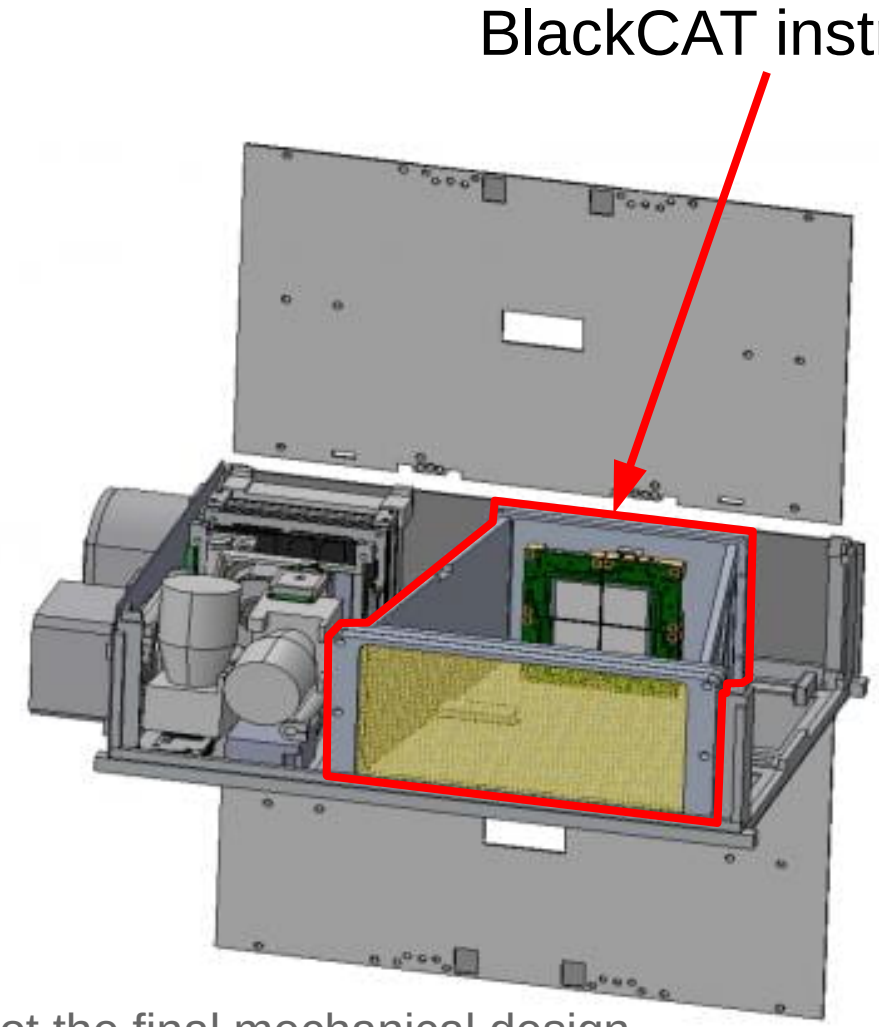

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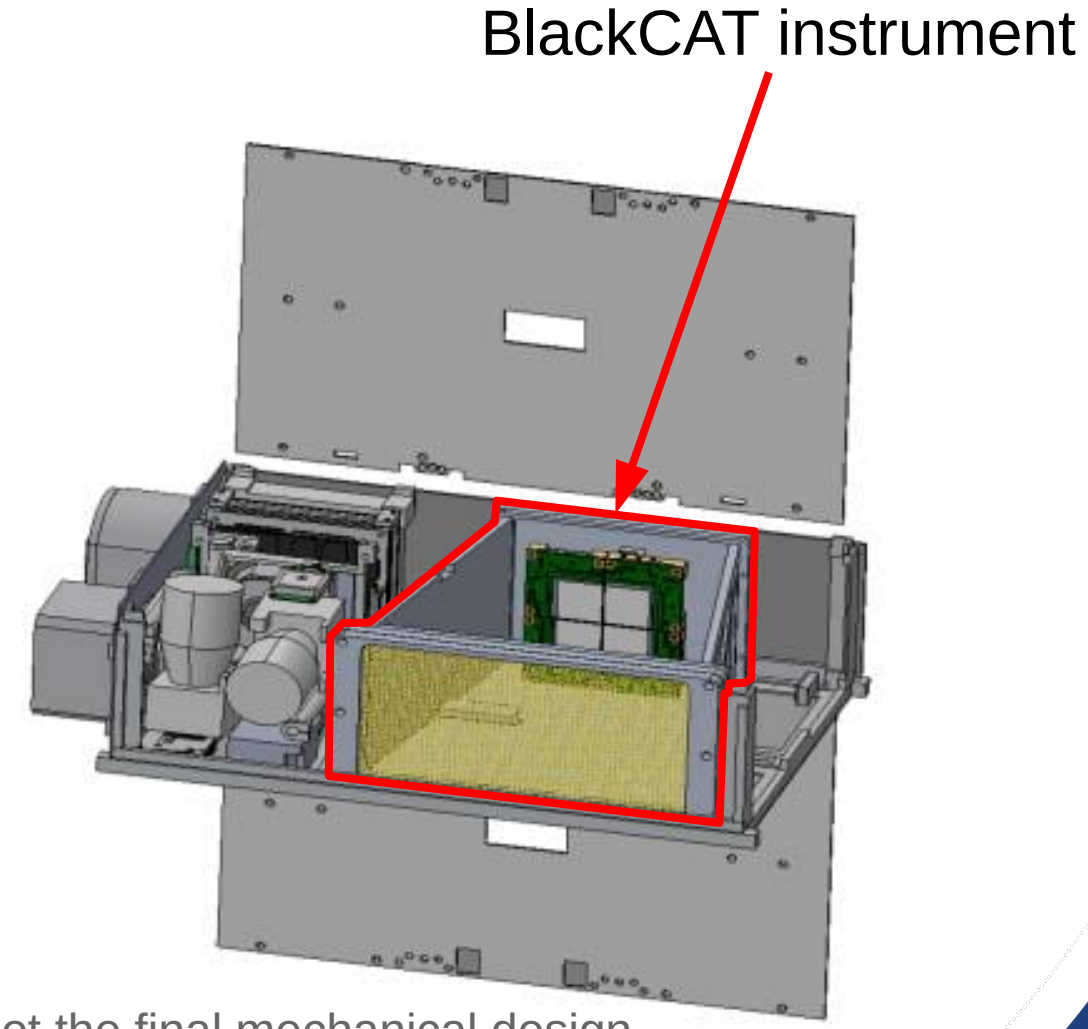
BlackCAT

- Instrument hardware/ gateware/software and science ops provided by the BlackCAT team (PSU/LANL)
- Spacecraft bus, non-instrument avionics, and ground station provided by NanoAvionics
- Sensor development by PSU and Teledyne Imaging Systems
- Mission and sensor dev. funding by NASA



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Important BlackCAT flight software requirements

- Needs to be able to enable, disable, and configure each of the four detectors, and analyze their output
- Needs to be able to recognize probable interesting transients (gamma-ray bursts, etc.) within seconds and localize their position on the sky
- Needs to be able to send notifications of transients to ground-side systems in near real time (~1–3 min delay)
- Needs to send (during scheduled ground-station passes) X-ray photon events around the time of transients (stretch goal: and all other times as well)

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BlackCAT flight software environment

- Instrument computer: Xiphos Q7S
- Zynq-7020: 2 Cortex-A9 cores at ~700 MHz + FPGA fabric
- 256 MiB ECC DRAM
- Operating system: Linux (Yocto-based distribution w/ Xiphos customizations)
- Flight software framework: Core Flight System (cFS)
- BlackCAT peripherals:
  - 4 TIS Speedster-EXD 550 detectors
  - DACs and PWM for power supplies
  - Instrument health: voltage monitors, temperature sensors, heaters
  - RS-422 serial to spacecraft avionics

