Pragmatics of Rust and C++: The implementation of a window manager

Max van Deurzen

June 19, 2021

Technische Universität München

Agenda

Agenda

1. What is *Pragmatics*?
2. The *Common Objective*
3. External Dependency Management
4. Main Event Loop
5. Input Bindings
6. Clients
7. Results
8. Discussion

Pragmatics

Definition

1. **Syntax**
   Set of rules that define the *structure* and *composition* of allowable symbols into correct statements or expressions in the language

2. **Semantics**
   The *meaning* of these syntactically valid statements or expressions

3. **Pragmatics**
   "...[T]he third general area of language description, referring to practical aspects of how constructs and features of a language may be used to achieve various objectives."

   Robert D. Cameron, 2002

Example: Assignment Statements

1. **Syntax** (*structure*)

   $x = y * 3;$

2. **Semantics** (*meaning*)
   - x

     Location in memory
   - $y * 3$

     Computation of a value based on an expression
   - $x = y * 3;$

     Store result of expression evaluation in location in memory
3. **Pragmatics** (*purpose*)

   Which objectives are assignment statements used *for*?
   - Setting up a temporary variable used to swap the values of two variables
   - Modifying some part of a compound data structure
   - ...

The Common Objective

Case Study: The implementation of a window manager

- **System Software**
  - Low-level
  - Platform-specific
- **Medium to Large-Sized**
  - Increased Risk of *Code Smells*
    - Monolithic classes
    - Global data
    - High interdependence (Coupling)
    - ...
- **Event-Driven**
  - Reacts to windowing system events
  - Deterministic event dispatch

Case Study: The implementation of a window manager

- **External Dependency Management**
  - Package management
  - Abstracting and decoupling
- **Main Event Loop**
  - Windowing system events
  - Internal events
  - Event dispatch
- **Input Bindings**
  - Storing and retrieving callable objects
- **Clients**
  - Distributed, mutable state

Case Study: The implementation of **two** window managers

- **Same structure**
  - Built on top of the X Window System
    - Library to communicate with the X server as external dependency
- **Same behavior**
  - ICCCM and EWMH compliant
  - Reparenting, tiling
- **Different languages**
  - One implemented in C++: wmCPP
  - One implemented in Rust: wmRS

External Dependency Management

External Dependency Management

Practicalities of working with external code

1. **Package management**
    - *Availability* of external code
2. **Decoupling dependencies**
    - *Maintainability* of external code

Managing the availability of external code

- The ability to *aid* the programmer in assuring availability
  - Automatically download and compile source code
  - Built-in version control
  - Conflict detection
- Part of the *ecosystem* of a language
  - Installed with its compiler or development environment
- A *must* for any modern programming language

- *No* official package manager
- *Ad hoc* package management
  - Third-party package management tools
    - *Conan*
    - *Vcpkg*
    - *build2*
  - Custom configure and build scripts
  - Let the user manage the dependencies themselves (e.g. through their distribution's package manager)
- Example: Make script

```
CXXFLAGS  := -std=c++20 -march=native -O3
LDFLAGS   := `pkg-config --libs x11 xrandr` -flto
SRC_FILES := $(wildcard src/*.cc)
OBJ_FILES := $(patsubst src/%.cc,obj/%.o,${SRC_FILES})
all: ${OBJ_FILES}
    g++ ${OBJ_FILES} ${LDFLAGS} -o bin/wmCPP
obj/%.o: src/%.cc
    g++ ${CXXFLAGS} -MMD -c $< -o $@
```

