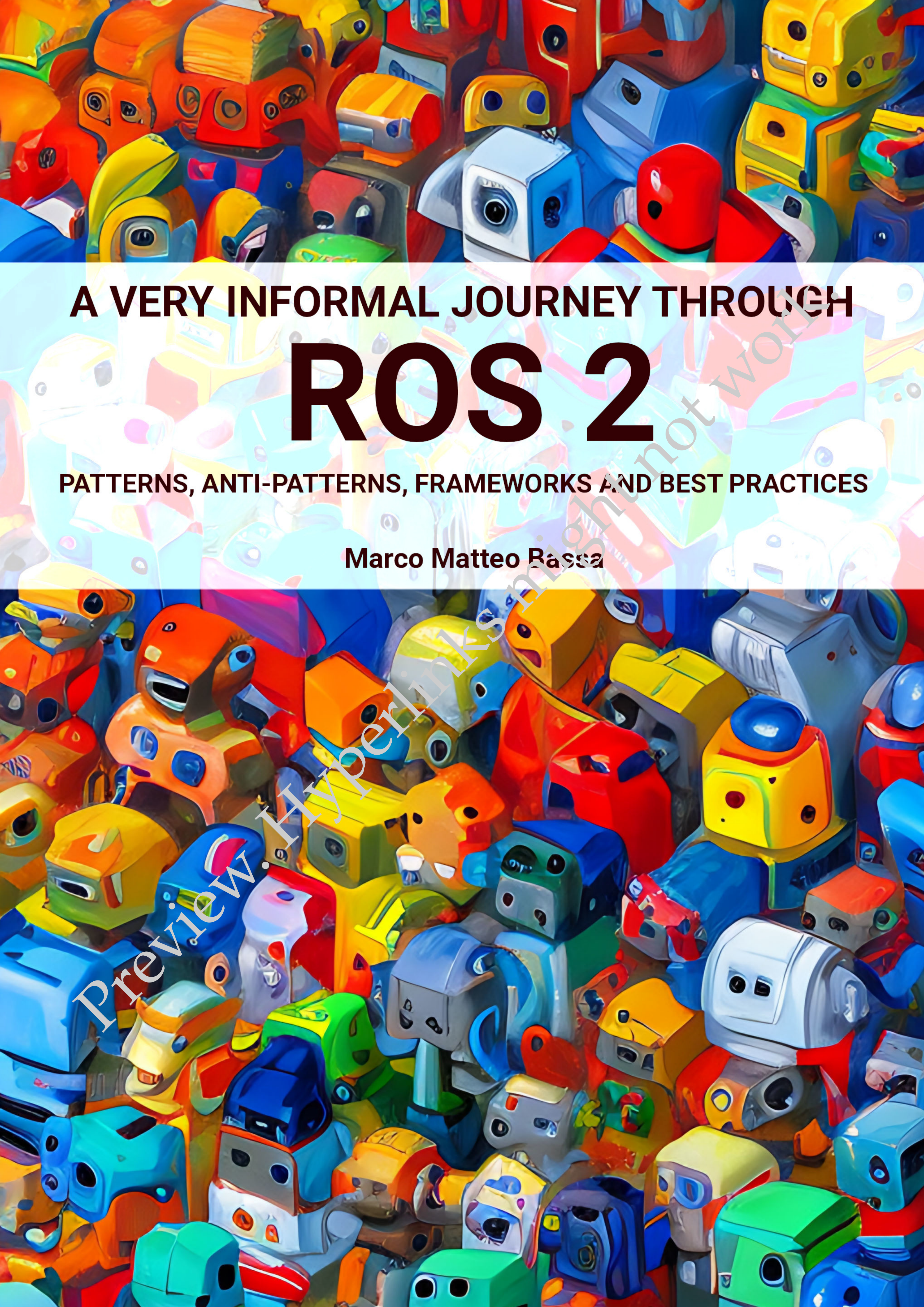

A VERY INFORMAL JOURNEY THROUGH

ROS 2

PATTERNS, ANTI-PATTERNS, FRAMEWORKS AND BEST PRACTICES

Marco Matteo Bassa

A very informal journey through ROS 2

patterns, anti-patterns, frameworks and best practices

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Robotics is the art of bringing some piece of your own brain to work on a machine.
I hope you aren't a psychopath.