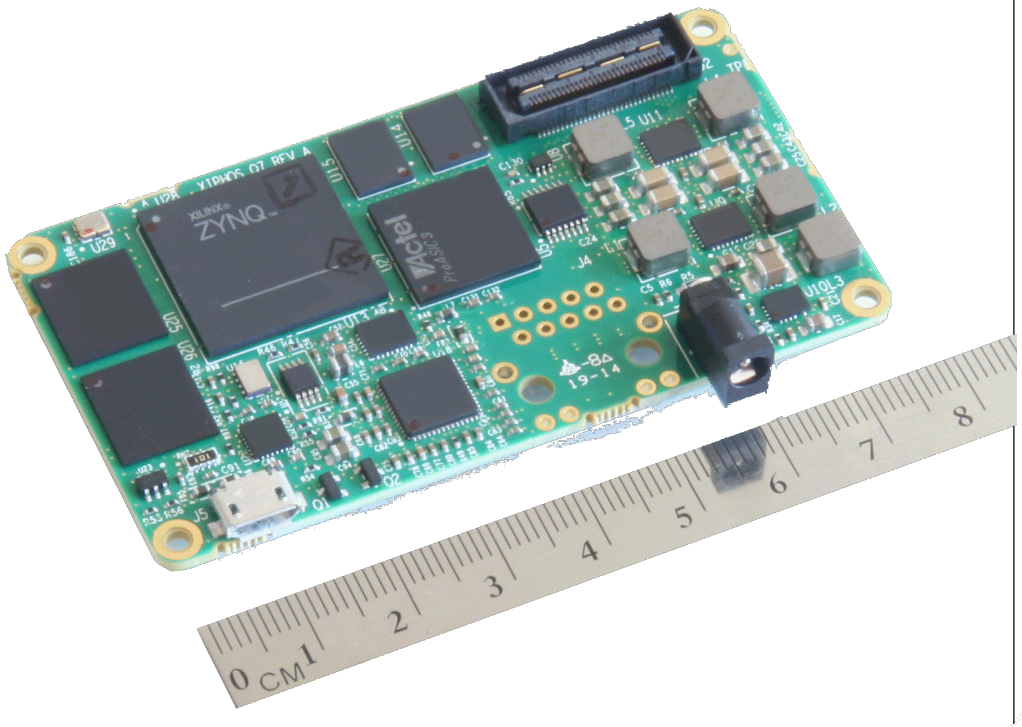

Image credit: Xiphos Systems Corp.

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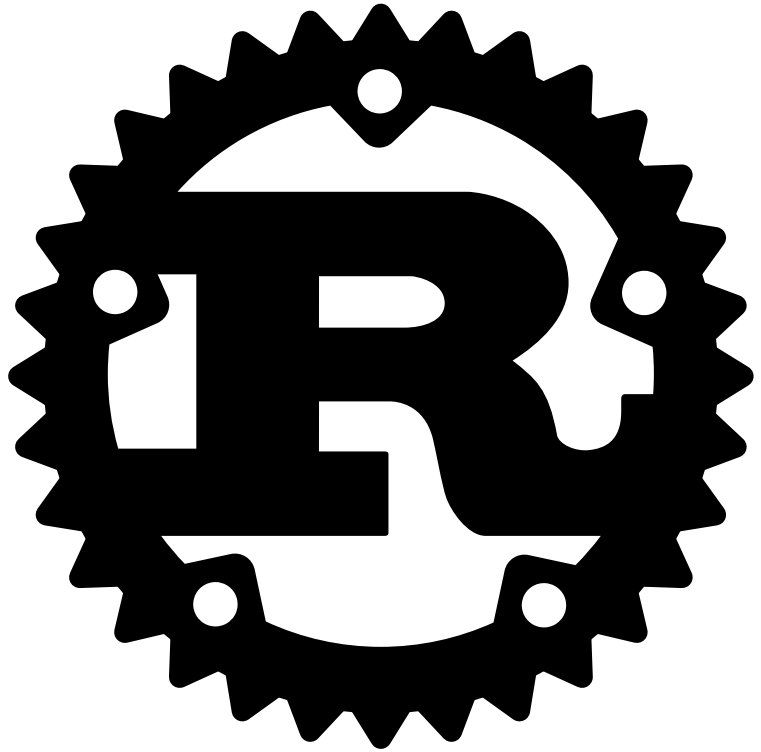
The Rust programming language

