

Pragmatics of Rust and C++:

The implementation of a window manager

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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

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

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++: WMCP
 - One implemented in Rust: WMRS

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 interface 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 signature
- 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:

```
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:

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

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

```
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:

```
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

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

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 alternative
- Example: WMCP's Event type:

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

struct Mouse { MouseEvent event; };
struct Key { KeyEvent event; };
struct CloseRequest { Window window; };
struct ScreenChange {};
// ...
```

WMRS:

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

WMCPP:

```
Event step();
```

WMRS:

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

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

WMCPP:

```
Event step();
```

```
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(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) => {  
            // ...  
        },  
        _ => {}  
    }  
}
```


3. Delegate work to different parts of the program

- *Visit* the alternatives in `std::variant` using `std::visit`
 - *Visitor* object implementing *function-call operator* overloads
 - `std::variant` instance to visit

3. Delegate work to different parts of the program

- Example: WMCPP's visitor object:

```
struct EventVisitor
{
    EventVisitor(Model& model): model(model) {}
    void operator()(std::monostate)      {}
    void operator()(Mouse event)        { model.handle_mouse(event); }
    void operator()(Key event)          { model.handle_key(event); }
    void operator()(CloseRequest event) { model.handle_close(event); }
    void operator()(ScreenChange)       { model.handle_screen_change(); }
    // ...
private:
    Model& model;
} event_visitor = EventVisitor(*this);
```

3. Delegate work to different parts of the program

- Example: WMCPP's visitor object:

```
struct EventVisitor
{
    EventVisitor(Model& model): model(model) {}
    void operator()(std::monostate) {}
    // ...
private:
    Model& model;
} event_visitor = EventVisitor(*this);
```

- *Implicit* “no valid event” encoding
- Analogous to *no-op* event

3. Delegate work to different parts of the program

- Example: WMCPP's main event loop:

```
while (running)
    std::visit(event_visitor, conn.step());
```

1. Retrieve generated event from windowing system connection
2. Rely on visitor to deduce type of event
3. Call associated handler

- Rust and C++ both achieve desired behavior
- Visiting tagged unions in C++ is more verbose, less clear in communicating intent
- Difference worsens as more complex (or pattern-reliant) situations arise

Input Bindings

Input Bindings

- **Bind functionality to sets of peripheral input states**
 - *Mouse* bindings
 - *Keyboard* bindings
 - *Sensors*
 - ...
- **Hardware and platform dependent**
 - Initiated by the connection with the windowing system
- **Concrete input information to abstract window manager events**
 - Mouse event variant
 - Key event variant
 - ...

Three-step process:

1. **Establish abstract notion of input**

- Convert concrete input states to abstract input events
 - *Mouse* input abstractions, *keyboard* input abstractions, ...
 - *Windowing system specifics* to *window manager abstractions*

2. **Map input to window management actions**

- Input abstractions to *closures*

3. **Retrieve and perform window management actions**

1. Establish abstract notion of input

- Example: WMRS's *mouse input* abstractions:

```
#[derive(Clone, Copy, PartialEq, Eq, Hash)]
pub enum MouseEventKind { Press, Release, Motion, }

#[derive(Clone, Copy, PartialEq, Eq, Hash)]
pub enum Button { Left, Middle, Right, ScrollUp, /* ... */ }

#[repr(u8)]
#[derive(Clone, Copy, PartialEq, Eq, Hash)]
pub enum Modifier {
    Ctrl  = 1 << 0,
    Shift = 1 << 1,
    Super = 1 << 2,
    Alt   = 1 << 3,
    // ...
}
// ...
```

1. Establish abstract notion of input

- Example: WMRS's *mouse input* abstractions (cont.):

```
// ...  
#[derive(PartialEq, Eq)]  
pub struct MouseButton {  
    pub button: Button,  
    pub modifiers: HashSet<Modifier>,  
}  
#[derive(PartialEq, Eq, Hash)]  
pub struct MouseEvent {  
    pub kind: MouseEventKind,  
    pub input: MouseButton,  
    pub window: Option<Window>,  
}
```

