Engineering embedded software

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“Bad programmers worry about the code. Good programmers worry about data structures and their relationships.”

Linus Torvalds

What will we see?

How to code properly

- “Properly?”
- In such a way that your code becomes scalable, maintainable, robust..
- Do engineer’s job!

Three pillars

- SOLID programming
- Design patterns (for embedded systems)
- CLEAN code architecture

*Disclaimer: these two are **<u>not</u>** born for embedded systems*

SOLID programming

SOLID programming

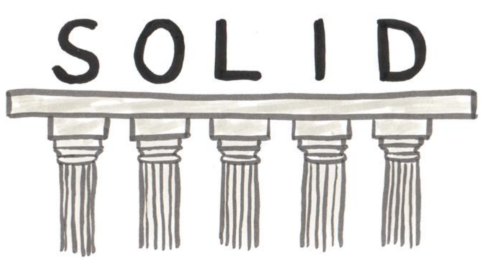
Aka: **Object Oriented Design**

Five principles that ~~save your life~~ make the difference between a programmer/coder and a software architect

› (Or between an happy person and a sad person)

Applicable to object-oriented programming (but not only)

1. **S**ingle Responsibility
2. *Open/Close principle*
3. *Liskov substitution*
4. **I**nterface segregation
5. **D**ependency inversion



Single responsibility principle

A software entity should have only one reason to change

- Aka: every class should have a single responsibility or single job or single purpose

- **Answers to**: "What should I put into a class?"
- **Pros**: you always know where/what/how to change your code, and don't mess up things
- (**Cons**: increase number of classes and effort...)

<u>How to implement this in embedded code?</u>

- Replace "class" with "module" in the above sentence

Open/Close principle

Entities should be open for extension, but closed for modification

- Aka: you should never change anything, always adding new behavior using polymorphism

- **Answers to**: “How should I extend my code?”
- **Pros**: reduce the number of bugs and headaches
- (**Cons**: N/A)

<u>How to implement this in embedded code?</u>

- Might not be easy to implement

Liskov substitution principle

You should be able to substitute any parent class with any of their children without any behavior modification

- Aka: “Rectangles vs Squares”

- **Answers to**: “When and what should I inherit?”
- **Pros**: code is scalable, and minimize changes upon modifications
- (**Cons**: you have to think before you code)
  - not actually a con…

<u>How to implement this in embedded code?</u>

- Replace “class” with “module” in the above sentence

Interface segregation principle

Many client specific interfaces are better than a big one

› Aka: Interfaces should be the minimal set of behaviors you need

› **Answers to**: "When should I create an interface?"
  – Spolier: "as much as you can"
› **Pros**: you minimize dependencies in your code (thus, programming effort)
› (**Cons**: trust me...NONE)

Always remember: an interface is a contract. You can build (automatic) tests over contracts!

<u>How to implement this in embedded code?</u>

› Replace "interface" with "C[++] header" in the above sentence

Dependency inversion principle

Your project shouldn't depend of anything, make those things depend of interfaces

- Design wrappers around your dependencies
  - (This is **NOT** "dependency injection"...but its good friend)

- **Answers to**: "How can I avoid getting crazy with dependencies?"
- **Pros**: isolation between code components; your code reflects the analysis/model of business
- (**Cons**: additional programming effort)

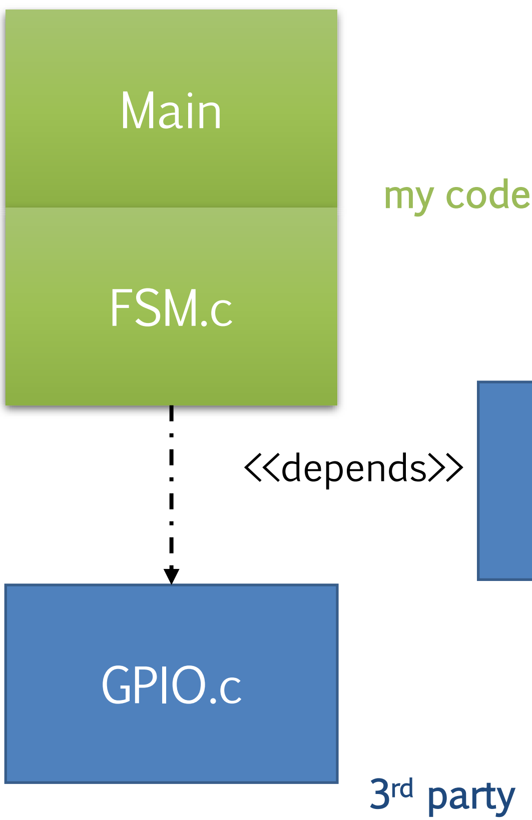
<u>How to implement this in embedded code?</u>

- We'll see this now....

Dependency inversion principle

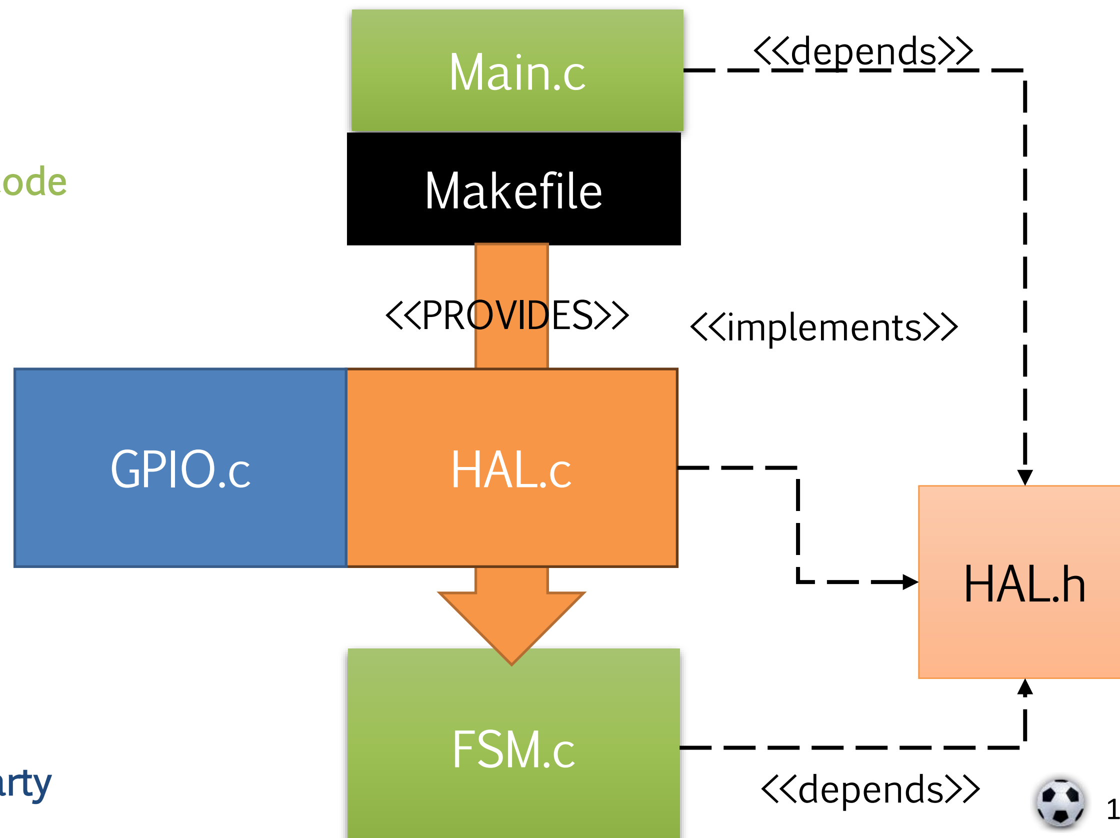
Library-like approach

- Tied to 3rd party code



Framework-like approach

- Inversion of control
- Dependency injection



Dependency inversion principle

HAL.c

```c
#include "GPIO.h" // External lib

/* Implementation */
void toggle_led(int led_id, bool onoff) {
  // ...
}
```