Or: how I learned to stop worrying and love the borrow checker

Rust

- Rust is a systems programming language
- “helps you write faster, more reliable software”
  —Introduction, *The Rust Programming Language*
- Uses an ownership system and reference lifetimes to ensure memory and thread safety by default
- Incorporates concepts from higher-level languages when they impose little or no runtime overhead
- *De facto* standard compiler, `rustc`, outputs fast native code (using language-specific optimization, followed by LLVM)



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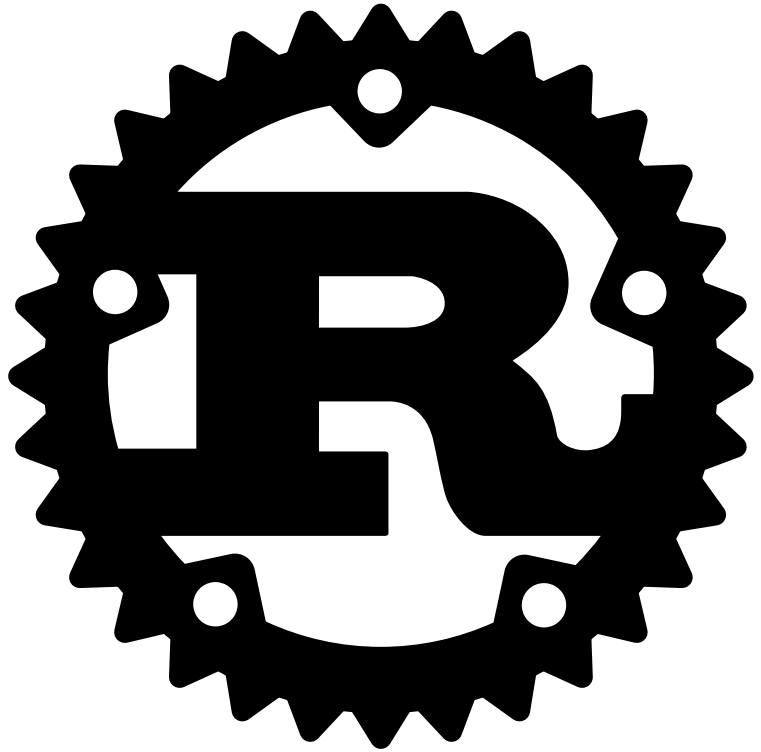
Rust history, very briefly

- 2006: started by Graydon Hoare as a personal project
- 2010: made public after Mozilla took interest
- 2015: language stabilized enough for 1.0 release
- present: under active development, but with stability guarantees post-1.0
  - separate `stable` and `nightly` channels
- Used within Firefox
- Used in production by Google, AWS, etc., etc.



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Language characteristics

- C-esque syntax
- Few new language concepts (but sometimes the first popular language with the concept)
- Expression-based
- Variables immutable by default
- Strongly, statically-typed, but with type inference
- Memory-safe by default (but with `unsafe` keyword for temporary exceptions)

```
fn an_operation(a: u32, b: u8) -> u32 {
    let x = match (b, a) {
        (0, a) => a % 2,
        (1, _) => 42,
        (_, a) => {
            let a = (a % 2);
            a + (b as u32)
        }
    };

    x + 3
}
```

Language characteristics

- Product (`struct`) and sum (`enum`) types
- Generics for types and functions/methods
- No object-oriented inheritance, but traits available for behaviors generic over certain types
- References: pointers, but with additional semantics around mutability, lifetimes; never `NULL`!
- Much more!

```
struct A {
    fld1: u32,
    fld2: bool,
    fld3: Option<i32>,
}

enum B {
    CaseA,
    CaseB(A),
    CaseC,
}

trait MyOperation {
    fn op(&self) -> bool;
}

struct GenericStruct<'a, T: MyOperation> {
    subject: T,
    field_x: &'a B,
    field_y: A,
}
```

