ENPM702

Introductory Robot Programming

L9: Robot Operating System (ROS) - Part I

v2.0

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Semester/Year: Summer/2025

MARYLAND APPLIED
GRADUATE ENGINEERING

Table of Contents

Changelog

- *v2.0*: Fized typos and inconsistencies.
- *v1.0*: Original version.

Learning Objectives

By the end of this session, you will be able to:

- **Understand ROS 2 Architecture**: Explain the distributed system design and core components (nodes, topics, messages).
- **Set Up ROS 2 Development Environment**: Create and configure workspaces, understand package structure and dependencies.
- **Build ROS 2 Packages**: Use colcon build system, manage dependencies, and understand workspace overlays.
- **Create ROS 2 Nodes**: Implement both functional and object-oriented node designs using `rclcpp`.
- **Work with Messages**: Use standard message types, understand message introspection, and handle message dependencies.
- **Implement Publishers**: Create publishers to send messages to topics with appropriate QoS settings.
- **Implement Subscribers**: Create subscribers with callbacks to receive and process messages from topics.
- **Apply Node Spinning**: Understand different spinning methods and keep nodes alive for message processing.
- **Analyze Communication Patterns**: Debug publisher-subscriber systems and understand message flow scenarios.

Prerequisites

Add the following function to your shell configuration file:

For .zshrc users:

```
function ros702 {
    #ws="/home/zeid/Documents/ros702_ws"
    source /opt/ros/jazzy/setup.zsh
    #source "${ws}/install/setup.zsh"
    #eval "$(register-python-argcomplete ros2)"
    #eval "$(register-python-argcomplete colcon)"
    #cd ${ws}
}
# call the function
ros702
```

For .bashrc users:

```
function ros702 {
    #ws="/home/zeid/Documents/ros702_ws"
    source /opt/ros/jazzy/setup.bash
    #source "${ws}/install/setup.bash"
    #source
    ↪  /usr/share/colcon_argcomplete/hook/colcon-argcomplete.bash
    #cd ${ws}
}
# call the function
ros702
```

After Adding the Function

- Reload your shell: `source ~/.bashrc` or `source ~/.zshrc`
- Use the function: `ros702`
- This will setup your ROS 2 environment and navigate to your workspace.

What is ROS?

The Robot Operating System (ROS) is an open-source framework designed for developing, building, and deploying robotic applications.

- Prototypes originated from Stanford AI research and officially released by Willow Garage in 2007.
- ROS 2 was redesigned from the ground up and released in 2017.
- Currently maintained by **Open Robotics**

Despite its name, ROS is not a standalone operating system; rather, it is a flexible set of software tools, libraries, and conventions that help developers create complex and modular robot software.

Watch the video at **https://ros.org/**

Resources

- Official website: http://wiki.ros.org/
- ROS 2 Documentation: https://docs.ros.org/en/humble/
- Tutorials: http://wiki.ros.org/ROS/Tutorials
- Package index: https://index.ros.org
- Community forum: https://discourse.ros.org/
- ROS Enhancement Proposals: https://www.ros.org/reps/
- GitHub organizations: ros2, ros-planning, ros-perception

Debian Packages

- Located in: /opt/ros/<distribution>/share
- Installed via:

```
sudo apt install ros-<distribution>-*
```

- Use for stable and production systems.
- Automatic dependency management.

Source Installation

- Located in: Your workspace src directory
- Built with: `colcon build`
- Use for development and customization.
- Easy to modify and debug.

Can override Debian packages.

Never modify packages installed in /opt/ros/, instead copy packages to your workspace and modify the copies.

Where is ROS 2 Used?

Transportation:

- Autonomous vehicles (CARLA, Autoware)
- Delivery drones (Amazon Prime Air, UPS Flight Forward)
- Maritime autonomous systems (Kongsberg Maritime)
- Railway automation (Siemens Mobility)

Manufacturing:

- Industrial robotic arms (KUKA, ABB Robotics)
- Quality inspection (Cognex, Keyence)
- Collaborative robots (Universal Robots, Rethink Robotics)
- Warehouse automation (Amazon Robotics, Berkshire Grey)

Specialized Domains:

- Medical robots (Intuitive Surgical, Stryker Mako)
- Space exploration (NASA JPL, NASA Astrobee)
- Agricultural automation (Blue River Technology, John Deere)
- Search and rescue (Boston Dynamics Spot, ANYbotics)
- Research and education (TurtleBot, Husarion)

Emerging Areas:

- Home service robots (iRobot, Savioke)
- Entertainment (Anki, SoftBank Pepper)
- Security (Knightscope, Cobalt Robotics)
- Environmental monitoring (Ocean Infinity, Clearpath Robotics)

Resources

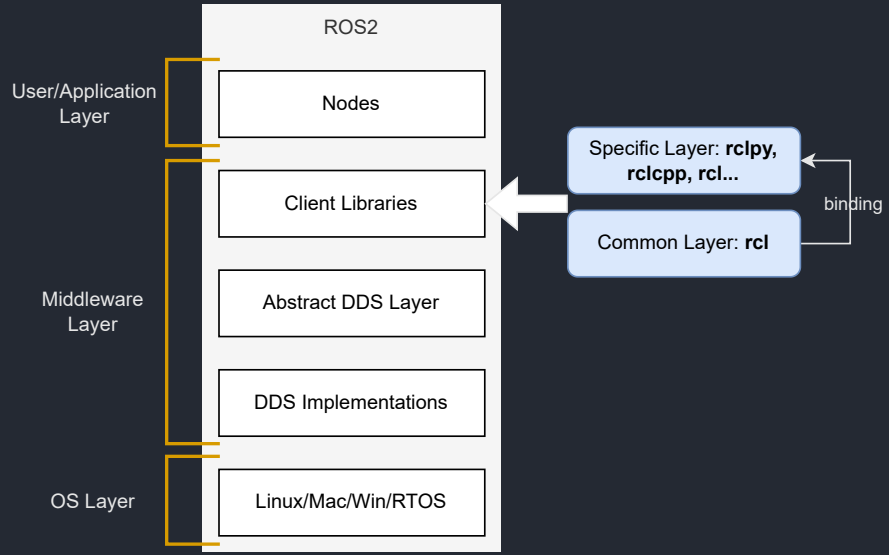
- ROS Robotics Companies

Framework/Solution	Key Features	Differences
Microsoft Robotics Developer Studio (MRDS)	Windows-based, visual programming, simulation support	Primarily for Windows
Open Robot Control Software (ORoCoS)	Real-time control, deterministic execution	Focuses on industrial control; ROS 2 offers more flexibility and integration ease
Mission Oriented Operating Suite (MOOS)	Marine robotics, real-time autonomy	Specialized for marine applications, whereas ROS 2 is more general-purpose
Yet Another Robot Platform (YARP)	Inter-process communication, modularity	Emphasizes communication, whereas ROS 2 provides a more standardized middleware layer with DDS
Custom-built solutions	Optimized for specific applications	Lack modularity, community support, and extensibility that ROS 2 provides

Choose ROS 2 when you need:

- Rapid prototyping and development.
- Large ecosystem of existing solutions.
- Community support and collaboration.
- Standard interfaces and protocols.

ROS 2 Architecture



Core Components

- **Nodes**: Individual processes performing specific computations or tasks
- **Topics**: Named channels for asynchronous data streaming (Publisher/Subscriber model)
- **Services**: Synchronous request-response communication between nodes
- **Actions**: Long-running, interruptible tasks with feedback
- **Interfaces**: Data structures for messages, services, and actions
- **Launch files**: Automation scripts for starting multiple nodes with configuration

Quality of Service (QoS)

- **Reliability**: Best effort vs. reliable delivery
- **Durability**: Transient vs. volatile data storage
- **History**: Keep last N messages vs. keep all
- **Deadline**: Maximum expected time between messages

What is the ROS 2 Daemon?

A background process that caches ROS 2 discovery information to optimize CLI performance.

Key Functions

- **Discovery Cache**: Maintains a live cache of nodes, topics, services, and actions.
- **Performance Boost**: CLI commands return instantly instead of waiting for discovery.
- **Network Efficiency**: Reduces repeated DDS discovery traffic.
- **Automatic Management**: Starts automatically when needed.

Common Commands

- `ros2 daemon status` - Check if daemon is running.
- `ros2 daemon stop` - Stop the daemon (commands will be slower).
- `ros2 daemon start` - Manually start (usually automatic).

When to Restart the Daemon

- `ros2 topic list` shows outdated information
- After changing `ROS_DOMAIN_ID`
- Network configuration changes

The daemon only affects CLI tool performance. Nodes communicate directly without it.