HAL.h

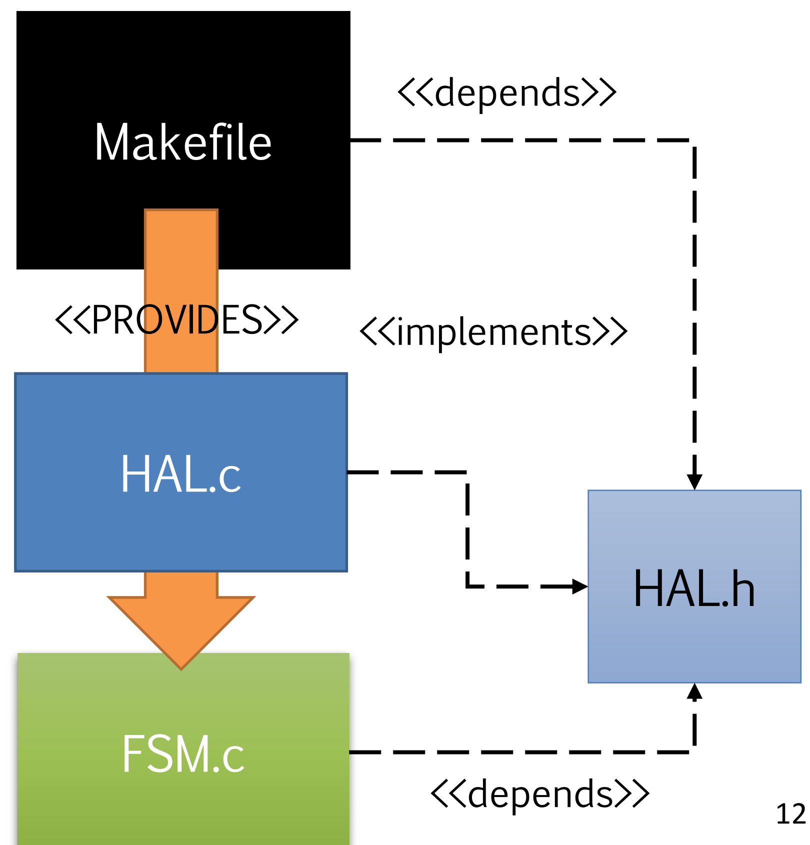
```c
/* Turns on the blue led */
void toggle_led(int led_id, bool onoff);
```

FSM.c

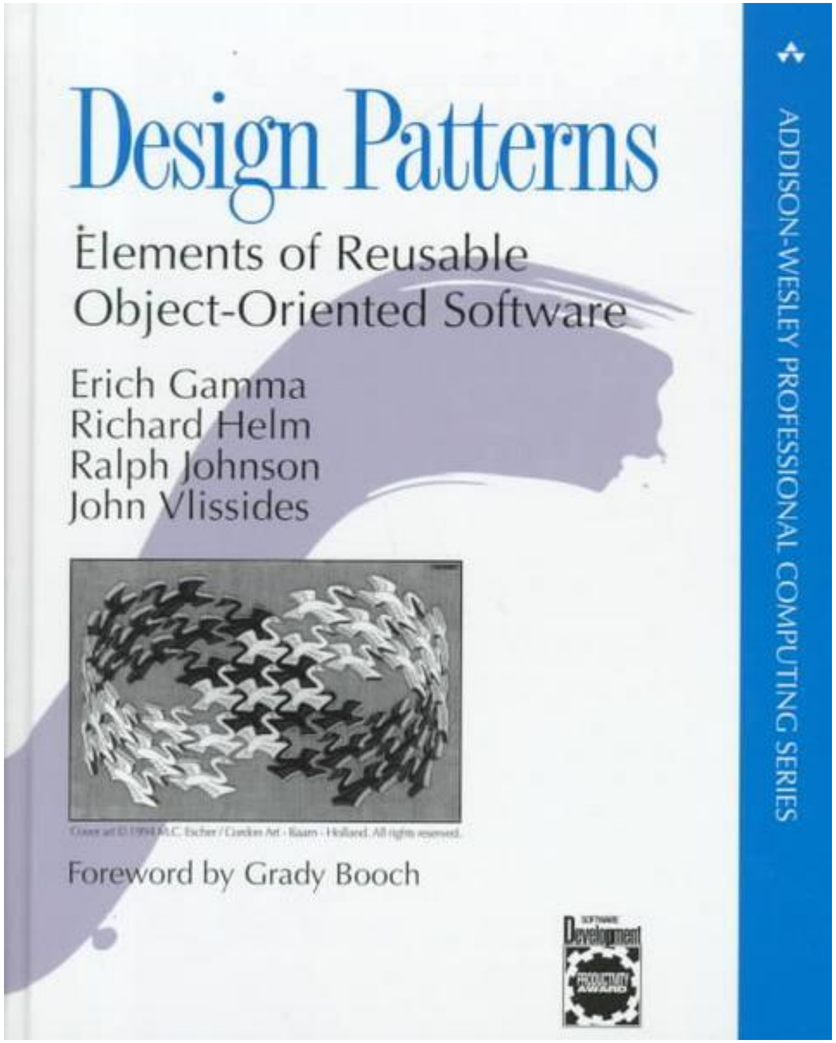
```c
#include "HAL.h"

/* Computes output. Moore machine. */
void mfn(int currState) {
  switch(currState) {
    case 0:
      toggle_led(BLUE, true);
      break;
    case 1:
      // ...
```

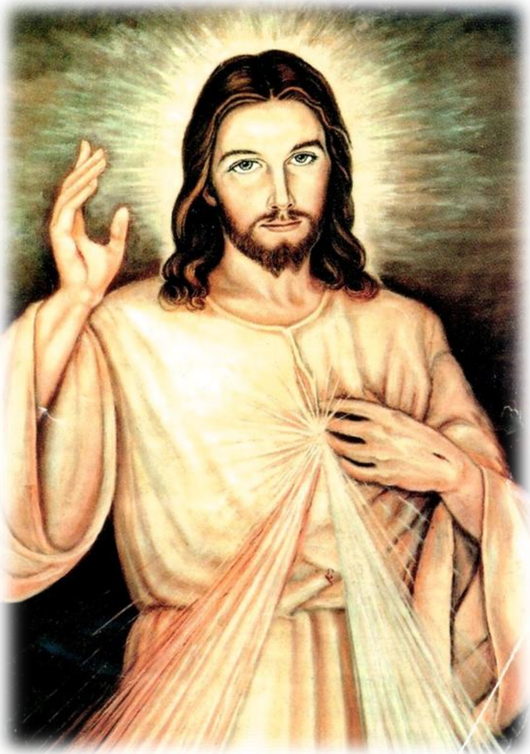
Framework-like approach

- Inversion of control
- Dependency injection



Design patterns





The Gang of Four

Elements of reusable Object Oriented Software *

Elements

of reusable

Object Oriented

Software

** Cit. Wikipedia*

Elements of reusable Object Oriented Software *

Elements

- Simple, basic parts of

of reusable

- We did mistakes, we learned from them

Object Oriented

- Yet can be reused in non-OOP structure

Software

- ....

** Cit. Wikipedia*

As simple as that

Your parents, grandparents, teachers, ancestors faced problems

They found solutions

- ..smart solutions...

This is their (our) legacy

- Hundreds of know problems, with known solutions
- All of them build upon basic principles
- Sync/vs async, de-coupling, SOLID, etc

Ok, let's be clear

What design patter can give you

- A common, known vocabulary
- Solve complex problems way ahead of time
- Provide solid ground to motivate your design choices

What they cannot give you

- Exact solution: each problem/project is unique
- Full-fledged solution for every design/programming problem

But they can save you a lot of headaches!

How do they help you?

They force you to

- Find appropriate objects to model your domain (aka: decomposition)
- Determine objects granularity (e.g., *Creational* patterns such as *Factory*)

Clearly define interfaces (.h) and modules (.c/.cpp)

- Defining implementations...
- ...and the relations among them

Implement reusable code

- Separate modules for separate functionalities
- Delegation (e.g., *Adapter*, *Strategy*, *Visitor*) implements loose coupling among SW entities
- *"Who has control?"*, *"Who creates objects?"* ...focus on the **role** of your SW entities!

Commonly known (design) mistakes

...you didn't know about

- You explicitly declare object and modules
- You explicitly call methods, to implement an high-level operation
- You have strong dependencies on HW and SW platforms (e.g., embedded)
- Your module depend on internals of another module
- Your code might depend on algorithms that you implement
- Tightly coupling among components/modules/classes/...
- Always use subclasses to extend functionality/specialize behavior
- (not actually a mistake) you might need to modify a “closed” modules
- ...

The so-called Code smells

(Incomplete) taxonomy of design patterns

Creational

- Factory
- *Singleton*
- Builder
- Prototype

Structural

- **Adapter / HAL**
- Bridge
- Composite
- Façade
- **Proxy**
- Decorator
- FlyWeight

Behavioral

- Chain of Responsibility
- Command
- Iterator
- Interpreter
- Mediator
- Memento
- Observer
- State
- Strategy
- Visitor

...and...