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Default tooling

- Rustup: toolchain downloader/updater
- Cargo: standard package manager & build system
  - Crates.io: standard repository of open-source Rust crates
  - Build scripts: build-time code generation and customization for environment
- Rustdoc: generator of API documentation

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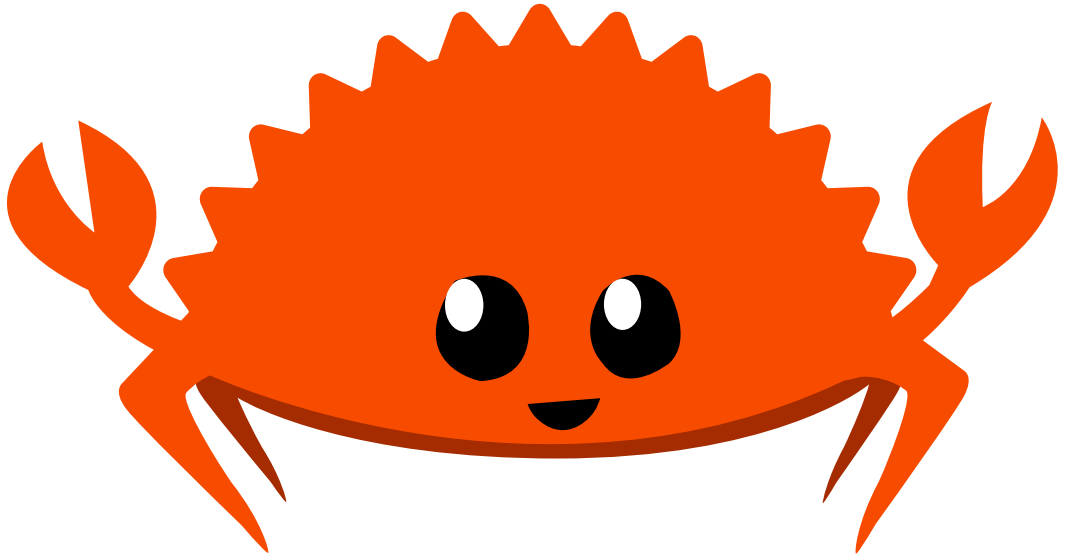
Evaluation

- I like it!
- Not perfect, but an improvement on C
- *Does* have a learning curve
- Generally, where language is complex, difficult, or just *different*, it is for good reasons
- Language has good ergonomics, a good compiler, good tooling, and good documentation



Ferris, the unofficial mascot of Rust

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cFS apps in Rust, how do I even

Rust bindings to cFS API functions

- To be a cFS application, we should use cFS API functions
- Rust can call out to C functions (in `unsafe` code)… but raw function calls aren't idiomatic in this case.
- Solution: create lightweight wrappers that provide a Rustic façade
- We call it `n2o4`.

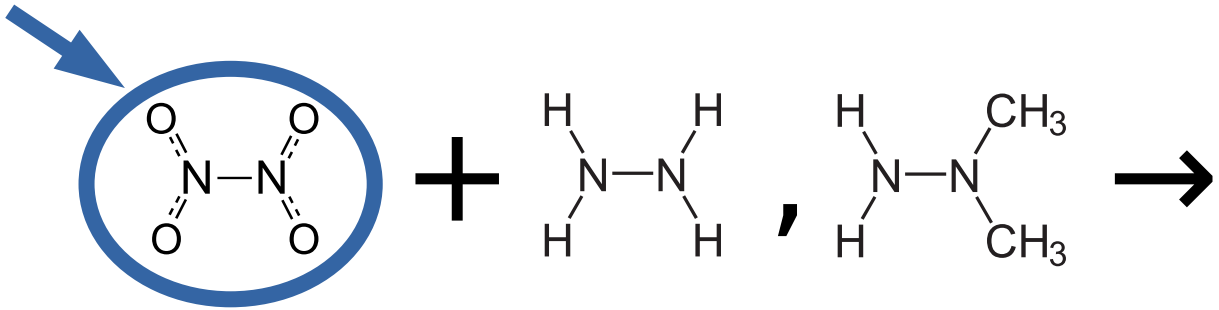

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Image credits: Wikipedia contributors; NASA