Node Discovery Mechanism

- **`ros2 daemon`** – Background process that caches information about active ROS 2 nodes, topics, services, and actions within a network.
  - Provides fast lookup of network topology.
  - Reduces discovery latency for new nodes.
  - Can be disabled for minimal overhead: `ros2 daemon stop`
- DDS (Data Distribution Service) – ROS 2's communication middleware providing automatic discovery
  - Implementations: Fast DDS (default), Cyclone DDS, RTI Connext DDS
  - See REP-2000 for DDS vendor support by distribution
  - Check your DDS implementation: `ros2 doctor --report`
  - Switch DDS: `export RMW_IMPLEMENTATION=rmw_cyclonedx_cpp`

DDS discovery uses UDP multicast by default. In network environments where multicast is blocked, you may need to configure static discovery or use different network settings.

Traditional Robotics: Monolithic Architecture

- Single Program Approach:
  - One large C++ program handles everything.
  - All sensors, actuators, and algorithms in one codebase.
  - Tight coupling between components.
  - Single point of failure.

Problems with Monolithic Design:
- Change sensor? Recompile everything.
- Add feature? Risk breaking existing code.
- Debug issue? Entire system complexity.
- Team development? Code conflicts.

Monolithic Robot Program

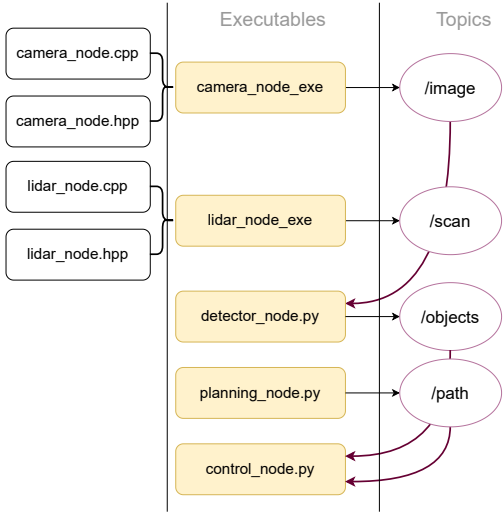
main.cpp

Camera Driver
Lidar Driver
Motor Control
Path Planning
Object Detection
Sensor Fusion
State Machine
Logger
...everything else

ROS Architecture: Distributed System

- Multiple Independent Programs:
  - Each component is a separate executable.
  - Different nodes can use different languages.
  - Loose coupling via message passing.
  - Start/stop components independently.
  - Fault isolation and recovery.

Benefits of Distributed Design:
- **Modular**: Swap components easily.
- **Scalable**: Add nodes without changes.
- **Robust**: One crash doesn't kill system.
- **Collaborative**: Teams work in parallel.



Real-World Example: Autonomous Vehicle

Instead of one massive program, an autonomous vehicle using ROS 2 runs many specialized programs:

Perception Nodes

- ***camera_driver*** (C++)
- ***lidar_driver*** (C++)
- ***radar_processor*** (Python)
- ***object_detector*** (Python/TF)
- ***lane_detector*** (C++/OpenCV)
- ***traffic_sign_reader*** (Python)

Planning Nodes

- ***global_planner*** (C++)
- ***local_planner*** (C++)
- ***behavior_planner*** (Python)
- ***trajectory_optimizer*** (C++)
- ***collision_checker*** (C++)

Control Nodes

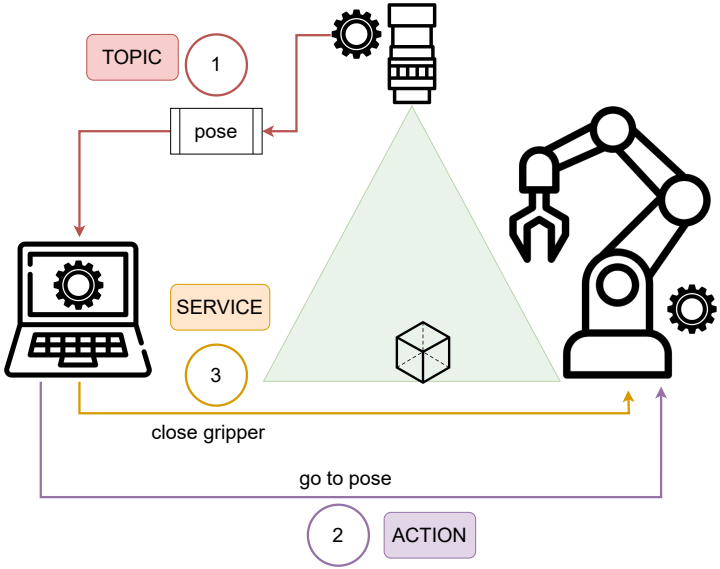
- ***vehicle_controller*** (C++)
- ***motor_driver*** (C++)
- ***brake_controller*** (C++)
- ***steering_controller*** (C++)
- ***diagnostics_monitor*** (Python)

Key Insight

Each node is a **separate executable program** that can be:

- Written in different languages (C++, Python, Rust, etc.)
- Developed by different teams or even different companies.
- Started, stopped, or replaced without affecting other nodes.
- Running on different computers in the same network.