1. Establish abstract notion of input

- Example: WMCPP's *mouse input* abstractions:

```
enum class MouseEventKind { Press, Release, Motion };  
enum class Button { Left, Middle, Right, ScrollUp, /* ... */ };  
enum Modifier {  
    Ctrl  = 1 << 0,  
    Shift = 1 << 1,  
    Super = 1 << 2,  
    Alt   = 1 << 3,  
    // ...  
};  
// ...
```

1. Establish abstract notion of input

- Example: WMCPP's *mouse input* abstractions (cont.):

```
// ...  
struct MouseButton final {  
    Button button;  
    std::unordered_set<Modifier> modifiers;  
};  
struct MouseEvent final {  
    MouseEventKind kind;  
    MouseButton input;  
    Option<Window> window;  
};
```

2. Map input to window management actions in a HashMap

- Example: WMRS's *input mappings*:

```
pub type KeyAction = Box<
    dyn FnMut(&mut Model<'_>)
>;
pub type MouseAction = Box<
    dyn FnMut(&mut Model<'_>, Option<Window>) -> bool
>;
pub type KeyBindings = HashMap<
    KeyInput, KeyAction
>;
pub type MouseBindings = HashMap<
    MouseInput, MouseAction
>;
```

2. Map input to window management actions in a HashMap

- Example: WMRS's mouse input mapping:

```
pub type MouseAction = Box<
    dyn FnMut(&mut Model<'_>, Option<Window>) -> bool
>;
// ...
```

- Box<T>: store value of type T on the *heap*
 - Constant size: pointer to heap address
- FnMut: closure trait that describes calling of function that mutates state
 - `dyn FnMut(...)` -> ...: *trait object* (dynamic dispatch)
 - Hooks into main window manager logic
 - Operates on clicked-on window (if any)

2. Map input to window management actions in a HashMap

- Example: WMRS's mouse input mapping:

```
#[derive(PartialEq, Eq)]
pub struct MouseButton {
    pub button: Button,
    pub modifiers: HashSet<Modifier>,
}
pub type MouseBindings = HashMap<
    MouseButton, MouseAction
>;
```

- MouseButton used as *key* to HashMap
 - PartialEq and Eq

2. Map input to window management actions in a HashMap

- Example: WMRS's mouse input mapping:

```
#[derive(PartialEq, Eq)]
pub struct MouseButton {
    pub button: Button,
    pub modifiers: HashSet<Modifier>,
}

pub type MouseBindings = HashMap<
    MouseButton, MouseAction
>;
```

- MouseButton used as key to HashMap
 - ~~PartialEq and Eq~~ (`#[derive(PartialEq, Eq)]`)

2. Map input to window management actions in a HashMap

- Example: WMRS's mouse input mapping:

```
#[derive(PartialEq, Eq)]
pub struct MouseInput {
    pub button: Button,
    pub modifiers: HashSet<Modifier>,
}
pub type MouseBindings = HashMap<
    MouseInput, MouseAction
>;
```

- MouseInput used as key to HashMap
 - ~~PartialEq~~ and ~~Eq~~ (`#[derive(PartialEq, Eq)]`)
 - Hash

2. Map input to window management actions in a HashMap

- Example: WMRS's mouse input mapping:

```
#[derive(PartialEq, Eq)]
pub struct MouseButton {
    pub button: Button,
    pub modifiers: HashSet<Modifier>,
}

pub type MouseBindings = HashMap<
    MouseButton, MouseAction
>;
```

- MouseButton used as key to HashMap
 - ~~PartialEq and Eq~~ (`#[derive(PartialEq, Eq)]`)
 - Hash (not automatically derivable)