- **CLEAN**

The typical structure of a design pattern

1. Name, purpose, aliases
2. Motivation - *Why the hack should I do so?*
3. Applicability - *Where it applies, and where it doesn't*

=> What to do (Personal note: even if you don't know why…use them!)

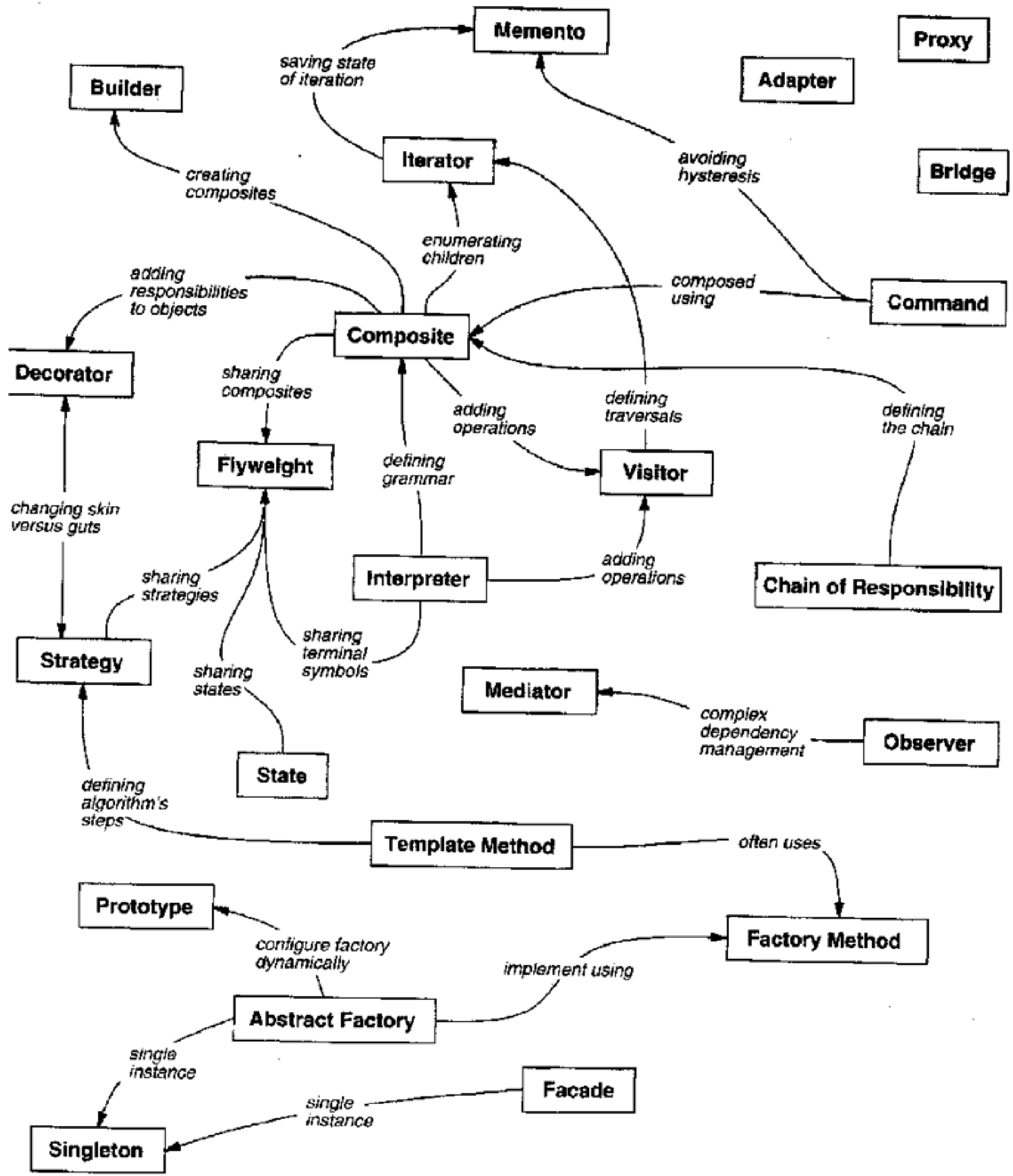
A full set of example/code snippets to implement it

- With known examples
- With related patterns (everything is part of a bigger picture!)
- With (wanted or unwanted) side effects

The bad news

- I will only teach you 2-3 of them
- Advanced (LM?) courses can give you a full
- Coding, coding, coding

Relationships between patterns



Hardware Abstraction Layer

(aka: Hardware Proxy, Hardware Adapter...)

We are closer to HW than ever

Software stack for General-purpose/HPC systems vs. Embedded systems

- Note: this is just a possible example

App
Libs
Docker
Runtime libs
Framework
OS
Hyper-V
BSP/HAL

Can even be compiled all together

App
SDK libs
(OS- MicroK)??
BSP/HAL

The challenge: abstracting the HW

- Cores and caches are hidden, however specific functionalities might exist (ex: RISC-V extensions)
- Explicit memory management: call `free`/`delete` after `malloc`/`new`
- HW devices are typically memory-mapped: I/O space
- We speak with them setting-unsetting bits, registers, using masks, etc

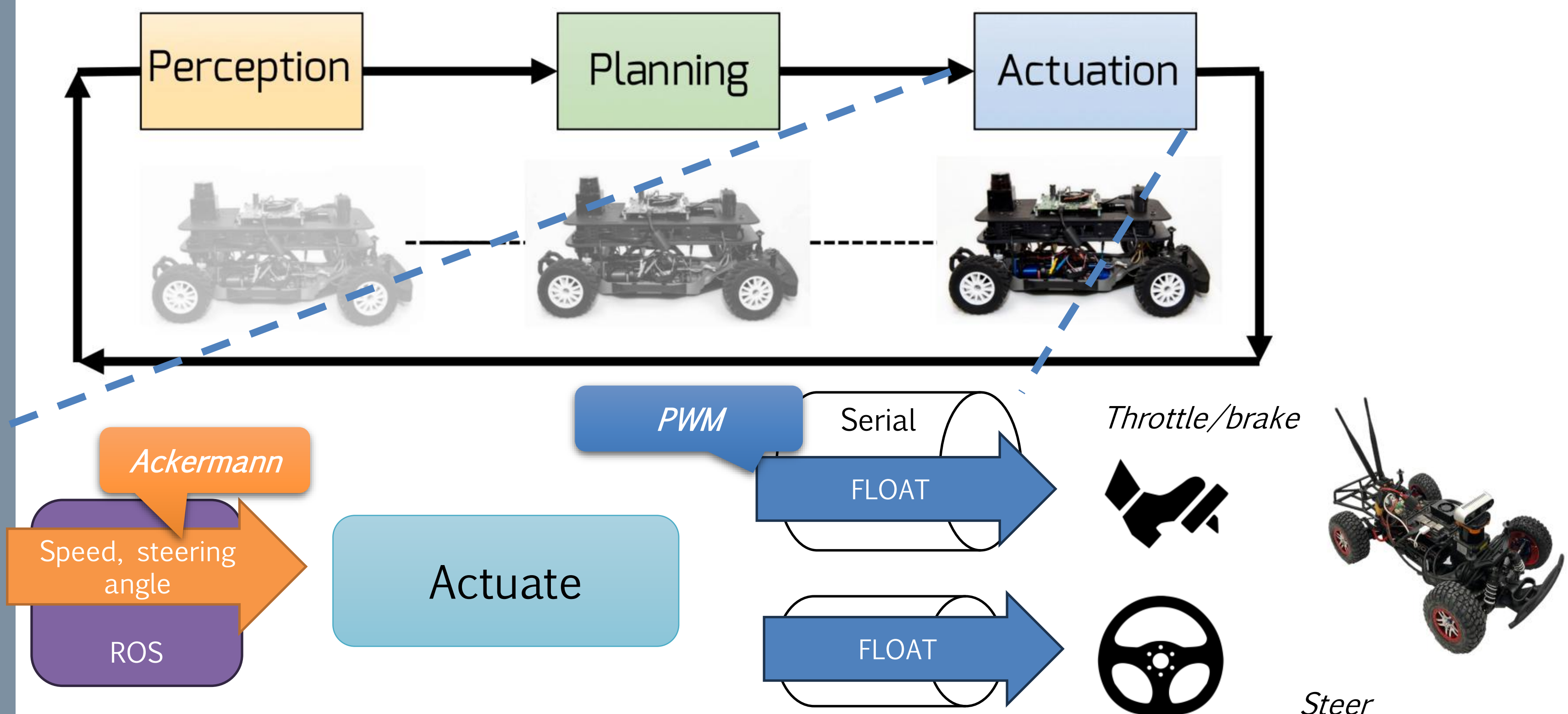
Every device has a specific protocol!