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Colophon
This document was typeset with the help of KOMA-Script and LaTeX using the kaobook class.

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Introduction 1

1.1 ROS 2

The Robot Operating System, widely known as ROS, was for the first time released in 2007, and has since then revolutionized the way developers create, and most importantly share, software for modern robots around the world. Roboticists tend to have mixed feelings about this framework: while it allows for the fast development of code for robotic platforms, reusing existing modules that are common between different use-cases, it is often criticized for not being an "industry ready solution", good only for prototyping and for research purposes. In the past few years, many companies have been fighting against this idea, bringing on the market solutions based on ROS capable of running with good reliability over an extended period of time. However, over time, the ROS community has developed an awareness of the limitations of the original architecture, and realized that it would not be possible to overcome all of them through incremental upgrades.

As a result, in 2017, a new version of the operating system appeared in the robotics world: ROS 2. Along the book more insights will be given about why this transition happened / is happening, for now the reader should know that support for the last release of "ROS1"[1], 'Noetic Ninjemis', is set to end in May 2025. As a consequence, the whole community was invited to continue the development of new features using the new version of ROS. Another important aspect of the transition is that, while the architecture of ROS 2 resembles in many aspects that of the original ROS, the two are not compatible. Even though some ROS packages can be converted to/from the new version of ROS with relatively little effort, a successful transition often involves significant architectural changes across the entire system.

1: I will sometimes use this notation instead of "ROS" to make de distinction between the old and the new version clearer.

1.2 Why this book?

The ROS community made significant efforts to provide users with tutorials [1], documentation [2] and open discussion forums like discourse.ros.org[3] or answers.ros.org[4] in order to make the learning and the troubleshooting of ROS 2 as smooth as possible. Chances are that, before reading this, you already went through most of it. If not, please do it. This book is not a programming guide that teaches ROS 2 from the basics, as the previously mentioned resources already do that exceptionally well. There is plenty of free, dynamic and entertaining material for beginners that will enable you to create your first ROS 2 nodes in no time. However, while the ROS documentation is really good at explaining how to perform "single operations", if you'll be dealing with the development of a large system, you will likely soon be asking yourself questions like: "is this the proper way of doing stuff?", "How does the rest of the world usually tackle this problem using ROS?". These questions almost inevitably arise because ROS often provides the developers with multiple ways to achieve the same objective. Oftentimes, the answer to these dilemmas will not be unique and universal, but will depend from the requirements and the constrains of the specific system. However, it is also true that some patterns can be identified that generally make the architecture more reusable, modular and less error-prone. At the same time, anti-patterns exist that, if introduced in your code, will most likely make you struggle and lose time / performance as the system expands.

1.3 How and when to read this book

Given the big amount of quality material about ROS 2 already existing on the web, this book will strive to avoid repeating basic examples and concepts, and will instead make extensive use of references and links to direct you to the most current information available. As this is a book about programming, the author assumes that you have access to some form of digital device that will facilitate your ability to follow the references and try out examples (so please don't print this and save some tree).

Each chapter ends with a short homework assignment. While you may be tempted to (and most likely will) skip it and quickly move on with the book, it's important to note that "The biggest drop in retention happens soon after learning. Without reviewing or reinforcing our learning, our ability to retain information plummets"[5]. In the context of programming tools, I believe it's crucial to put what you've learned into practice by writing your own code. With time, I will provide the solution to some of the exercises on this github repository and in the last chapter. If you don't find what you are looking for, feel free to contact me to discuss any solution.

Regardless of whether you are an expert robotic engineer used to work with the "old ROS", a developer used to work with other kinds of frameworks, or someone venturing for the first time into the magic world of robotics, this book will hopefully provide you with some good tips on how to choose and properly use the correct tools in the ROS 2 world.