API definitions: rewrite it in Rust… *automatically*

- *Problem*: Rust doesn’t natively read C header files
- *Solution*: use the `bindgen` crate in a build script!

build.rs (simplified)

```
extern crate bindgen;

fn main() {
    let bindings = bindgen::builder()
        .header("cfs-all.h")
        .allowlist_type("(CFE|OS|OSAL|CCSDS).*")
        [...]
        .generate()
        .expect("Unable to generate bindings");
    bindings
        .write_to_file("${OUT_DIR}/cfs-all.rs");
}
```

cfs-all.h (excerpt)

```
#include <cfe.h>
#include <osapi.h>

#include <cfe_es_msg.h>
#include <cfe_evs_msg.h>

[...]
```

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API definitions: rewrite it in Rust… *almost automatically*

- *Problem*: Rust doesn’t natively read C header files
- *Solution*: use the `bindgen` crate in a build script!
- …and compile a small C file with wrappers for `static inline` functions

build.rs (simplified)

```
extern crate bindgen;
extern crate cc;

fn main() {
    let bindings = bindgen::builder()
        .header("cfs-all.h")
        .header("cfs-shims.h")
        .allowlist_type("(CFE|OS|OSAL|CCSDS).*")
        [...]
        .generate()
        .expect("Unable to generate bindings");
    bindings
        .write_to_file("${OUT_DIR}/cfs-all.rs");

    cc::Build::new()
        .file("cfs-shims.c")
        .compile("cfs-shims");
}
```

cfs-shims.c (excerpt)

```
#include <cfe.h>

[...]

CFE_SB_MsgId_Atom_t SHIM_CFE_SB_MsgIdToValue(
    CFE_SB_MsgId_t MsgId
) {
    return CFE_SB_MsgIdToValue(MsgId);
}

[...]
```

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Wrapping it up: simple example

- cfs-all.rs now has a bunch of usable definitions, but not as a safe, idiomatic Rust interface
- So we write small, safe wrappers
- Often the wrappers will be inlined completely for zero runtime overhead

${OUT_DIR}/cfs-all.rs

```
[...]
pub type CFE_ES_RunStatus = ::core::ffi::c_uint;
pub const
CFE_ES_RunStatus_CFE_ES_RunStatus_APP_RUN:
CFE_ES_RunStatus = 1;
pub const
CFE_ES_RunStatus_CFE_ES_RunStatus_APP_EXIT:
CFE_ES_RunStatus = 2;
pub const
CFE_ES_RunStatus_CFE_ES_RunStatus_APP_ERROR:
CFE_ES_RunStatus = 3;
[...]

extern "C" {
    pub fn CFE_ES_ExitApp(ExitStatus: uint32);
}

[...]
```

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Wrapping it up: simple example

- cfs-all.rs now has a bunch of usable definitions, but not as a safe, idiomatic Rust interface
- So we write small, safe wrappers
- Often the wrappers will be inlined completely for zero runtime overhead

src/cfe/es.rs

```
/// The status (or requested status)
/// of a cFE application.
#[repr(u32)]
pub enum RunStatus {
    AppError
        = CFE_ES_RunStatus_CFE_ES_RunStatus_APP_ERROR,
    AppExit
        = CFE_ES_RunStatus_CFE_ES_RunStatus_APP_EXIT,
    AppRun = CFE_ES_RunStatus_CFE_ES_RunStatus_APP_RUN,
    [...]
}
[...]

/// Exits from the current application.
#[inline]
pub fn exit_app(exit_status: RunStatus) -> ! {
    unsafe { CFE_ES_ExitApp(exit_status as u32) };

    // If we get here, something's gone wrong with cFE:
    unreachable!("CFE_ES_ExitApp returned, somehow");
}
```