- Actually, also GP system have this issue...but they have full-fledged OS such as GNU/Linux and Win
- How can we convert low-level drivers/protocols into high level protocols?
- E.g.; "Set a bit here" => "Activate the robotic arm"

Motivational example: ~~F1/10~~ Roboracer

- The engine controller (aka: VESC) speaks *PWM* protocol, via Serial
- Driving system runs using *Ackermann* control protocol, via ROS2

Different protocols, different data formats



Hardware Proxy / Hardware Abstraction Layer

A **structural** pattern

Purpose

- Represent a given device with specific (C) structure and primitives, that provide access to it

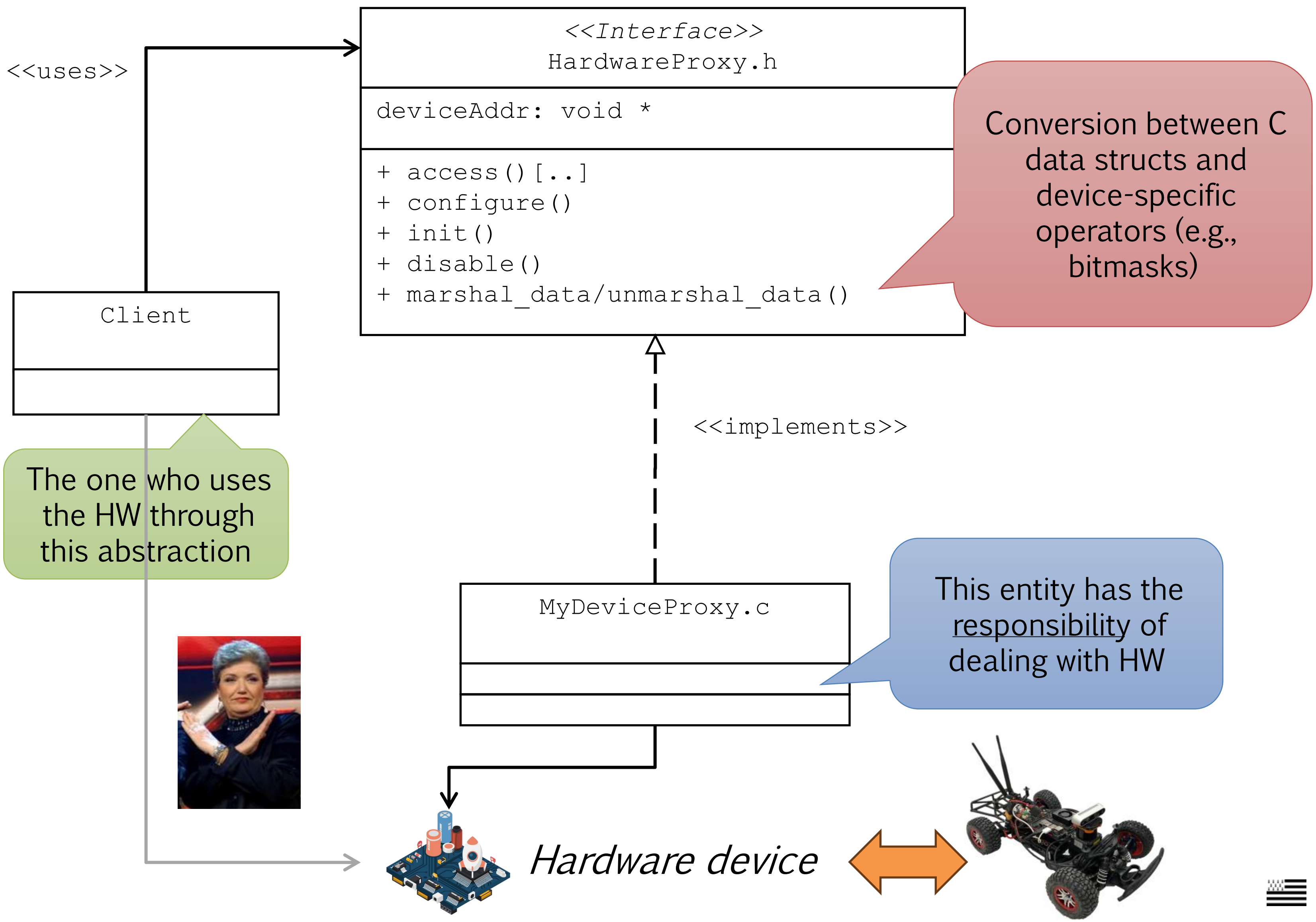
Motivation

- If we access HW directly, changes to HW might affect our code, so we wrap it in a **proxy**

Applicability

- Whenever you need to abstract HW which is not "standard" in the sense that there exist no standard representation for it (ex: threads are an abstraction for CPU cores)

Pattern structure



Does this remind of something?

HAL.h

```c
/* Turns on the blue led */
void turn_on(LED led_id);
```

FSM.c

```c
#include "GPIO.h"

/* Computes output. Moore machine. */
void mfn(int currState) {
  switch(currState) {
    case 0:
      turn_on(BLUE);
      break;
    case 1:
      // ...
```

HAL.c

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void turn_on(LED led_id) {
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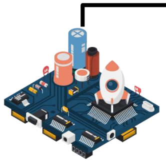


Hardware device

Hardware Adapter pattern

A **structural** pattern

Purpose

- Adapt the specific HW interface to the format required by the application

Motivation

- While all HW interfaces have similar operations (see HW Proxy pattern), their data format might certainly differ!
- Actually, it is typically used together with Proxy!

Applicability

- When you need to adapt application data structs to HW

Consequences/side effects

Same as previously seen in Adapter, plus

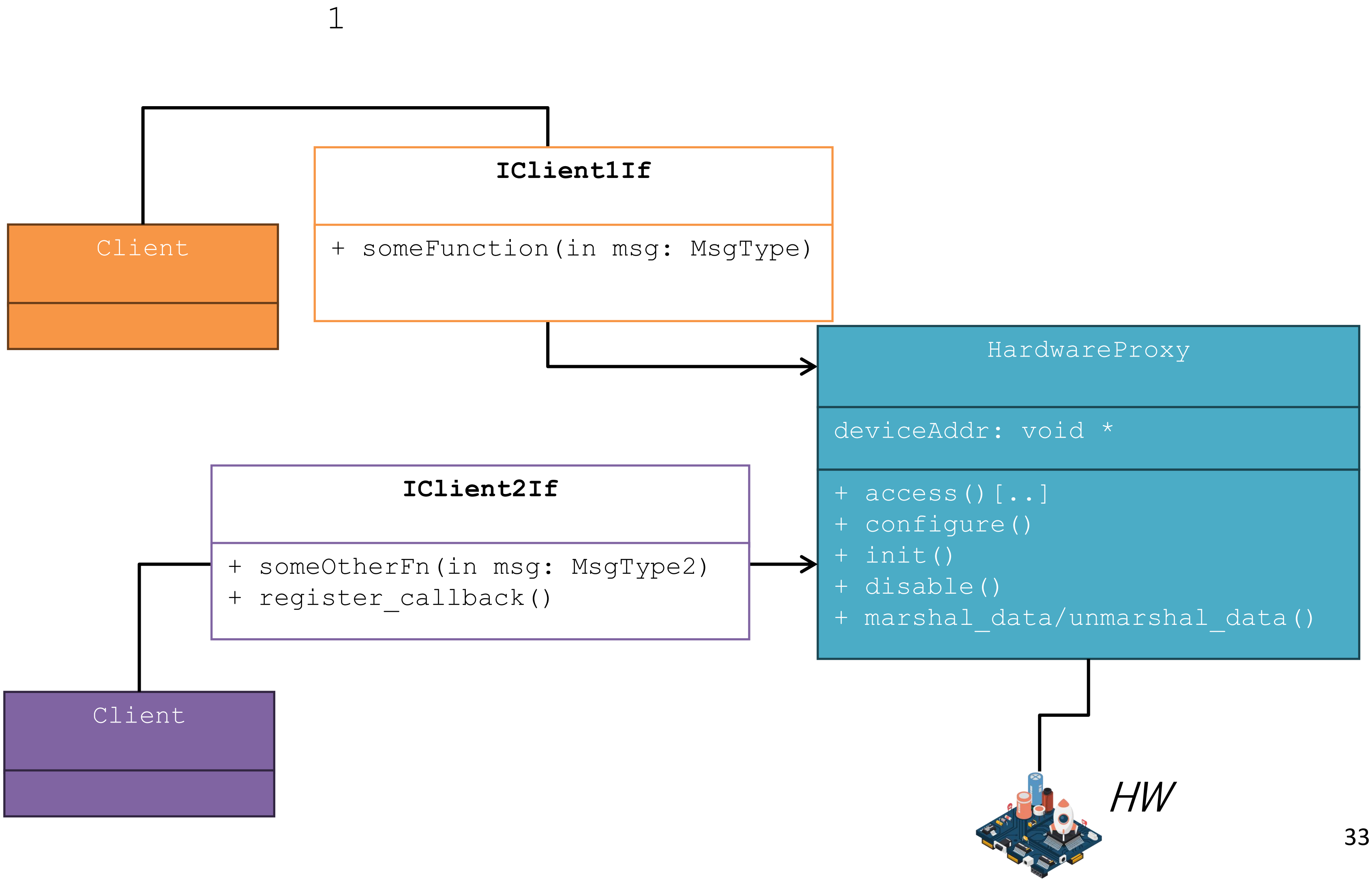
- You have to handle concurrency (with locks, critical regions...we'll see this)
- You shall implement interrupt-base device-to-app communication (e.g., callbacks)
- Format conversion might add delays (which, in embedded systems, are extremely unwanted!)