Many robots have been cursed, hit, smashed into walls and boxes and (partially) burned while gaining the material on which this book was based. I hope I can help to make your journey less troubled, but just as fun as mine.

2 The Node

In ROS 2, just like in the dear old ROS, the basic unit of execution for each program is called a Node. While it would look like there's not much to say about it [1][6], the way you'll create your Nodes deeply affects the way your application can be managed, integrated into the rest of the system, and the functionalities it will be able to provide.

1: A description of the core Node concept can be found here

2.1 How to (properly) instantiate it

As you probably already figured out, there are two main ways to create a Node. The most immediate one, if you are using rclcpp, will look something like: [2]

2: Most of the code samples provided through this book are written in C++. The described concepts, however, almost always generalize to the other languages that can be used with ROS 2. Later in the book we will see how ROS 2 facilitates the support of most of its functionalities across different programming languages.

```
#include "rclcpp/rclcpp.hpp"
int main(int argc, char **argv)
{
    rclcpp::init(argc, argv);
    auto node = std::make_shared<rclcpp::Node>("best_node_name");
    rclcpp::spin(node);
    rclcpp::shutdown();
    return 0;
}
```

The node is created as a shared pointer to a rclcpp::Node class instantiated with your favourite name. This pointer can now be used to read parameters, create publishers, subscribers, and all the other fancy features[7] that a good node should provide. You can also share this little guy (that somewhat resembles the retired nodehandle[8]) with other functions or classes, who can optionally store a copy of it. After all, it's a shared pointer, why not? We'll soon see how, in many cases, this solution can prove to be problematic.

Another way to instantiate a node, is through a class deriving from rclcpp::Node :

```
#include "rclcpp/rclcpp.hpp"

class OurClass : public rclcpp::Node {
```

```
  public:
    OurClass() : Node("best_node_name") {
      // Some constructor
    }
}

int main(int argc, char **argv)
{
    rclcpp::init(argc, argv);
    auto node = std::make_shared<OurClass>();
    rclcpp::spin(node->get_node_base_interface());
    rclcpp::shutdown();
    return 0;
}
```

The first thing that you'll notice is that we now have to write more code, so why bother to do this? The key answer to this is reusability. Once you created your own Node class, it is easy to isolate it into a library that is independent from the execution of a process. This allows us to easily replicate and share whatever logic we decided to implement in our Node, at least at compile-time. ROS 2 actually allows us to do something even better than that: the execution of a node can be controlled at runtime. In order to achieve that, another couple of steps are required.

2.1.1 Components and when to use them

Components are **the recommended way to create nodes in ROS 2**. Once a Node is created as a component, its execution can (optionally) be controlled by an executor[3], who can run multiple components at the same time. Let's take a look at how to make our class a component.

3: In Chapter 3 you will find a detailed description of executors.

```
#include "rclcpp/rclcpp.hpp"

namespace our_namespace
{

class OurClass : public rclcpp::Node {
  public:
    OurClass(const rclcpp::NodeOptions & options) : Node("best_node_name",
      options) {
      // Some constructor
    }
}

}
#include "rclcpp_components/register_node_macro.hpp"
RCLCPP_COMPONENTS_REGISTER_NODE(our_namespace::OurClass)
```

In addition to this, some trick needs to be applied in the CMakeLists.txt file of our package:

```
add_library(our_component SHARED
  src/our_file.cpp)

# For Windows compatibility
target_compile_definitions(our_component
  PRIVATE "COMPOSITION_BUILDING_DLL")

ament_target_dependencies(our_lib
  "rclcpp"
  "rclcpp_components")

rclcpp_components_register_nodes(our_component "our_namespace::OurClass")
```

What we did here is creating a way to allow the component to be discoverable when its library is being loaded into a running process (for example the executor). A component can be loaded into an executor at runtime using command line commands(see here[9] for the details) , through a launchfile (see this example[10]), or can be manually integrated into your program at compile time, just like we did with our class above. Since it is compiled as a shared library, you can easily export it and link other packages against it[11]. If you are compiling for Windows, you might want to check these tips [12].