Wrapping it up: simple example

- cfs-all.rs now has a bunch of usable definitions, but not as a safe, idiomatic Rust interface
- So we write small, safe wrappers
- Often the wrappers will be inlined completely for zero runtime overhead

user of n2o4

```
use n2o4::cfe::es;

[...]

if unrecoverable_error() {
    es::exit_app(es::RunStatus::AppError);
}
```

Observations on cFS APIs from a Rust perspective

- Handles make for nice, easy-to-wrap abstractions
- Obeying temporal restrictions on pointer accesses can be enforced statically

User of n2o4

```
use n2o4::cfe::sb::{Pipe, TimeOut};

let mut p: n2o4::cfe::sb::Pipe = [...];

p.receive_buffer(TimeOut::Forever, |msg_maybe| {
    if let Ok(msg) = msg_maybe {
        [...process message...]
    }
});
```

src/cfe/sb.rs

```
/// A software bus pipe.
pub struct Pipe {
    /// cFE ID for the pipe.
    pub(crate) id: CFE_SB_PipeId_t,
}

impl Pipe {
    #[inline]
    pub fn receive_buffer<T, F>(
        &mut self,
        time_out: TimeOut,
        closure: F
    ) -> T
    where
        F: for<'a> FnOnce(Result<&'a Message, Status>) -> T,
    {
        [...]
        let s: Status = unsafe {
            CFE_SB_ReceiveBuffer(&mut buf_ptr,
                self.id, time_out.into())
        }.into();
        [...]
    }

}
```

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Observations on cFS APIs from a Rust perspective

- Even things like printf(3) format strings and their use can be type-checked at compile time without special compiler support

```
use core::ffi::c_char;
use n2o4::cfe::evs::{
    EventSender, EventType::Information
};
use printf_wrap::PrintFmt;

const FMT: PrintfFmt<(u32, c_char)>
    = PrintfFmt::new_or_panic("A: %x, B: %c\0"); // OK
const BAD_FMT: PrintfFmt<(u32)>
    = PrintfFmt::new_or_panic("%s %s %s\n\0");    // compile
                                                  // error

[...]

fn do_a_thing(ev: &EventSender) {
    [...]
    ev.send_event2(4, Information, FMT,  // OK
        5u32, b'x' as c_char
    );
    [...]
    ev.send_event2(4, Information, FMT,  // compile
        5u32, 42u32                      // error
    );
    [...]
}
```

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But wait...

What about actually integrating into the cFS build system?

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Building a Rust-based cFS app

CMakeLists.txt

```
project(CFE_FOO_APP C)

add_cfe_app(foo)
```

rust-fsw/Cargo.toml

```
[package]
name = "foo"
version = "0.0.0"
edition = "2021"

[dependencies]
n2o4 = {
  git = "https://github.com/BlackCAT-CubeSat/n2o4.git",
  rev = "1ad09b2dbbca8687bc8a710cfccd4e7e5d78952e"
}
```

rust-fsw/src/lib.rs

```
#![no_std]

use n2o4::cfs::{es, evs, sb};

/// Entry point of application.
pub fn foo_APP_MAIN() {
    [...]
}
```

Doesn't "just" work. Need to integrate build systems.

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Building a Rust-based cFS app