- *Cargo*, Rust's official package manager
  - Automatically downloads and compiles dependencies
  - A Rust project is a Cargo *package*
  - A package is a collection of *source files* plus a *manifest* file
  - The manifest file describes the package's *meta-information*, *dependencies*, and a set of *target crates*
  - A crate represents a *library* or *binary executable* program
- Example: `Cargo.toml` manifest file

```
[package]
name = "wmRS"
version = "0.1.0"
edition = "2018"
license = "BSD3"
default-run = "core"
description = """
An ICCCM & EWMH compliant X11
reparenting, tiling window manager,
written in Rust
"""
```

```
[lib]
name = "winsys"
path = "src/winsys/mod.rs"
[[bin]]
name = "core"
path = "src/core/main.rs"
[[bin]]
name = "client"
path = "src/client/main.rs"
[dependencies]
x11rb = "0.8.0"
```

Managing the maintainability of external code

- The ability to *decouple* own code from external code
  - Changes to own code don't affect interface with external code
  - Changes to external code *only* affect inerface with external code
- When external code changes:
  - Only interface with external code needs to be recompiled
- When own code changes:
  - Only own code needs to be recompiled

Decouple window manager from windowing system

1. Hide the connection with the windowing system behind an *interface*
   - Provide *abstraction* and *encapsulation*
   - Describe *common behavior*
   - *Usage* is *agnostic* of concrete implementation
2. Implement the interface for *each* targeted windowing system
   - *X Window System*
   - *Wayland*
   - *Desktop Window Manager* (Windows)
   - *Quartz Compositor* (macOS)
   - ...
3. Have the window management logic call into the interface

1. Hide the connection with the windowing system behind a trait

- *Zero-overhead* collection of methods
  "What you don't use, you don't pay for [Stroustrup, 1994]. And further: What you do use, you couldn't hand code any better."

  Bjarne Stroustrup
- Comparable to, *but not the same as*, the concept of an OOP *interface*
  - Implementation does not require changes to the implementor
    - Traits can be implemented on *external* code
    - No ambiguity when two implemented traits share method name and prototype
- Can define *stateless* default implementations

1. Hide the connection with the windowing system behind a trait

- No inheritance, only implementation
  - No downcasting or reference casting
- Declared for some (at declare-time) unknown type `Self`
  - When implemented `Self` becomes the implementing type
- Example: WMRS's `Connection` trait:

```
pub trait Connection {
    fn step(&self) -> Option<Event>;
    fn move_window(&self, window: Window, pos: Pos);
    fn resize_window(&self, window: Window, dim: Dim);
    fn close_window(&self, window: Window);
    // ...
}
```

2. Implement the trait for each targeted windowing system

- Example: wmRS's `XConnection` structure:

```rust
use x11rb::connection;
pub struct XConnection<'xconn, XConn: connection::Connection> {
    xconn: &'xconn XConn,
    // ...
}
impl<'xconn, XConn: connection::Connection> Connection
    for XConnection<'xconn, XConn>
{
    fn step(&self) -> Option<Event> { /* ... */ }
    // ...
}
```

- `x11rb`: Rust library to interact with the X Window System
  - External dependency
  - Rust bindings to interact with the X server

3. Have the window management logic call into the interface

- Example: WMRS's core window manager logic:

```
pub struct Model<'model> {
  conn: &'model mut dyn Connection,
  // ...
}
```

- *Polymorphism* to abstract away from the concrete implementation
- `Model` *contains* a reference to *some* `Connection` implementor
- The trait methods of this implementor are called where needed
  - Static dispatch
    - Concrete method to call is baked into the binary
  - Dynamic dispatch
    - Concrete method to call is looked up *at runtime*

Static dispatch

- Concrete method to call is baked into the binary
  - *Monomorphization* at compile time
  - Generic code is converted into "specific" code
  - One version for each concrete type used as generic argument
  - Size of concrete type is always known
- No additional time overhead at runtime
- Example: wmRS's `Cycle` structure:

```rust
pub struct Cycle<T>
where
    T: Identify + Debug,
{ /* ... */ }

impl<T> Cycle<T>
where
    T: Identify + Debug,
{ /* ... */ }
```

```rust
pub struct Model<'model> {
    // ...
    workspaces: Cycle<Workspace>,
    // ...
}

pub struct Workspace {
    clients: Cycle<Window>,
}
```