2. Map input to window management actions in a HashMap

- Example: WMRS's mouse input mapping:

```
#[derive(Clone, Copy, PartialEq, Eq, Hash)]
pub enum Button { Left, Middle, Right, ScrollUp, /* ... */ }

#[derive(PartialEq, Eq)]
pub struct MouseInput {
    pub button: Button,
    pub modifiers: HashSet<Modifier>,
}
```

- Hash (not automatically derivable)
 - HashSet not automatically derivable
 - *Manual* implementation

2. Map input to window management actions in a HashMap

- Example: WMRS's MouseInput's Hash implementation:

```
#[derive(PartialEq, Eq)]
pub struct MouseInput {
    pub button: Button,
    pub modifiers: HashSet<Modifier>,
}

impl Hash for MouseInput {
    fn hash<H: Hasher>(&self, state: &mut H) {
        self.button.hash(state);
        self.modifiers.iter()
            .fold(0u8, acc, &m acc | m as u8)
            .hash(state);
    }
}
```

2. Map input to window management actions in a HashMap

- Example: WMRS's MouseInput's Hash implementation:

```
impl Hash for MouseInput {  
    fn hash<H: Hasher>(&self, state: &mut H) {  
        self.button.hash(state);  
        self.modifiers.iter()  
            .fold(0u8, acc, &m acc | m as u8)  
            .hash(state);  
    }  
}
```

- <H: Hasher>: hashing function's logic
 - *Streaming* hasher
 - *State* changes as data is being hashed
 - Final state is hashed value

2. Map input to window management actions in a HashMap

- Example: Registering a mouse binding in WMRS:

```
let mut mouse_bindings = HashMap::new();
mouse_bindings.insert(
    MouseButton {
        button: Button::Right,
        modifiers: {
            let mut modifiers = HashSet::with_capacity(2);
            modifiers.insert(Modifier::Ctrl);
            modifiers.insert(Modifier::Super);
            modifiers
        },
    },
    Box::new(|model: &mut Model, win: Option<Window>| -> bool {
        if let Some(window) = win {
            model.set_floating_window(window);
            true
        }
    })
);
```

2. Map input to window management actions in a std::unordered_map

- Example: WMCPP's *input mappings*:

```
typedef
```

```
    std::function<void(Model&)>
```

```
    KeyAction;
```

```
typedef
```

```
    std::function<bool(Model&, std::optional<Window>)>
```

```
    MouseAction;
```

```
typedef
```

```
    std::unordered_map<KeyInput, KeyAction>
```

```
    KeyBindings;
```

```
typedef
```

```
    std::unordered_map<MouseInput, MouseAction>
```

```
    MouseBindings;
```

2. Map input to window management actions in a std::unordered_map

- Example: WMCPP's mouse input mapping:

```
typedef
    std::function<bool(Model&, std::optional<Window>)>
    MouseAction;

// ...
```

- `std::function<T>`: *class template*
 - Polymorphic function wrapper
 - Callable *target*
 - C++ *type erasure*
 - Dynamic dispatch
 - *Small Buffer Optimization*

2. Map input to window management actions in a std::unordered_map

- Example: WMCPP's mouse input mapping:

```
struct MouseButton final {  
    Button button;  
    std::unordered_set<Modifier> modifiers;  
};  
typedef  
    std::unordered_map<MouseButton, MouseAction>  
    MouseBindings;
```

- MouseButton used as *key* to std::unordered_map
 - `operator==`
 - `std::hash<MouseButton>::operator()`

2. Map input to window management actions in a std::unordered_map

- Example: WMCPP's MouseInput's `operator==` overload:

```
struct MouseInput final {  
    Button button;  
    std::unordered_set<Modifier> modifiers;  
};  
  
inline bool  
operator==(const MouseInput& lhs, const MouseInput& rhs)  
{  
    return lhs.button == rhs.button  
        && lhs.modifiers == rhs.modifiers;  
}
```