Notes

- In C coding, headers contain contracts, hence, interfaces!

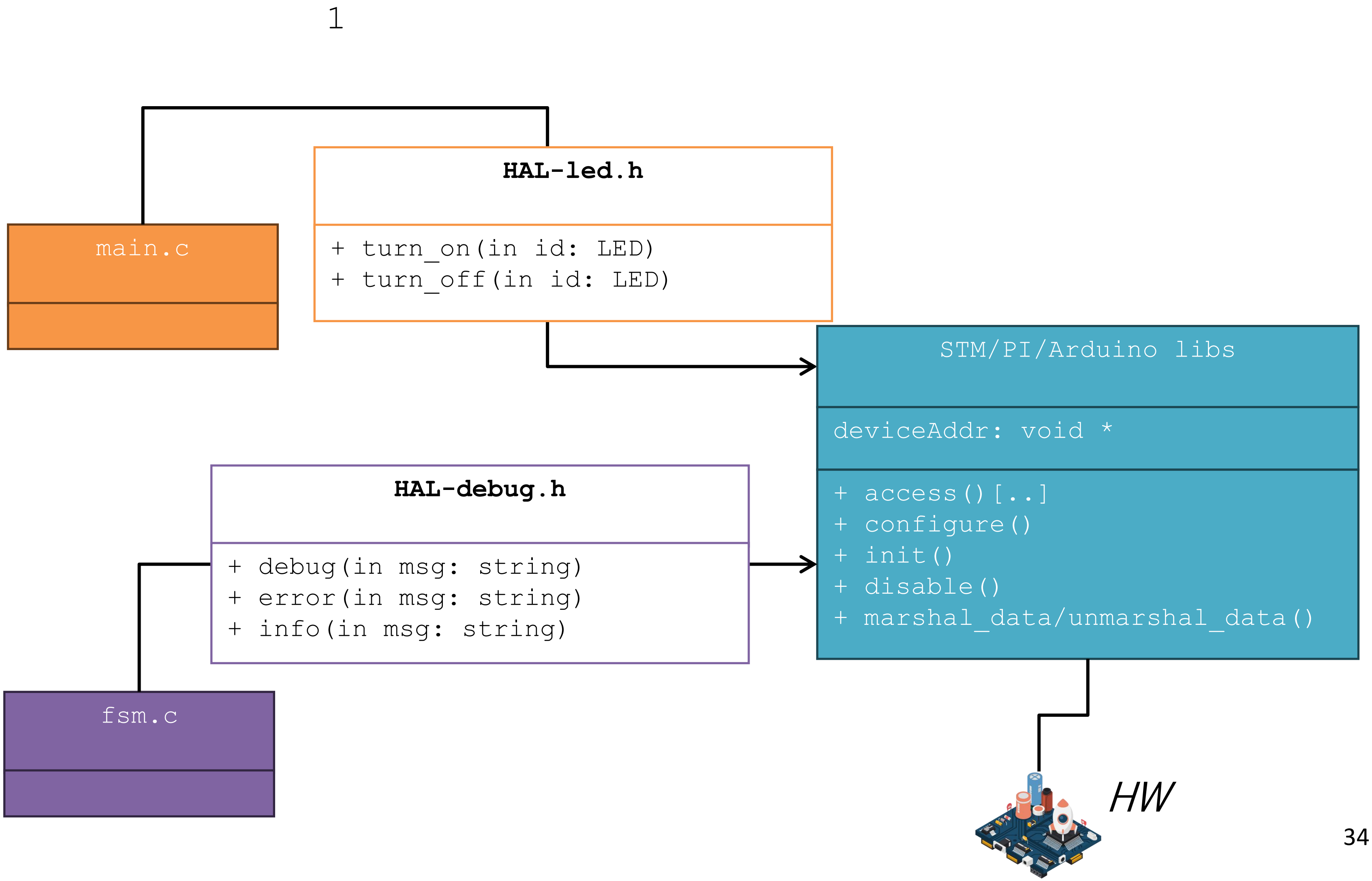
Roles

- Note. Here, I omit the structure of Proxy for the sake of readability



Roles (in our example)

- Note. Here, I omit the structure of Proxy for the sake of readability



Motivational example: F1/10

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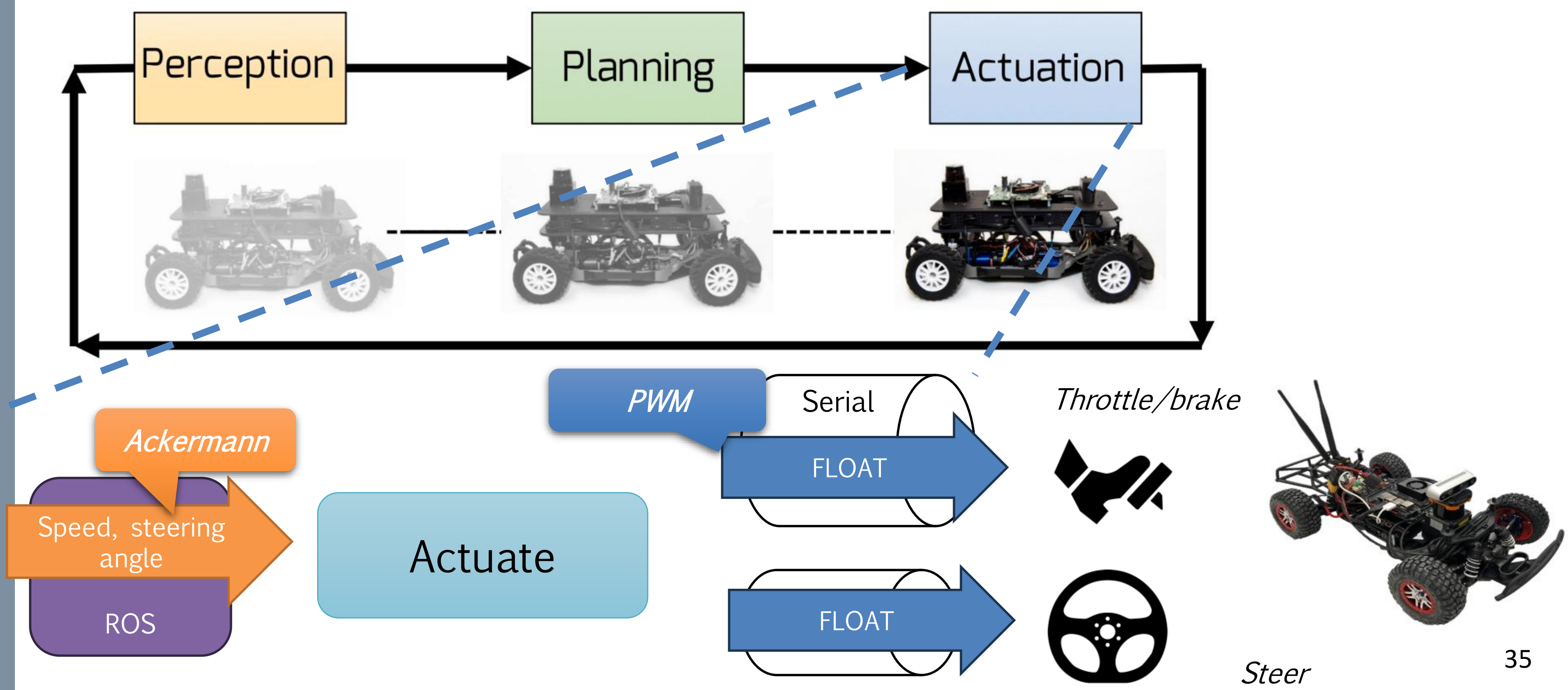
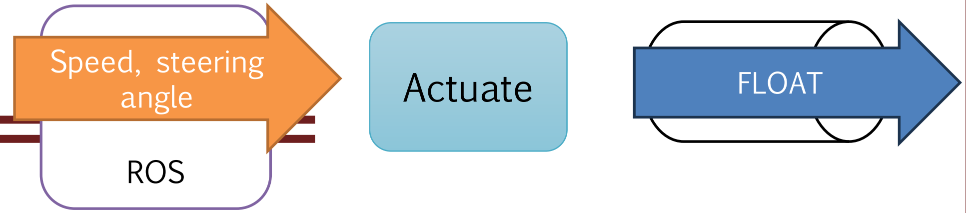
Different protocols, different data formats