While it is common for components to derive from rclcpp::Node, this is not mandatory. The requirements for a class to be exported as a component are:

- Have a constructor that takes a single argument that is a rclcpp::NodeOptions instance
- Have a method of the signature:

```
rclcpp::node_interfaces::NodeBaseInterface::SharedPtr
    get_node_base_interface(void)
```

When should we implement our nodes as components? The short answer is: always.[4]

4: Ok, you can actually skip this for small scripts and tests, but it's a good idea to use it for your core components.

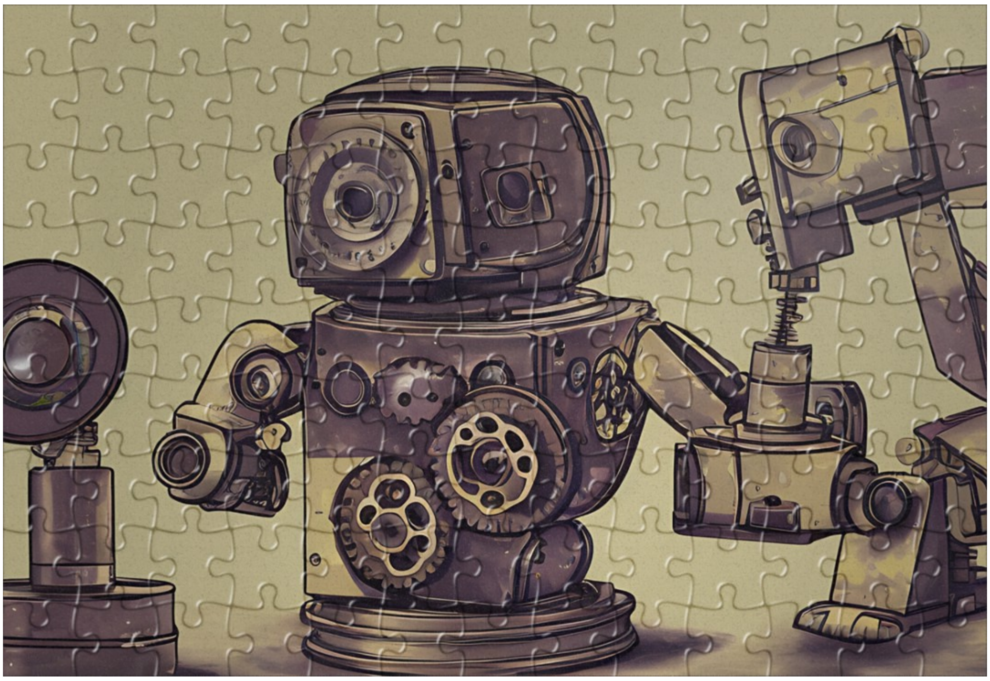
You might think that it's not worth the overhead of doing all these declarations if, at the end of the day, you don't plan to put your node in an executor at runtime. However, you should not assume that the way you are using your code today is the way it will be used tomorrow. One day, your grandchildren might stumble upon your old component and decide that it should run in an executor. Since there is no relevant drawback (at least that I know) from implementing it as a component, you shouldn't be too lazy and adopt from the beginning a structure that will make the life of your grandchildren easier.

Now that we've structured our node as a component, you might be asking yourself: "Why would my grandchildren want to run multiple components within a single executor?"; there are three possible motivations I can think about (but let me know if you come up with more):

- While an executor can spawn as many threads as it likes, all the managed components will be running in the same process. This reduces a little bit the effort made by your operating system when performing context switching, since switching between threads of the same process is slightly faster[13]. Some experiments[14] have shown how the communication latency between two nodes is significantly lower if these are running within the same process.
- When two components are running within the same process, they will be sharing the same memory space, and hence cool features like the zero copy publish and subscribe mechanism[15] can be used [5]. This is especially useful when dealing with devices producing a big amount of data, like for example cameras: if both the drivers and the consumer are implemented as components and run in the same executor, they will be able to transfer data using smart pointers. If they are executed in different processes, ROS will instead perform data serialization without any need for modifications in your code.
- Putting many components with a limited workload into an executor that is using a small number of threads (or only one), can

5: In case you are wondering, yes, this is the ROS 2 equivalent of the old nodelet[16], however in ROS 2 their role is much more important reduce the total number of threads running on the system, which results, especially on low-end platforms, in a happier scheduler and increased overall performance.