ROS 2 Communication Patterns



When to Use Each Pattern

- **Topics**: Continuous data streams (sensor readings, robot state).
- **Services**: Request specific information or trigger actions (get current pose, save map).
- **Actions**: Long-running tasks with progress updates (navigate to goal, pick object).

Publish/Subscribe Model

The publish/subscribe model allows nodes to communicate asynchronously via topics. A publisher sends messages to a specific topic, and any subscribers listening to that topic receive the messages.

Key Benefits

- **Loose coupling**: Nodes don't need to know each other's existence
- **Scalability**: Easy to add new publishers or subscribers
- **Fault tolerance**: Nodes can start/stop independently
- **Flexible patterns**: Supports 1-to-many, many-to-1, many-to-many
- **Quality of Service**: Configurable reliability and performance guarantees

Real-world Example

- Camera node publishes images to t **/camera/image_raw**.
- Object detection node subscribes to process images.
- Visualization node also subscribes to display images.
- Navigation node subscribes for obstacle detection.
- All work independently and can be started in any order.

Analogy: Radio Towers

An analogy from Edouard Renard demonstrates how nodes, topics, and messages work together.

Nodes

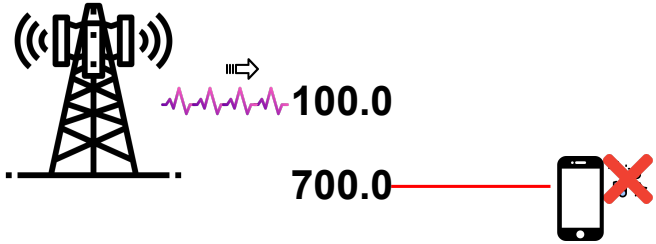
Topics

100.0 700.0

Messages

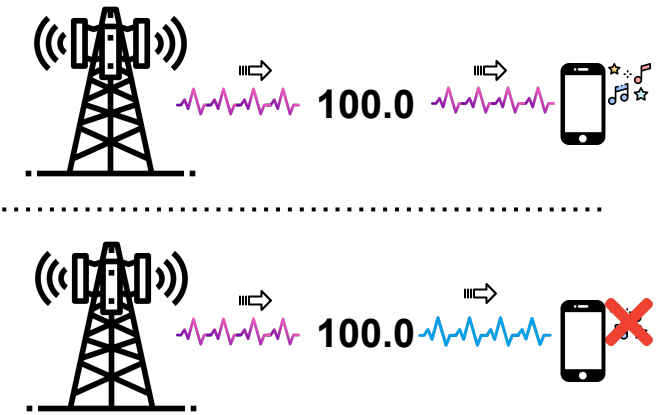
Rule 1: Topic Name Matching

A subscriber must subscribe to the same topic that the publisher is using.



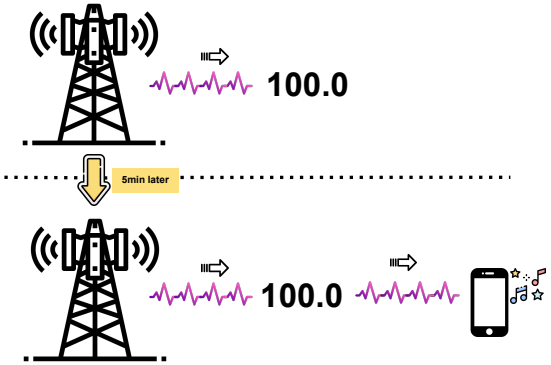
Rule 2: Message Type Compatibility

A subscriber must use the same message type as the publisher to receive the messages.



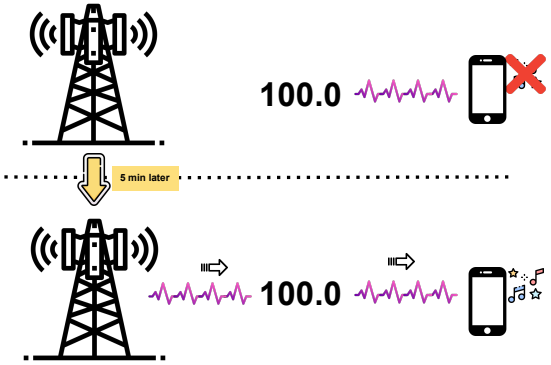
Rule 3: Publishers Don't Wait

Publishers send messages regardless of whether subscribers are listening.