2. Map input to window management actions in a std::unordered_map

- Example: WMCPP's `std::hash<MouseButton>::operator()` implementation:

```
struct MouseButton final {
    Button button;
    std::unordered_set<Modifier> modifiers;
};
namespace std
{
    template <>
    struct hash<MouseButton>
    {
        size_t
        operator()(const MouseButton& input) const
        {
            size_t button_hash = hash<Button>()(input.button);
            size_t modifiers_hash = hash<size_t>()(
                accumulate(input.modifiers.begin(), input.modifiers.end(),
                    static_cast<Modifier>(0), bit_or<Modifier>())
            );
            return button_hash ^ modifiers_hash;
        }
    };
}
```

2. Map input to window management actions in a std::unordered_map

- Example: WMCP's `std::hash<MouseButton>::operator()` implementation:

```
size_t
operator()(const MouseButton& input) const
{
    size_t button_hash = hash<Button>()(input.button);
    size_t modifiers_hash = hash<size_t>()(
        accumulate(input.modifiers.begin(), input.modifiers.end(),
            static_cast<Modifier>(0), bit_or<Modifier>())
        );

    return button_hash ^ modifiers_hash;
}
```

- `std::hash<T>::operator()`: T's hashing function's logic
 - *Hash coding* hasher
 - Final state within function

2. Map input to window management actions in a std::unordered_map

- No automatic deriving of operator overloads
- Example: WMCP's Modifier's `operator|` implementation:

```
inline Modifier  
operator|(Modifier lhs, Modifier rhs)  
{  
    return static_cast<Modifier>(  
        static_cast<std::size_t>(lhs)  
        | static_cast<std::size_t>(rhs)  
    );  
}
```

2. Map input to window management actions in a std::unordered_map

- Example: Registering mouse bindings in WMCPP:

```
Model(/* ... */)
: mouse_bindings({
    { { Button::Right, { Ctrl, Super } },
      [](Model& model, std::optional<Window> window) {
          if (window)
              model.set_fullscreen_window(*window);
      }
    },
    // more mouse bindings
})
{ /* ... */ }
```

3. Retrieve and perform window management actions

- Example: WMRS's mouse event handler:

```
pub struct MouseEvent {  
    pub kind: MouseEventKind,  
    pub input: MouseInput,  
    pub window: Option<Window>,  
}  
  
pub type MouseBindings = HashMap<  
    MouseInput, MouseAction  
>;  
  
fn handle_mouse(  
    &mut self,  
    event: MouseEvent,  
    mouse_bindings: &MouseBindings,  
) {  
    // ...  
    if let Some(action) = mouse_bindings.get(&event.input) {  
        action(self, event.window);  
    }  
    // ...  
}
```

3. Retrieve and perform window management actions

- Example: WMCPP's mouse event handler:

```
struct MouseEvent final {      typedef
    MouseEventKind kind;      std::unordered_map<MouseInput, MouseAction>
    MouseInput input;         MouseBindings;
    Option<Window> window;
};

void
Model::handle_mouse(MouseEvent& event)
{
    MouseBindings& mb = this->mouse_bindings;
    if (mb.count(event.input) > 0)
        mb.at(event.input)(*this, event.window);
}
```


Input Bindings: Remarks

- Rust and C++ both achieve desired behavior
- Rust: *streaming* hasher
 - Arbitrary amount of data
 - Byte-per-byte
 - Central hash function (Hasher trait)
- C++: *hash coding* hasher
 - Reduced into single integer
 - Local hash function

Input Bindings: Remarks

- Rust: operator overloading through *traits*
 - Trait bounds
- C++: non-uniform operator overloading
 - *Class methods*
 - *Non-method functions*
 - *Non-method friend functions*
 - *Concrete templated class implementations*