CMakeLists.txt

```
project(CFE_FOO_APP C)

add_cfe_app(foo fsw/src/placebo.c)

set(RUST_TARGET "armv7-unknown-linux-gnueabihf")

set(RUST_SOURCE_DIR ${CMAKE_CURRENT_SOURCE_DIR}/rust-fsw)
set(CARGO_TARGET_DIR ${CMAKE_CURRENT_BINARY_DIR}/target)
set(LIB_BUILD_DIR ${CARGO_TARGET_DIR}/${RUST_TARGET}/release)
set(LIB_FILE ${LIB_BUILD_DIR}/libfoo.a)

add_custom_command(
  OUTPUT ${LIB_FILE}
  WORKING_DIRECTORY ${RUST_SOURCE_DIR}
  COMMAND ${CMAKE_COMMAND} -E env
    "RUST_CFS_SYS_COMPILE_DEFINITIONS=[...]"
    "RUST_CFS_SYS_INCLUDE_DIRECTORIES=[...]"
    "RUST_CFS_SYS_COMPILE_OPTIONS=[...]"
    "CFLAGS=[...]"
    "CRATE_CC_NO_DEFAULTS=true"
    "BINDGEN_EXTRA_CLANG_ARGS=[...]"
    cargo +nightly build --jobs 1 -Z build-std=std,panic_abort
    --release --target ${RUST_TARGET} --target-dir ${CARGO_TARGET_DIR} --quiet
  DEPFILE ${LIB_BUILD_DIR}/libfoo.d
  DEPENDS ${RUST_SOURCE_DIR}/Cargo.toml
  VERBATIM
)

add_custom_target(foo_rust_build DEPENDS ${LIB_FILE})

add_library(foo_rust_lib STATIC IMPORTED)
add_dependencies(foo_rust_lib foo_rust_build)
set_target_properties(foo_rust_lib
  PROPERTIES
  IMPORTED_LOCATION ${LIB_FILE}
)

target_link_libraries(foo foo_rust_lib m)

target_link_options(foo
  PUBLIC LINKER:--require-defined=foo_APP_MAIN
)

set_directory_properties(
  PROPERTIES
  ADDITIONAL_CLEAN_FILES ${CARGO_TARGET_DIR}
)
```

rust-fsw/Cargo.toml

```
[package]
name = "foo"
version = "0.0.0"
edition = "2021"

[lib]
crate-type = ["staticlib"]

[dependencies]
n2o4 = { [...] }

[profile.release]
panic = "abort"
```

fsw/src/placebo.c

```
const char placebo = 'a';
```

rust-fsw/src/lib.rs

```
#![no_std]

use n2o4::cfs::{es, evs, sb};

/// Entry point of application.
#[no_mangle]
pub extern "C"
fn foo_APP_MAIN() {
    [...]
}

#[panic_handler]
fn panic([...]) -> ! {
  es::exit_app(
    es::RunStatus::AppError
  );
}
```

Integration can be done... with a lot of stitching...

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Building a Rust-based cFS app

CMakeLists.txt

```
project(CFE_FOO_APP C)

# Assuming rust_cfs_app.cmake is included from
# arch_build_custom.cmake, and RUST_TARGET
# and a couple other variables are set in
# toolchain-*.cmake:

add_cfe_app(foo fsw/src/placebo.c)

cfe_rust_crate(foo foo)

target_link_options(foo
  PUBLIC LINKER:--require-defined=foo_APP_MAIN
)
```

rust-fsw/Cargo.toml

```
[package]
name = "foo"
version = "0.0.0"
edition = "2021"

[lib]
crate-type = ["staticlib"]

[dependencies]
n2o4 = { [...] }

[profile.release]
panic = "abort"
```

fsw/src/placebo.c

```
const char placebo = 'a';
```

rust-fsw/src/lib.rs

```
#![no_std]

use n2o4::cfs::{es, evs, sb};

/// Entry point of application.
#[no_mangle]
pub extern "C"
fn foo_APP_MAIN() {
    [...]
}

#[panic_handler]
fn panic([...]) -> ! {
  es::exit_app(
    es::RunStatus::AppError
  );
}
```

*...**much** of which can be wrapped for easy re-use.*

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Conclusions, and an invitation

Conclusions

- Rust is pretty good
- You *can* write cFS applications in Rust
  ...with a fair bit of non-default setup
  - and currently only with the `nightly` channel
- So far, application development has justified building this infrastructure

Invitation to join in

- n2o4 and the build support are a work in progress, and you can help make it better!
  - Bindings for more cFE, OSAL APIs
  - Better testing support
  - API version flexibility
  - Building for non-Linux targets
  - Cargo build concurrency
  - …
- We're open to questions, pull requests, issues, etc.
- Or just use what we've made so far!

https://github.com/BlackCAT-CubeSat/n2o4

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Questions

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