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

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June 20, 2021

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Agenda

Agenda

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 <u>window manager</u>

- **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 <u>window manager</u>

- **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

Practicalities of working with external code

1. **Package management**
   - *Availability* of external code

2. **Decoupling dependencies**
   - *Maintainability* of external code

Managing the <u>availability</u> 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]                            [lib]
name = "wmRS"                        name = "winsys"
version = "0.1.0"                    path = "src/winsys/mod.rs"
edition = "2018"                     [[bin]]
license = "BSD3"                     name = "core"
default-run = "core"                 path = "src/core/main.rs"
description = """                     [[bin]]
An ICCCM & EWMH compliant X11        name = "client"
reparenting, tiling window manager,  path = "src/client/main.rs"
written in Rust                      [dependencies]
"""                                  x11rb = "0.8.0"
```

Managing the <u>maintainability</u> 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 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:
  ```rust
  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:
  ```rust
  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:~~

  ```rust
  use x11rb::connection;

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

- Example: WMRS's conn trait object:

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

1. Hide the connection with the windowing system behind an <u>abstract class</u>

- 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 <u>abstract class</u>

- Example: WMCPP's `Connection` abstract class interface:
  ```cpp
  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:

```cpp
#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:
  ```cpp
  #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:
  ```cpp
  #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

Rust <u>traits</u> vs C++ <u>abstract classes</u>

- 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 <u>enum</u>

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

2. Create windowing system agnostic event <u>std::variant</u>

- 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:

```cpp
typedef std::variant<        struct Mouse { MouseEvent event; };
    std::monostate,          struct Key { KeyEvent event; };
    Mouse,                   struct CloseRequest { Window window; };
    Key,                     struct ScreenChange {};
    CloseRequest,            // ...
    ScreenChange,
    // ...
> Event;
```

wmRS: wmCPP:

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

WMRS:

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

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

WMCPP:

```cpp
Event step();

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

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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:

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

- Equivalent to:
```rust
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:
```cpp
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++ 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
  - ...

Input Bindings

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:

```rust
#[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.):

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

1. **Establish abstract notion of input**

   - Example: WMCPP's *mouse input* abstractions:
     ```cpp
     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.):

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

2. Map input to window management actions in a `HashMap`

- Example: WMRS's *input mappings*:

```rust
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:
  ```rust
  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:
  ```rust
  #[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

2. Map input to window management actions in a `HashMap`

- Example: WMRS's mouse input mapping:

```rust
#[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)])

2. Map input to window management actions in a `HashMap`

- Example: WMRS's mouse input mapping:
  ```rust
  #[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:

```rust
#[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 (not automatically derivable)

2. Map input to window management actions in a `HashMap`

- Example: WMRS's mouse input mapping:

```rust
#[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:

```rust
#[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:

```rust
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:

```rust
let mut mouse_bindings = HashMap::new();
mouse_bindings.insert(
    MouseInput {
        button: Button::Middle,
        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:

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

  - MouseInput used as *key* to std::unordered_map

    - operator==
    - std::hash<MouseInput>::operator()

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

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

```cpp
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<MouseInput>::operator()
  implementation:

```cpp
struct MouseInput final {
    Button button;
    std::unordered_set<Modifier> modifiers;
};
namespace std
{
    template <>
    struct hash<MouseInput>
    {
        size_t
        operator()(const MouseInput& 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: WMCPP's std::hash<MouseInput>::operator()

  implementation:
  ```cpp
  size_t
  operator()(const MouseInput& 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

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

- *No* automatic deriving of operator overloads
- Example: WMCPP's Modifier's operator| implementation:

```cpp
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::Middle, { Ctrl, Shift, 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:

```rust
pub struct MouseEvent {              pub type MouseBindings = HashMap<
    pub kind: MouseEventKind,            MouseInput, MouseAction
    pub input: MouseInput,           >;
    pub window: Option<Window>,
}

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++ 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*

- Example: Constructing mouse bindings in WMRS's using *declarative macros*:

```rust
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 similarly powerful metaprogramming feature

Clients

Second Frame

Hello, world!