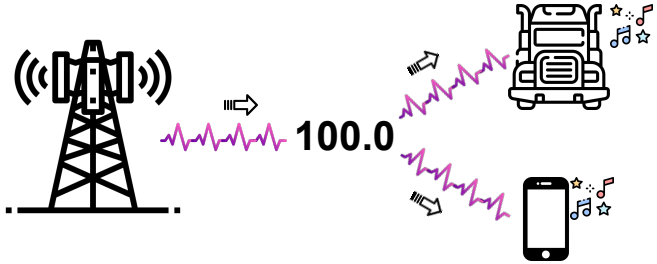
Rule 4: Subscribers Don't Require Publishers

Subscribers can listen to topics even when no publisher is active.



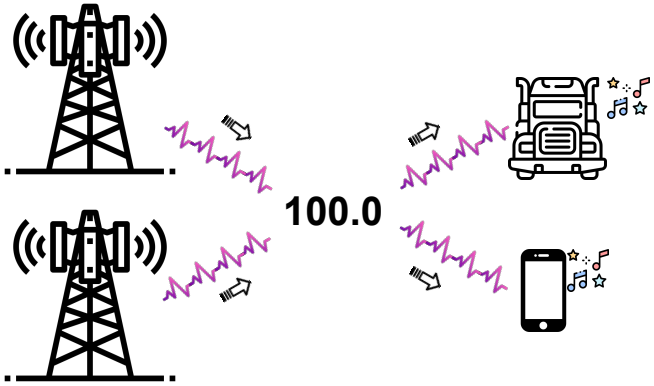
Pattern 1: One-to-Many Communication

A single publisher can send data to multiple subscribers.



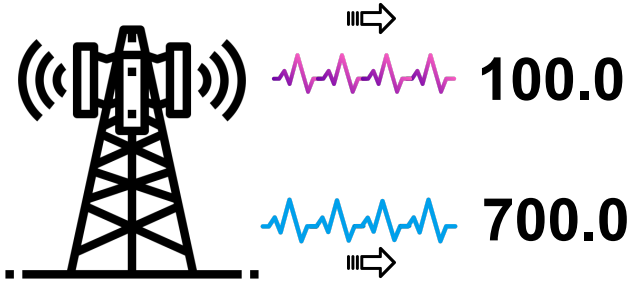
Pattern 2: Many-to-One Communication

Multiple publishers can send data to a single topic (requires careful management).



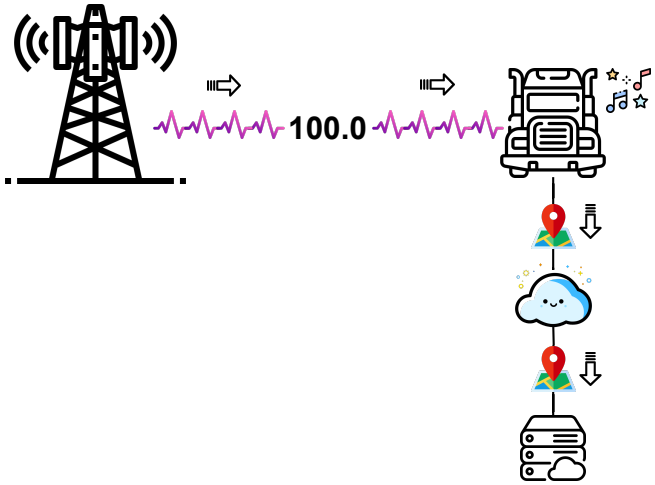
Pattern 3: Multi-Topic Publishers

A single node can publish to multiple topics with different message types.



Pattern 4: Bidirectional Communication

A node can act as both publisher and subscriber for different topics.



Two Ways to Run ROS Nodes

1. `ros2 run <package> <executable>` starts *exactly one* node.
2. `ros2 launch <package> <launch file>` starts *one or more* nodes with configuration.

When to Use Each Approach

- `ros2 run` – Quick testing, debugging single nodes, simple demonstrations.
- `ros2 launch` – Production systems, complex multi-node applications, parameterized configurations.

`ros2 run` - Single Node Execution

The `ros2 run <package> <executable>` command launches a single node where `<package>` is the ROS package name and `<executable>` is the executable file name.