There is anyway an implicit danger when putting multiple components on the same process. Sharing the same memory space implies that errors like a segmentation fault will no longer crash only the affected component, but the entire executor with his family. Consequently, when "merging" two components in the same executor, you should ask yourself: "Should one of them run into trouble, is it important for the other to continue normal operation?". Let's consider for example a component implementing a camera driver and a component using the data from the camera to detect people in a room. If the camera driver dies, the other component probably becomes useless, and it's ok for it to stop working. However, if the camera is additionally used for something else, you'll have to choose if you want to keep those functionalities active in the case of a people-detector malfunction. You probably shouldn't put your camera driver together with the driver of your mobile base. If the camera driver crashes, you still want to be able to drive and maybe charge your robot while waiting for help. Another consequence of using the components structure, is that it forces the programmer to give-up the control over the spinning of the callbacks. Components are meant to be paired with an executor; calling functions like *spin_some*, *spin_once*, and *spin_until_future* on an already paired node results in an exception. In Chapter 3, I will explain how to properly manage this inconvenience.



2.2 The Node types

After taking a look at the ROS 2 tutorials and at some examples[17], you might be tricked into thinking that, in order to write a ROS node, your class will have to derive from rclcpp::Node, or rclpy.node. There's nothing wrong in deriving from these classes, and this is indeed the most convenient way to create your node; however, you should not assume that any node you'll be dealing with will be using them. Other classes exist, that allow you to create a node with special functionalities. You could also choose to create your own customized version.

2.2.1 Managed Nodes

The most common kind of "special node" you'll likely encounter while strolling around the ROS 2 world is the lifecycle node[18][6]. When using this as base for your class, the resulting node will become a "managed node", whose internal state can be controlled through a set of service calls. A description of all the states and transitions that such a node implements, can be found on the corresponding design article[20].

6: A python based implementation is available here[19]

The transitions of a set of managed nodes are usually handled by a dedicated manager, which can implement any kind of customized logic to choose the order in which the nodes are configured, activated, and eventually deactivated. A complete example can be found in the Nav 2 lifecycle manager[21], that, in addition to handle the initialization of its components, keeps track of their status using a heartbeat strategy.

Starting from ROS 2 Iron, it is possible to trigger these transitions directly from a launchfile using a dedicated roslaunch action: LifecycleTransition. Here is an example of launcher using this functionality to configure and activate two nodes:

```python
from launch import LaunchDescription
from launch_ros.actions import LifecycleNode
from launch_ros.actions import LifecycleTransition
from lifecycle_msgs.msg import Transition

def generate_launch_description():
  return LaunchDescription([
    LifecycleNode(package='package_name', executable='a_managed_node',
     name='node1'),
    LifecycleNode(package='package_name', executable='a_managed_node',
     name='node2'),
    LifecycleTransition(
      lifecycle_node_names=['node1', 'node2'],
      transitions_ids=[
        Transition.TRANSITION_CONFIGURE,
        Transition.TRANSITION_ACTIVATE]
    )
])
```

This strategy, however, should be used only for test purposes, since it can't perform proper error management.

Lifecycle-managed nodes are very handy when the program is dealing with components implementing a long initialization routine. If other components in the system need to wait for the initialization of the previous ones, a waiting strategy needs to be implemented. The managed nodes provide in this case a clean, standardized way to control their ordered initialization or their deactivation.