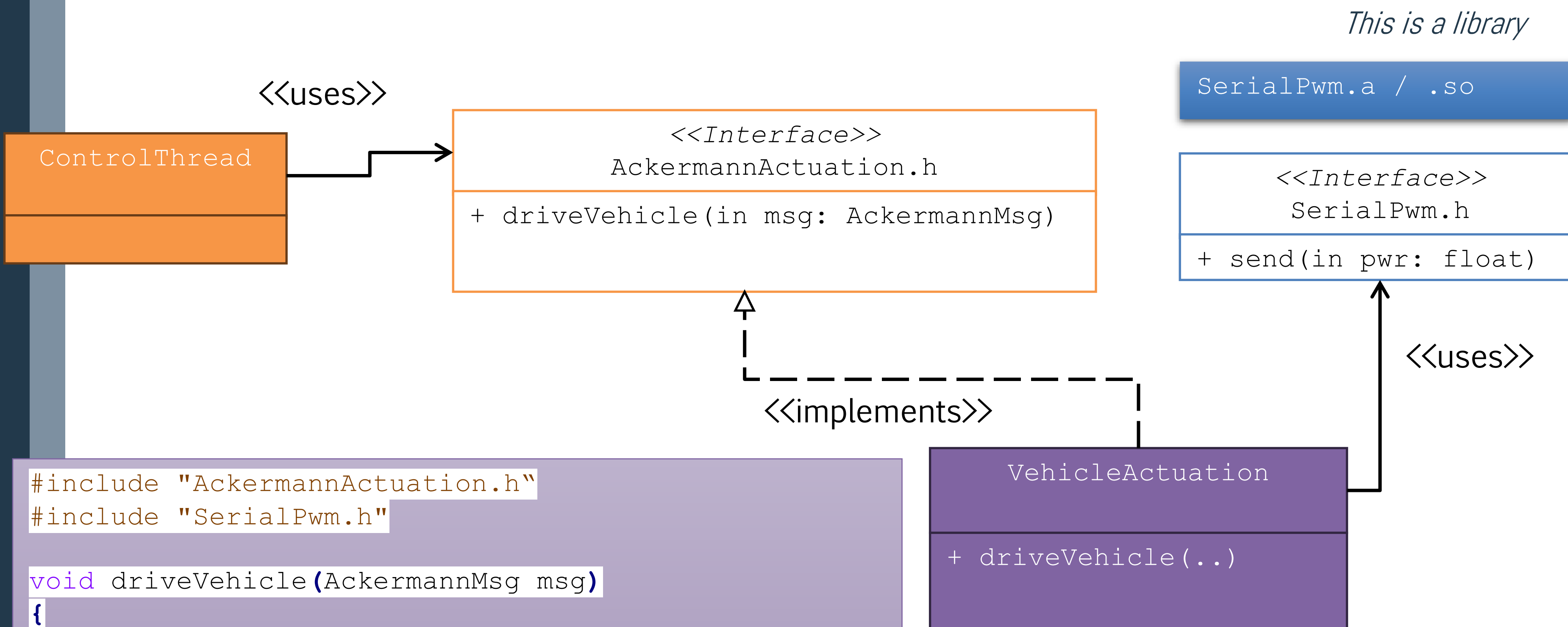


Example: the F1/10



Note

› Here, I implemented using C-style primitives



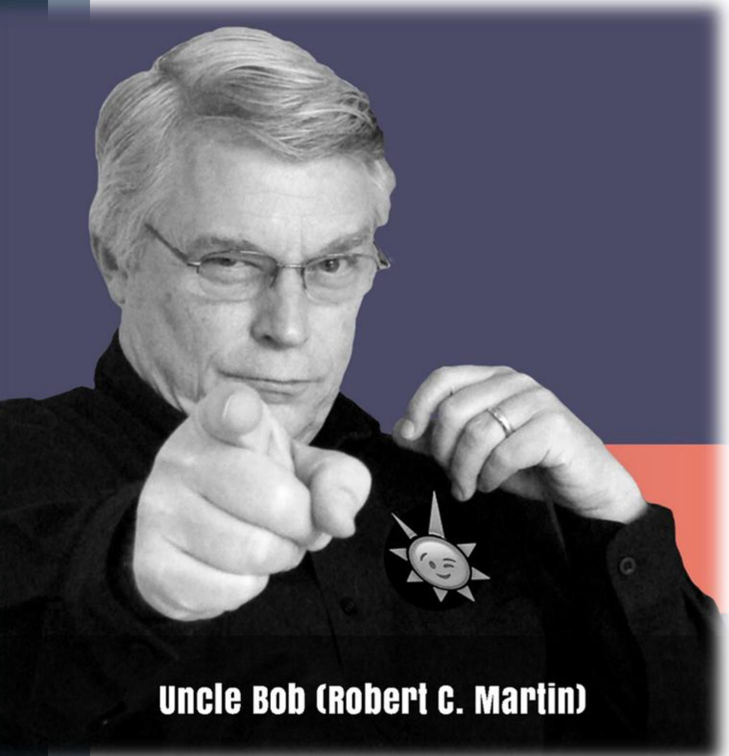

```c
#include "AckermannActuation.h"
#include "SerialPwm.h"

void driveVehicle(AckermannMsg msg)
{
  send(/* ... */);
}
```

CLEAN code architecture

What is it?

A code architectural pattern

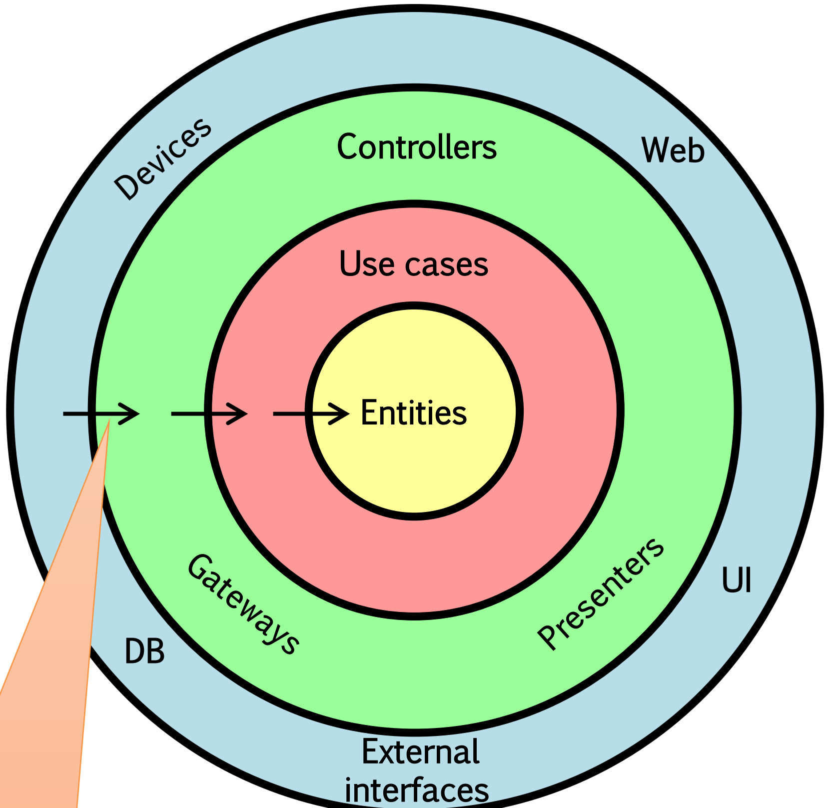
- A structure that enables building software that is more scalable, testable, maintainable
- Built upon/heavily relies on good coding practices (e.g., SOLID, design patterns..)
- Disclaimer: +15-20% dev time overhead



- Formalized by “Uncle Bob”
- Started his blog in 2011
- Adopted by nearly all mid- and large-scale projects