Dynamic dispatch

- Concrete method to call is looked up *at runtime*
- *Trait objects* keep instances abstract until concretization is required
  - Opaque value of a type that implements some set of traits
  - Until further inspection, concrete type is unknown
  - *Dynamically sized*: size of underlying concrete type is not known up front
- Under the hood, 2 pointers:
  - 1 pointer to data
  - 1 pointer to *virtual method table* (*vtable*)
- Virtual method table points to that object's concrete method implementations

Dynamic dispatch

- Example: wmRS's `XConnection`'s `xconn` reference:

```
use x11rb::connection;

pub struct XConnection<'xconn, XConn: connection::Connection> {
    xconn: &'xconn XConn,
    // ...
}
```

- Example: wmRS's conn trait object:

```
pub struct Model<'model> {
    conn: &'model mut dyn Connection,
    // ...
}
```

Dynamic dispatch

- ~~Example: wmRS's XConnection's xconn reference:~~

```
use x11rb::connection;
pub struct XConnection<'xconn, XConn: connection::Connection> {
    xconn: &'xconn XConn,
    //...
}
```

- Example: wmRS's conn trait object:

```
pub struct Model<'model> {
    conn: &'model mut dyn Connection,
    // ...
}
```

1. Hide the connection with the windowing system behind an abstract class

- Abstract type that cannot be implemented, only *derived*
- Establish common denominator between types
- Can define *stateful* default implementations
- Same as OOP interface when it *only* contains *pure virtual* methods
  - No associated inline logic
  - *Must* be implemented by inheriting subclasses
- Derived class concrete method invocation *only* through dynamic dispatch

1. Hide the connection with the windowing system behind an abstract class

- Example: wmCPP's `Connection` abstract class interface:

```
class Connection
{
public:
    virtual ~Connection() {}
    virtual Event step() = 0;
    virtual void move_window(Window, Pos) = 0;
    virtual void resize_window(Window, Dim) = 0;
    virtual void close_window(Window) = 0;
    // ...
};
```

- `Connection` contains *at least* 1 virtual method
  - `Connection` is an abstract class
- `Connection` has 0 inline method implementations
  - `Connection` is a proper OOP interface

1. Hide the connection with the windowing system behind an abstract class

- Pure virtual methods *can* be defined to be called *statically*
- Example: wmCPP's `Connection`'s implementation:

```
#include "connection.hh"
#include "log.hh"

void
Connection::close_window(Window window)
{
    Logger::log_info("Closing 0x%#08x.", window);
}

// ...
```

2. Derive the abstract class for each targeted windowing system

- Example: wmCPP's `XConnection` derived class:

```
#include "connection.hh"
extern "C" {
#include <X11/Xlib.h>
// ...
}
class XConnection final: public Connection
{
public:
    void close_window(Window window) override {
        Connection::close_window(window); // non-virtual call
        // ...
    }
    // ...
};
```

- `<X11/...>`: Xlib library to interact with the X Window System
  - External dependency

3. Have the window management logic call into the interface

- Example: wmCPP's core window manager logic:

```
#include "connection.hh"
class Model final
{
public:
    Model(Connection& conn): conn(conn) { /* ... */  }
    // ...
private:
    Connection& conn;
    // ...
};
```

- *Polymorphism* to abstract away from the concrete implementation
- `Model` *contains* a reference to *some* `Connection` implementor
- The overridden methods of this implementor are dynamically called where needed

Remarks

Additional C++ external dependency management difficulties:

- Problem: *double inclusion*
- Possible solution: **header guards**
  - Preprocessor directives
  - Include idempotence
  - Not fail-safe
  - Hard-to-trace symbol collision errors
  - `#pragma once` as unofficial solution
- Problem: *includes are non-commutative*
- Possible solution: none
- Rust's *module* system does not have these issues