If you take a closer look at the implementation of the lifecycle node, you'll notice that this doesn't inherit from rclcpp::Node, but only uses some of

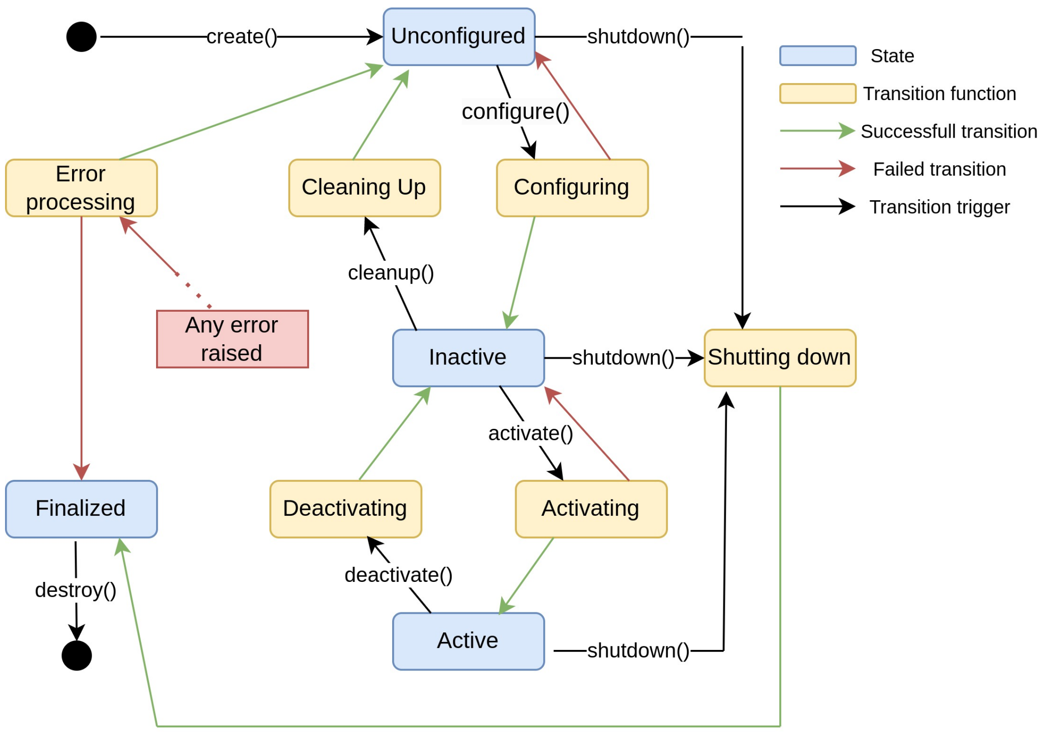


Figure 2.1: Diagram of the state machine implemented by lifecycle managed nodes. Based on `https://design.ros2.org/articles/node_lifecycle.html`

its components, while providing a new set of interfaces to access them. We'll see why in the coming section.

2.2.2 Custom base nodes

If you are not satisfied with the current implementation or rclcpp::Node, and you want to create a new class that provides additional or modified functionalities, you have multiple options:

The first thing that could come to your mind, is to simply inherit from rclcpp::Node and extend its public interface with additional functionalities. This works perfectly fine until the moment your application needs to provide some of these functionalities to a nested class or library. [7] In this scenario, you won't be able to share your custom node using smart pointers, since a call to *shared from this* will resolve the base rclcpp::Node. This partially explains why the implementation of the lifecycle node doesn't inherit from Node, but verbosely reproduces its interfaces. The process is a bit longer, but the resulting node is much more versatile.

7: It is a common practice to implement libraries / classes that, even if interacting with the ros apis, are not intended to be used as a stand-alone node, but within the context of an existing one. If you need to be able to load these classes at runtime, plugins[22] might help you.

To provide a node with the functionalities necessary to interface with ROS 2 without deriving from rclcpp::Node, a possible way is to instantiate the required node interfaces[23]. Most of these classes require to first instantiate a NodeBaseInterface object, which can be seen as the "core" of the node, and then use it to provide the different functionalities that you would usually access using a node pointer. For example, the NodeTopics class will allow you to create publishers and subscriptions to topics, the NodeParameters to interact with parameters and so on. Once these classes are instantiated, you can wrap and combine them to create your own custom interface. If you respect the rules described in the components section, and declare your class using *enable_shared_from_this*[24], your node will be ready to be run as base for your applications.