Input Bindings: Remarks

- Rust: *verbose* HashMap construction
 - *Macro metaprogramming*
 - *Declarative*: eliminate duplicate code
 - *Procedural*: operate on AST
- Example: Constructing mouse bindings in WMRS's using *declarative macros*:

```
let mouse_bindings = init_mouse_bindings!(  
    "A-C-S-Middle" => execute_model_window!(model, win,  
        if let Some(window) = win {  
            model.set_fullscreen_window(window);  
        }  
    ),  
    // more mouse bindings  
);
```

- C++: no such feature

Clients

- **Window as main windowing system entity**
 - Application GUI
 - Integer representation
 - Unique identification
 - *Stateless*
- **Client as main window manager entity**
 - Window coupled with *state*
 - Title
 - Floating, tiled region
 - Process identifier (PID)
 - *Fullscreen?*
 - *Floating?*
 - *Iconified?*
 - ...

- Major memory safety aspect: **mutability**
 - `mut`: two *types* of semantics
 - Patterns: *changeable underlying value*
 - References: *changeable underlying value, aliasing* not allowed
- *aliasing XOR mutability*
 - Either *distribute* or *mutate*
 - Safe to mutate only if *no other* references exist
- Example: WMRS's Client structure:

```
pub struct Client {  
    window: Window,  
    frame: Window,  
    workspace: usize,  
    parent: Option<Window>,  
    children: Vec<Window>,  
    floating: bool,  
    fullscreen: bool,  
    // ...  
}
```

Distributing references to client structures

- **Option 1:** distribute `&mut Client`
 - Client-mutating methods
 - No more than a single reference outstanding

Option 1: distribute `&mut Client`

- Clients must be centrally stored
 - Map Window to its Client
- Example: WMRS's Client instance storage:

```
pub struct Model<'model> {  
    // ...  
    client_map: HashMap<Window, Client>,  
    // ...  
}
```

- Mutability *bubbles up*
 - Surrounding structures *also* mutable
 - *Inherited, exterior mutability*
 - Mutating single client field: `&mut Client`
 - Mutating `&mut Client`: `fn ...(&mut self, ...)`

Option 1: distribute &mut Client

- Example: mutating client state in WMRS:

```
impl<'model> Model<'model> {  
    fn set_fullscreen_window(&mut self, win: Window) {  
        if let Some(client) = self.client_map.get_mut(&win) {  
            client.set_fullscreen(true);  
            self.apply_layout(client.workspace());  
        }  
    }  
    fn apply_layout(&self, index: usize) { /* ... */ }  
    // ...  
}
```

Option 1: distribute &mut Client

- Example: mutating client state in WMRS:

```
impl<'model> Model<'model> {
    fn set_fullscreen_window(&mut self, win: Window) {
        if let Some(client) = self.client_map.get_mut(&win) {
            client.set_fullscreen(true);
            self.apply_layout(client.workspace());
        }
    }
    fn apply_layout(&self, index: usize) { /* ... */ }
    // ...
}
```

error[E0502]: cannot borrow `*self` as immutable
because it is also borrowed as mutable

```
if let Some(client) = self.client_map.get_mut(&win) {
    ----- mutable borrow occurs here
    self.apply_layout(client.workspace());
    ^^^^
    ----- mutable borrow later used here
    |
    immutable borrow occurs here
```

Distributing references to client structures

- **Option 1:** ~~distribute `&mut Client`~~
 - ~~Client mutating methods~~
 - ~~No more than a single reference outstanding~~
- **Option 2:** distribute `&Client`
 - *More* than a single reference may be outstanding

Option 2: distribute &Client

- *Shared* mutable references with Cell and RefCell
- Example: WMRS's Client structure:

```
pub struct Client {  
    window: Window,  
    frame: Window,  
    workspace: Cell<usize>,  
    parent: Option<Window>,  
    children: RefCell<Vec<Window>>,  
    floating: Cell<bool>,  
    fullscreen: Cell<bool>,  
    // ...  
}
```

- Cell<...> and RefCell<...>: *mutable* fields
 - *Interior mutability* constructs
- Other fields: Client constants