- ROS 2 includes the demo package ***demo_nodes_cpp*** with executables for testing
- The ***talker*** sends messages and ***listener*** receives them
- Open two terminals and run:
  - Terminal 1: `ros2 run demo_nodes_cpp talker`
  - Terminal 2: `ros2 run demo_nodes_cpp listener`

Understanding the Output

- Talker publishes “Hello World” messages with incrementing numbers.
- Listener receives and displays these messages.
- Messages flow through the `t` **/chatter** topic.
- This demonstrates basic publisher-subscriber communication.

Try stopping and restarting either node. Notice how the system gracefully handles nodes joining and leaving!

`ros2 launch` - Multi-Node Systems

Launch files enable starting multiple nodes with complex configurations using `ros2 launch <package> <launch file>`.

ToDo

Run both talker and listener with a single command:

```
ros2 launch demo_nodes_cpp talker_listener.launch.py
```

Launch File Benefits

- Automation: Start entire robot systems with one command
- Configuration: Set parameters, namespaces, and remappings
- Coordination: Manage node dependencies and startup order
- Flexibility: Support different deployment scenarios

Launch File Types

- ***.launch.py**: Python-based (most flexible and common)
- ***.launch.xml**: XML-based (declarative, good for simple cases)
- ***.launch.yaml**: YAML-based (human-readable configuration)

ROS 2 Introspection and Debugging Tools

1. `ros2 node <option>` - Node management and information
   - `ros2 node list` - Lists all active nodes
   - `ros2 node info <node_name>` - Detailed node information
2. `ros2 topic <option>` - Topic inspection and interaction
   - `ros2 topic list [-t]` - Lists topics [with message types]
   - `ros2 topic info <topic_name> [-v]` - Topic details [verbose]
   - `ros2 topic echo <topic_name>` - Monitor live messages
   - `ros2 topic hz <topic_name>` - Measure message frequency
   - `ros2 topic pub <topic> <msg_type> <values>` - Publish test messages
3. `ros2 interface <option>` - Message and service type inspection
   - `ros2 interface list` - All available message types
   - `ros2 interface show <msg_type>` - Message structure details
4. `rqt_graph` - Visual network topology display

The colcon Build Tool

colcon (collective construction) is the official build tool for ROS 2, replacing the ROS 1 build tools (catkin_make, catkin_tools).

Key Features

- **Language Agnostic**: Builds C++, Python, and other package types.
- **Parallel Execution**: Builds multiple packages simultaneously for speed.
- **Isolated Builds**: Each package built in its own space (no cross-contamination).
- **Extensible**: Plugin architecture for custom build types.
- **Cross-Platform**: Works on Linux, Windows, and macOS.

Installation

- Install: `sudo apt install python3-colcon-common-extensions`
- Verify: `colcon version-check`

Essential colcon Commands

- `colcon build`: Build all packages in workspace
- `colcon test`: Run tests for packages
- `colcon test-result`: Display test results summary
- `colcon list`: List packages in workspace
- `colcon graph`: Show package dependency graph

Useful Build Options

- `--symlink-install`: Use symlinks for Python/config files (faster development)
- `--packages-select <pkg1> <pkg2>`: Build only specified packages
- `--packages-up-to <pkg>`: Build package and all its dependencies
- `--packages-above <pkg>`: Build all packages depending on specified package
- `--parallel-workers <N>`: Limit parallel build jobs (default: CPU cores)
- `--cmake-args <args>`: Pass arguments to CMake
- `--event-handlers console_direct+`: Show live build output
- `--build-base <dir>`: Custom build directory location

Memory-Limited Systems: Use `--parallel-workers 1` on systems with limited RAM to prevent build failures due to memory exhaustion.


Enable colcon command completion.

ROS 2 Workspaces

A ROS workspace is a directory structure that contains all the packages, dependencies, and build artifacts needed to develop and run ROS 2 applications.

- **Modular Development**: Organize code into logical, reusable packages.
- **Dependency Management**: Automatic resolution and building of package dependencies.
- **Overlay System**: Multiple workspaces can be layered for different projects.
- **Isolation**: Keep different projects and their dependencies separate.

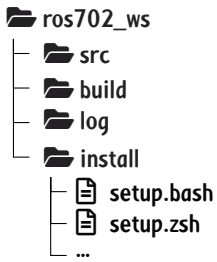
Create a workspace for this course

- Create the workspace directory: `mkdir -p ~/ros702_ws/src`
  - The **src** folder is where you will create custom ROS packages or clone existing ones from GitHub
- Navigate to workspace root: `cd ~/ros702_ws`
- Build the workspace: `colcon build`

You must be in the workspace root directory to build it.