Is there a downside in doing all this? Of course, building your system around a custom node implementation drastically reduces your capability of sharing it: whenever you will want to distribute a component based on it, the node implementation will have to follow. Custom nodes also create a very strong "dependency point": having many components depending on it implies that modifying its functionalities while ensuring to not break the existing behaviour of the system is going to be more and more difficult as your system expands. Moral of the story: unless you have a very good reason, stick with the existing default node-classes.

2.3 Using nodes in the interfaces

As we've just seen, even if the rclcpp::Node is the most used and convenient base class when creating a node, it is not the only one you might encounter during your ROS 2 adventure. As a consequence, whenever you implement a library or a class that requires ros functionalities, providing them through a pointer to rclcpp::Node will reduce its re-usability, since different kind of nodes won't be able to use it [8]. Using a pointer to your own custom node will make it even less re-usable, and re-usability is one of the things that make ROS great in the first place.

8: An example of component suffering from this issue can be found here.

So what can we do to generalize our solution? Here are some alternatives:

- Use the aforementioned node interfaces classes: if your library, for example, only requires to access parameters, provide a NodeParameters object instead of a full node. These interface classes will most likely be instantiated and exposed by any kind of node, so you should be safe (for example[25] executors were designed to take the node base interface as input).
- Rethink your design to use multiple small-nodes instead of integrating small libraries or plug-ins within the same program. Using ROS interfaces (topics, services, actions) makes it easier for other components to access the shared information without having to perform any change on the code of the data-producers. This doesn't apply if you need very deterministic low latency interfaces between the components, since real time ROS interfaces[26] are still only experimental.
- Try to make your component ROS-agnostic. If the ROS specific functionalities used by your code are limited and easy to replace, keeping it ROS-agnostic might not only force you to minimize its interface, but also make it more resilient to updates in the ROS libraries. This should make your packages (or at least a piece of them) easier to maintain, especially while transitioning to a new ROS version like ROS3.

Since sometimes none of these approaches leads to a clean implementation, a new strategy was recently developed for dealing with different kinds of nodes in a generic way: the "Generic node interfaces".

2.3.1 Generic node interfaces

Starting from ROS 2 Iron, it is possible to wrap different node interfaces into a unified object: the NodeInterfaces class[27]. Using this object, it is possible to provide to a function or a class multiple node-functionalities using only one parameter.

To better explain this, I'll report an example from here. Suppose that we have a function and that we want to use some of the functionalities provided by a node within it. Using the classic node interfaces, you would write a function definition like:

```

void fn(NodeBaseInterface::SharedPtr base_interface, NodeClockInterface::
    SharedPtr clock_interfaces);
```

You would later call fn like this:

```

rclcpp::Node node("some_node");
fn(node->get_node_base_interface(),
   node->get_node_clock_interface());
```

Using the NodeInterfaces class we can instead define:

```

void fn(NodeInterfaces<NodeBaseInterface, NodeClockInterface> interfaces);
```

The function fn can now be called in two different ways:

```

// explicitly
auto ni = NodeInterfaces<NodeBaseInterface, NodeClockInterface>(node);
fn(ni);

// implicitly
fn(node);
```

The implicit form is probably the one you will want to use: the function call is now much more compact and elegant, resembling what in ROS1 was done with a node-handle. If you need it, it is additionally possible to subset a node interface, to build it from aggregation or to extract its internal interfaces:

```

// subsetting
auto ni_base = NodeInterfaces<NodeBaseInterface>(ni);
auto ni_aggregated = NodeInterfaces<NodeBaseInterface, NodeClockInterface
    >(
  node->get_node_base_interface(),
  node->get_node_clock_interface()
)

auto base = ni.get<NodeBaseInterface>();
auto clock = ni.get_clock_interface();
```

Homework

Create two managed nodes as components, and a third node that, upon getting a request through a service, will initialize and start them sequentially. Put all these components within the same executor using a launchfile. You can find hints in the linked documentation.

The solution to the homework can be found here

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