As simple as this

- Aka: “Onion Architecture”

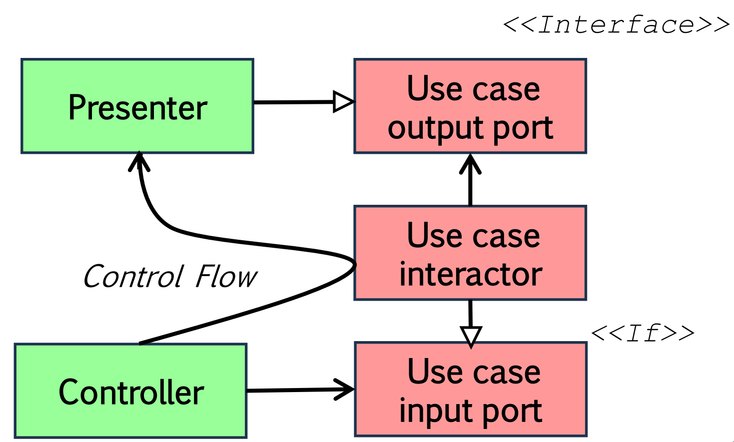


Enterprise business rule

Application business rule

Interface Adapters

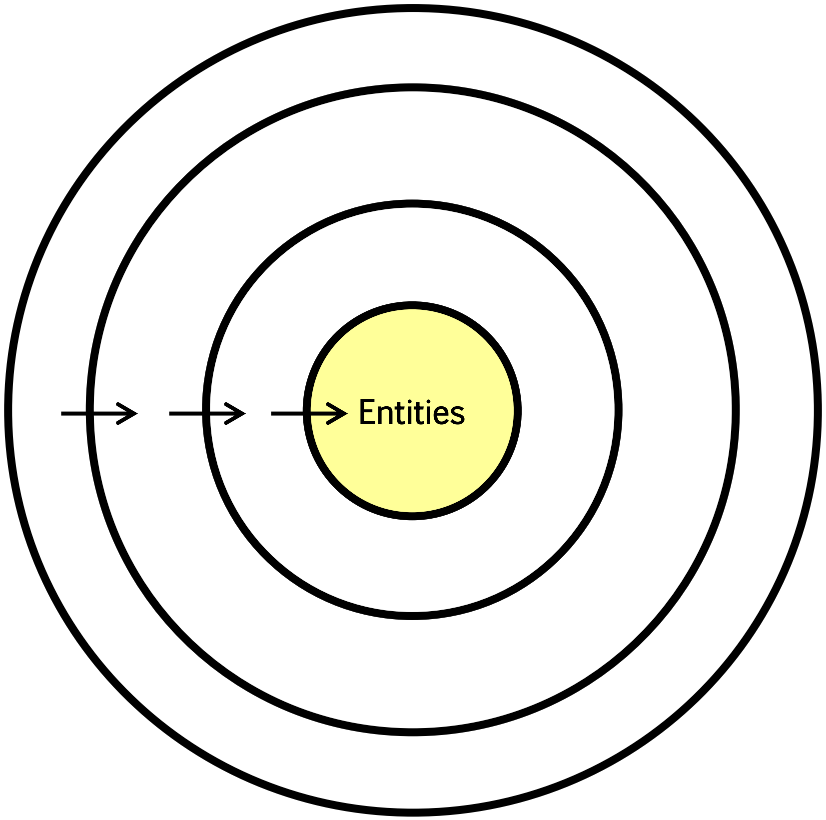
Frameworks & Drivers



Dependencies go from “out” to “in”

The Model

- Our view of the world: just field, and basic operations (get, set..)

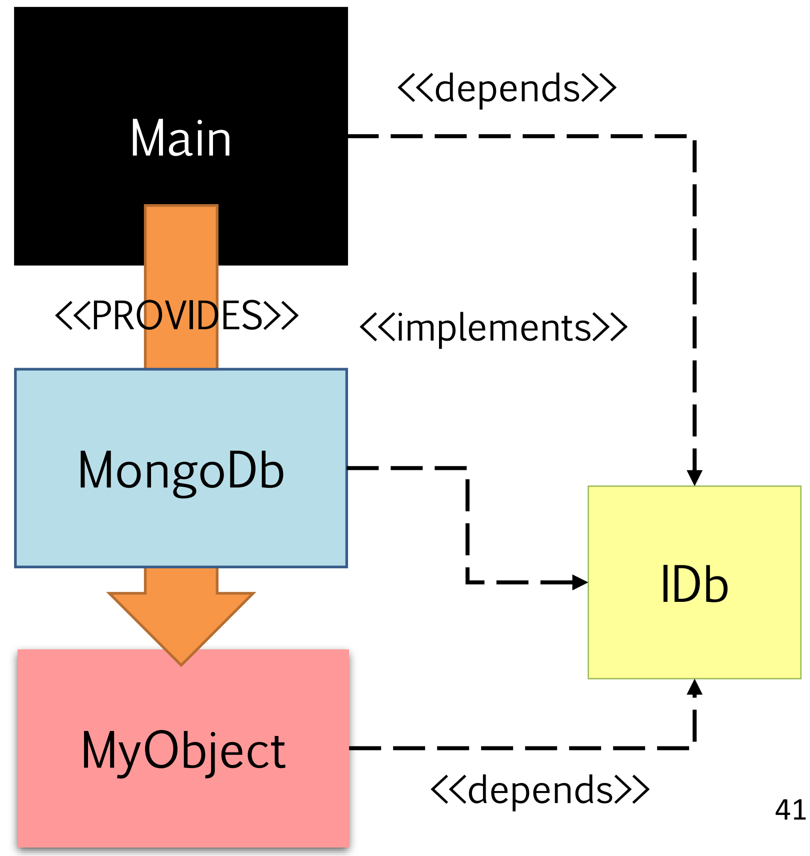


Enterprise business rule

- Everything depends on them/includes them, they do not depend on anything
- Why is this so important?

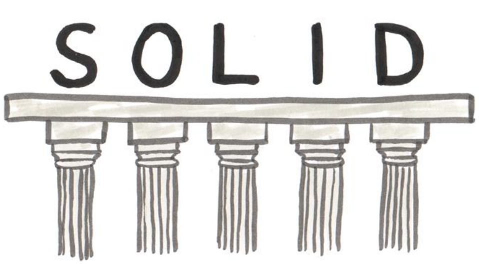
Dependency Inversion

- Reduce coupling
  - Avoids unnecessary dependencies that ultimately make the code hard to modify
- Enables fast testing and debugging
- Wraps functionalities (Interface Segregation)



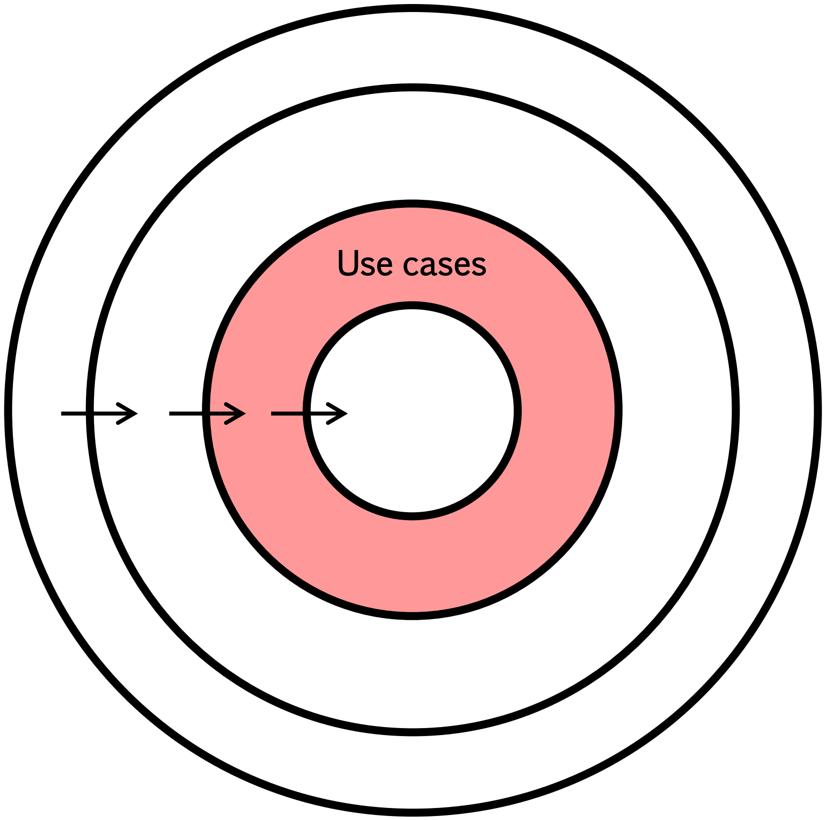
(Only one issue)

- You need to find a (elegant) way to provide the required services
- Dependency Injection!