Rust traits vs C++ abstract classes

- Abstract classes: *inheritance*
  1. Describe common behavior
  2. Code reuse
  3. Polymorphism
- Traits: *implementation*
  1. Describe common behavior
  2. Code reuse with **generics**: *abstraction* over different types
  3. Polymorphism with **trait bounds**: *constraints* on these type abstractions

Main Event Loop

Main Event Loop

Three core stages:

1. **Listen for windowing system events**
   - *Block* until an event has been generated
2. **Create windowing system agnostic event abstraction**
   - *Extract* and *bundle* concrete information into abstract window manager consumable
3. **Delegate work to different parts of the program**
   - Perform window management actions based on the type of the concrete event

1. Listen for windowing system events

1. Concrete `Connection`'s external dependency generates *events*
   - Input events
   - Map notification events
   - ...
2. Convert windowing system specific event information into higher-level event abstraction
   - Decouple *windowing system event* from *window manager event*
3. `Connection::step` method propagates event abstraction up to window manager logic
   - WMRS: `fn step(&self) -> Option<Event>;`
   - WMCPP: `Event step();`

2. Create windowing system agnostic event enum

- Definition of a type by *enumerating* its *variants*
- Encodes *meaning*
  - Associated integer called *discriminant*
  - Tagged union
- May attach *data*
  - Data can be *directly* associated with a variant
- Size as large as its largest variant
- Example: WMRS's `Event` enumeration:

```
pub enum Event {
    Mouse { event: MouseEvent },
    Key { event: KeyEvent },
    CloseRequest { window: Window },
    ScreenChange,
    // ...
}
```

2. Create windowing system agnostic event `std::variant`

- Definition of a type by *enumerating* its *alternatives*
- Type-safe tagged union class template
- Encodes *meaning*
- Contains *data*
  - Data can only *indirectly* be associated with an alternative
  - Strong type alias required for same-type alternatives
- Size as large as its largest variant
- Example: wmRS's `Event` enumeration:

```
typedef std::variant<
    std::monostate,
    Mouse,
    Key,
    CloseRequest,
    ScreenChange,
    // ...
> Event;
```

```
struct Mouse { MouseEvent event; };

struct Key { KeyEvent event; };

struct CloseRequest { Window window; };

struct ScreenChange {};

// ...
```

Event Abstraction: Remarks

wmRS:

```
fn step(&self) -> Option<Event>;
```

wmCPP:

```
Event step();
```

Event Abstraction: Remarks

wmRS:

```rust
fn step(&self) -> Option<Event>;
```

```rust
pub enum Event {
    Mouse { event: MouseEvent },
    Key { event: KeyEvent },
    CloseRequest { window: Window },
    ScreenChange,
    // ...
}
```

wmCPP:

```cpp
Event step();
```

```cpp
typedef std::variant<
    std::monostate,
    Mouse,
    Key,
    CloseRequest,
    ScreenChange,
    // ...
> Event;
```

3. Delegate work to different parts of the program

- `match` on specific *type* of event
  - Call appropriate *handler*
  - Pass encoded information to handler
- Example: wmRS's main event loop:

```
while self.running {
    if let Some(event) = self.conn.step() {
        match event {
            Event::Mouse { event, }
                => self.handle_mouse(event, /*...*/),
            Event::Key { keycode, }
                => self.handle_key(keycode, /*...*/),
            Event::CloseRequest { window, }
                => self.handle_close_request(window),
            Event::ScreenChange
                => self.handle_screen_change(),
            // ...
        }
    }
```

3. Delegate work to different parts of the program

- Example: wmRS's main event loop:

```
while self.running {
    if let Some(event) = self.conn.step() {
        // ...
    }
}
```

- Equivalent to:

```
while self.running {
    match self.conn.step() {
        Some(event) => {
            // ...
        },
        _ => {}
    }
}
```

Input Bindings

Second Frame

Hello, world!

Clients

Second Frame

Hello, world!