Interior mutability: Cell and RefCell

- Cell: move or copy values *in* and *out*
 - *No* reference to contained value
- RefCell: references instead of values
 - Acquire a *lock* before mutating
 - *Dynamic borrowing*
- *Move* mutability to individual fields
 - *Interior* borrow checking
 - Mutate non-exclusive reference
 - Mutate **and** *alias*

Option 2: distribute &Client

- Example: mutating client state in WMRS:

```
impl Client {  
    pub fn set_fullscreen(&self, bool: value) {  
        // copy `value` into the Cell  
        self.fullscreen.set(value);  
    }  
    // ...  
}  
  
impl<'model> Model<'model> {  
    fn set_fullscreen_window(&self, win: Window) {  
        if let Some(client) = self.client_map.get(&win) {  
            client.set_fullscreen(true);  
            self.apply_layout(client.workspace());  
        }  
    }  
    fn apply_layout(&self, index: usize) { /* ... */ }  
    // ...  
}
```

- **All** mutability is interior mutability
 - *Every* reference can be aliased
 - *No* restriction on mutability of references
- Example: WMCPP's Client structure:

```
typedef struct Client* Client_ptr;  
typedef struct Client final  
{  
    Window window;  
    Window frame;  
    unsigned workspace;  
    Client_ptr parent;  
    std::vector<Client_ptr> children;  
    bool floating;  
    bool fullscreen;  
    // ...  
}* Client_ptr;
```

- Example: WMCPP's Client structure:

```
typedef struct Client* Client_ptr;
typedef struct Client final
{
    Window window;
    Window frame;
    unsigned workspace;
    Client_ptr parent;
    std::vector<Client_ptr> children;
    bool floating;
    bool fullscreen;
    // ...
}* Client_ptr;
```

- Client *pointers* instead of window representations
 - Main event loop invariant: window destruction gets reported
 - No need for *smart pointers*
 - We know *exactly* when to deallocate memory
- Other fields: Client constants

Distributing pointers to client structures

- Heap-allocated Client structures are centrally stored
- Example: WMCPP's Client instance storage:

```
class Model final
{
    // ...
private:
    std::unordered_map<Window, Client_ptr> client_map;
    // ...
};
```

Distributing pointers to client structures

- Example: mutating client state in WMCPP:

```
void
Model::set_fullscreen_window(Window window)
{
    if (client_map.count(window) > 0) {
        Client_ptr client = client_map.at(window);
        client->fullscreen = true;
        apply_layout(client->workspace);
    }
}
```

- Rust: borrow checker
 - More restrictive than strictly necessary
 - Language simplicity
 - Compilation speed
 - Need for interior mutability
 - Adds significant programmer effort
 - Renders programming patterns impossible
 - Self-referential structures
 - Adds runtime overhead

Results

- **Compared C++ and Rust in their pragmatics**

- *How* each language achieves common objectives
- The implementation of a window manager

- **Rust**

- Standard package manager and build system
- Guarantees to provide memory safety and prevent data races
- *Concise* and *eloquent* syntax
- Expressively powerful
 - Pattern matching
 - Tagged union enumerations
 - Derivable traits
 - Macros

- **Rust (cont.)**
 - Consistent
 - Operator overloading *only* through traits
 - Error mitigation
 - More programming effort
 - Runtime cost
 - Difficult to work with references
 - Programming patterns impossible
 - Interior mutability

- C++
 - Lack of standardized package manager and build system
 - Leaky include system
 - No safety guarantees
 - Complex syntax
 - Inconsistencies
 - Operator overloads
 - Easy to work with references, pointers

- **Rust**
 - Learnt how *not* to do it
 - Borrows from other languages
 - Restrictive but safe
 - Simple yet expressive
- **C++**
 - Lacks Rust's *hindsight*
 - Much more complex
 - Unrestrictive but unprotective
 - Decades of revisions
 - Initial core design goals