The build process scans **src** for packages and builds them. Even with no packages, build directories are created.

Workspace Directory Structure



- **src**: Contains source code for custom and external packages.
- **build**: Stores intermediate build artifacts (object files, CMake cache).
- **log**: Contains build logs for debugging compilation issues.
- **install**: Houses final build products (executables, libraries, headers).
  - Includes **setup.bash/zsh** files for environment configuration.
  - This is what gets "sourced" to use your workspace.

Build Process Flow

- Source code (**src**) → Compilation (**build**) → Installation (**install**)
- Build logs stored in **log** for troubleshooting

Workspace Sourcing

To use packages in your workspace, you must *source* the setup file to configure environment variables:

```
source ~/ros702_ws/install/setup.<bash|zsh>
```

Update your shell function to include the workspace.

Understanding Workspace Overlays

- **Base Layer**: System ROS installation (`/opt/ros/<distribution>`)
- **Overlay Layer**: Your workspace (`~/ros702_ws`)
- **Override Behavior**: Workspace packages override system packages with same name
- **Multiple Overlays**: Chain multiple workspaces for complex projects

Sourcing Order Matters!

Always source the base ROS installation first, then your workspace. Later sources take precedence over earlier ones.

ROS 2 Packages

Software in ROS 2 is organized into packages - self-contained units that provide specific functionality and can be easily shared and reused.

- **Modularity**: Each package serves a specific purpose
- **Reusability**: Packages can be shared across different projects
- **Dependency Management**: Clear declaration of package dependencies
- **Build System**: Standardized building and installation process

Package Build Systems

ROS 2 supports multiple build systems:

- **ament_cmake**: For C++ packages (most common for performance-critical code)
- **ament_python**: For Python packages (rapid prototyping, scripting)
- **ament_cmake with Python**: Mixed language packages

Build System Evolution

- **ROS 1**: Used *catkin* build system
- **ROS 2**: Uses *ament* - evolution of catkin with improved features
- **colcon**: Build tool that works with ament (replaces catkin_make)
- **Advantages**: Better dependency resolution, parallel builds, improved testing

Key Insight

ament provides the build system rules, while **colcon** is the tool that executes the build process across multiple packages.

ToDo

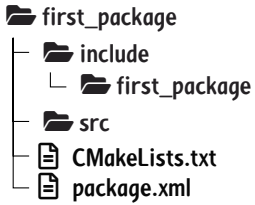
Create your first C++ ROS 2 package:

1. Navigate to source directory: `cd ~/ros702_ws/src`
2. Create the package:
   - `ros2 pkg create first_package --build-type ament_cmake --dependencies rclcpp`
   - Alternative shorter syntax: `ros2 pkg create first_package --dependencies rclcpp`
3. Build the package: `cd ~/ros702_ws && colcon build`
4. Source the workspace: `source ~/ros702_ws/install/setup.<bash|zsh>`
5. Verify creation: `ros2 pkg list | grep first_package`

First-Time Build: Always source your workspace after building a new package for the first time. Subsequent builds of the same package don't require re-sourcing.

Troubleshooting: If the package isn't listed, check: (1) Was the build successful? (2) Did you source the workspace? (3) Are you in the correct terminal session?

Package Structure



- **include/first_package/**: Header files (.hpp) for public interfaces.
- **src/**: Source files (.cpp) for implementation.
- **CMakeLists.txt**: Build configuration (executables, libraries, dependencies).
- **package.xml**: Package metadata and dependencies.

Package Discovery

Use `ros2 pkg` commands to interact with packages:

- `ros2 pkg list` - List all available packages.
- `ros2 pkg executables <package_name>` - Show package executables.
- `ros2 pkg xml <package_name>` - Display `package.xml` content.
- `ros2 pkg prefix <package_name>` - Show package installation path.

Package Manifest (package.xml)

The **package.xml** file is the package's "birth certificate": it defines metadata, dependencies, and build information.

Critical Functions

1. **Dependency Resolution**: *ament* uses this to determine build order
2. **Automated Installation**: Install missing dependencies with:
   - `cd ~/ros702_ws`
   - `rosdep install --from-paths ./src --ignore-packages-from-source -y`
3. **Package Index**: Information for ROS Index and package distribution

Essential Metadata to Update

- `<description>`: Clear, concise description of package functionality
- `<maintainer>`: Your name and email for support questions
- `<license>`: Legal terms (Apache-2.0, MIT, BSD, etc.)
- `<version>`: Semantic versioning (e.g., 1.0.0)
- Dependencies: `<depend>`, `<build_depend>`, `<exec_depend>`

Always edit **package.xml** immediately after creating a package!