Straight from requirements

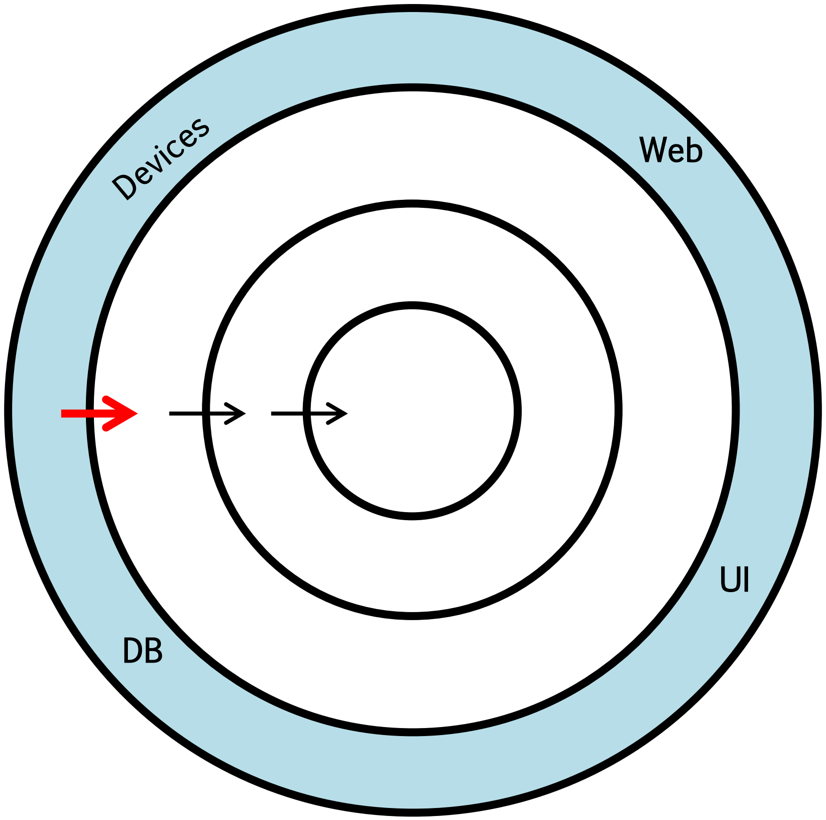
- Application specific logics: functionalities



Application business rule

“The bad world”

- This layer represents, and wraps, “external” dependencies, e.g., DTOs, MongoDb…

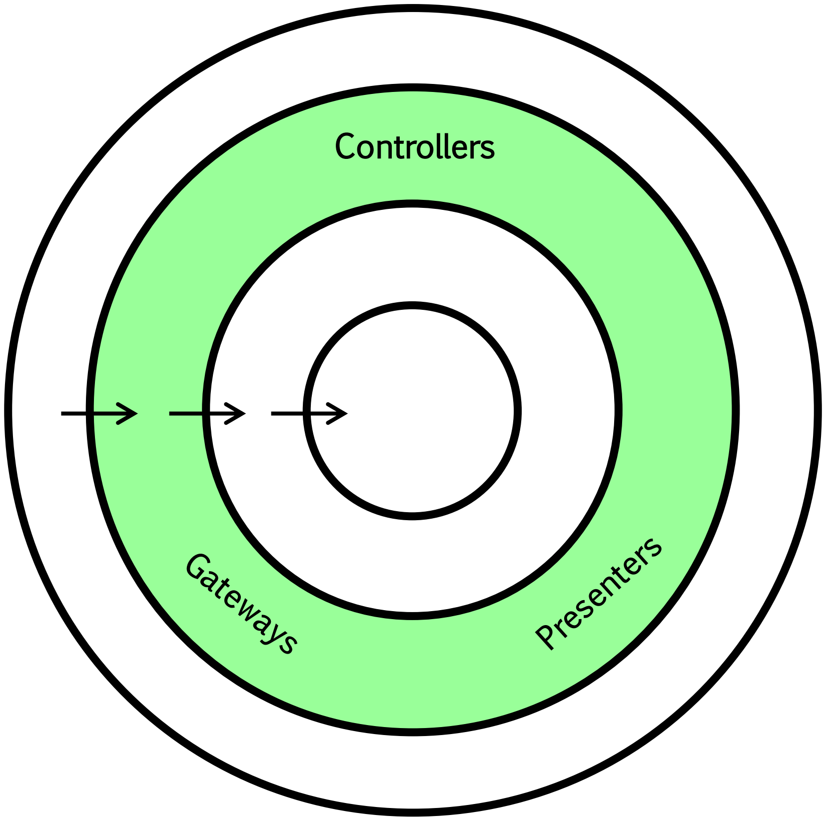


Frameworks & Drivers

- How do we implement the dependency?

Our good old friend

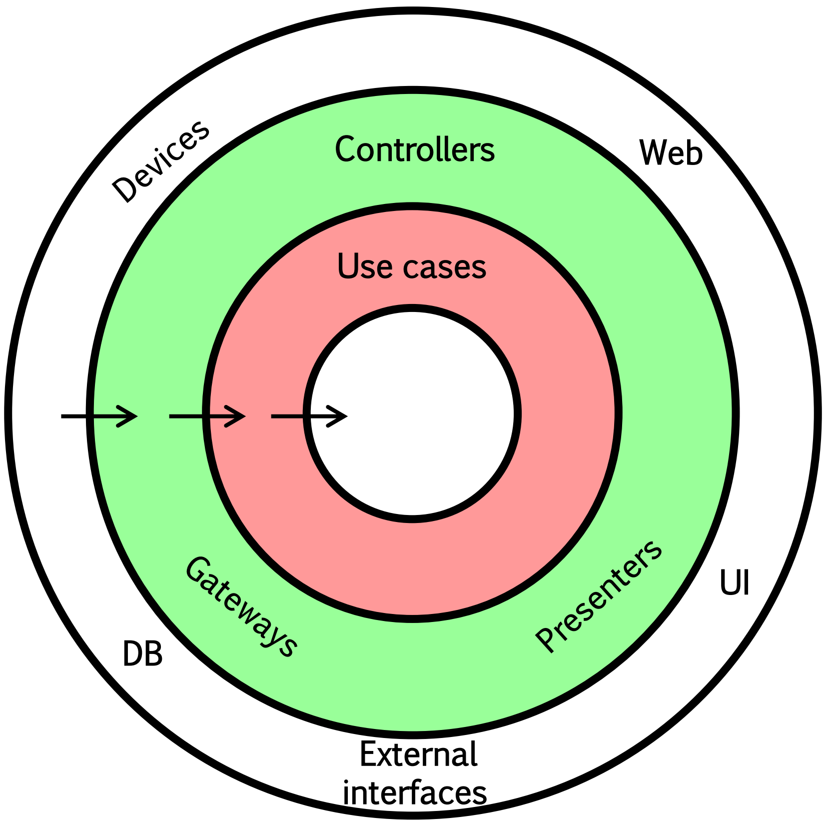
- Aka: “Onion Architecture”



Interface Adapters

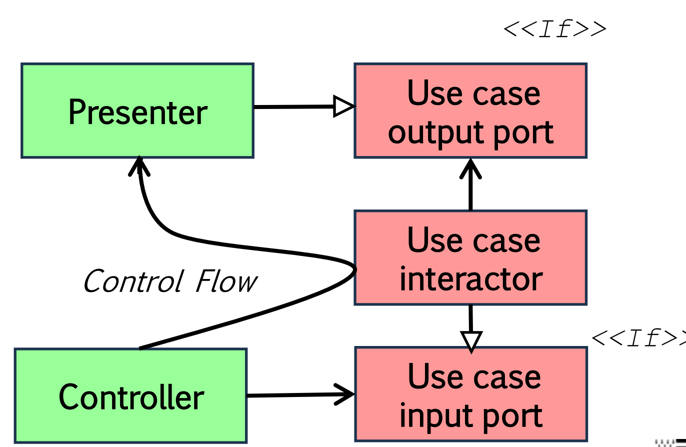
Control flow, and class diagram

- Note how we use Interfaces, and (consequently) Dependency Injection



Application business rule

Interface Adapters



References

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- http://hipert.unimore.it/people/paolob/pub/Industrial_Informatics/index.html

My contacts

- paolo.burgio@unimore.it
- http://hipert.mat.unimore.it/people/paolob/

Resources

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- A "small blog"
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