CMakeLists.txt Overview

CMakeLists.txt is used by *ament_cmake* to build C++ executables, libraries, and install files.

Key CMake Components

- `cmake_minimum_required(VERSION 3.8)`: Minimum CMake version
- `project(first_package)`: Package name (must match package.xml)
- `find_package(rclcpp REQUIRED)`: Declare dependencies
- `add_executable()`: Create executable targets
- `ament_target_dependencies()`: Link ROS dependencies
- `install()`: Specify what to install and where
- `ament_package()`: Finalize package setup (must be last!)

Important: Every time you add a new node or modify build targets, you must edit **CMakeLists.txt**. This tells the build system how to compile and install your code.

Writing Your First Node

Let's create a simple node that demonstrates the basic structure and lifecycle of a ROS 2 C++ node.

- **Goal**: Create a node that prints "Hello from ROS 2!" to the terminal.
- **Concepts**: Node initialization, logging, and proper shutdown.
- **Build Process**: CMake configuration and compilation.
- **Execution**: Running nodes with `ros2 run`

1. Create the package first_package
2. Create the source file: first_package/src/main.cpp
3. Implement the node hello
4. Configure the build system to generate *hello_demo*.
5. Build and run the executable.

```cpp
#include <rclcpp/rclcpp.hpp>

int main(int argc, char **argv) {
    // Initialize ROS 2
    rclcpp::init(argc, argv);

    // Create a node
    auto node = std::make_shared<rclcpp::Node>("hello");

    // Log a message
    RCLCPP_INFO_STREAM(node->get_logger(), "Hello from ROS 2!");

    // Shutdown ROS 2
    rclcpp::shutdown();
}
```

Understanding the Code

- `rclcpp::init(argc, argv)`: Initializes ROS 2 runtime and middleware.
  - Sets up global resources, parses ROS arguments.
  - Must be called before creating any ROS entities.
- `std::make_shared<rclcpp::Node>("hello")`: Creates a shared pointer to a Node.
  - Node name must be unique within the ROS network.
  - Shared pointer enables safe memory management.
- `RCLCPP_INFO_STREAM(node->get_logger(), "message")`: Logs an info-level message. See Logging Tutorial.
  - Uses the node's logger with automatic timestamping.
  - Other levels: `RCLCPP_DEBUG`, `RCLCPP_WARN`, `RCLCPP_ERROR`
- `rclcpp::shutdown()`: Cleanly shuts down ROS 2.
  - Destroys all nodes and cleans up resources.
  - Automatically called on SIGINT (Ctrl+C).

This is a **one-shot node** - it runs once and exits. Later we'll see nodes that run continuously using `rclcpp::spin()`.

Configure the build system by editing CMakeLists.txt

```
# Add this after find_package() statements
add_executable(hello_demo src/main.cpp)
ament_target_dependencies(hello_demo rclcpp)

# Add this before ament_package()
install(TARGETS
  hello_demo
  DESTINATION lib/${PROJECT_NAME}
)
```

Build and Run

1. Build the package: `cd ~/ros702_ws && colcon build --packages-select first_package`
2. Source workspace: `source install/setup.<bash|zsh>`
3. Run the node: `ros2 run first_package hello_demo`

Expected Output

```
[1699123456.789] [hello]: Hello from ROS 2!
```

ROS 2 Node Inheritance Pattern

- Inherit from `rclcpp::Node` to access all node functionality.
- Constructor calls base class constructor with node name.
- Use `this->` to access node methods and properties.
- Encapsulate node-specific logic in class methods.

Professional Development: Real-world ROS 2 applications almost always use OOP. Learn this pattern early to build good habits.

Refactor the node using object-oriented design.

Step 1: Create Header File

Create first_package/include/first_package/hello_node.hpp:

```cpp
#pragma once

#include <rclcpp/rclcpp.hpp>

namespace first_package
{

class HelloNode : public rclcpp::Node{
public:
    explicit HelloNode(const std::string& node_name);

private:
    void print_hello();
};

}  // namespace first_package
```

Step 2: Implement the Class

Create first_package/src/hello_node.cpp:

```cpp
#include "first_package/hello_node.hpp"

namespace first_package
{

HelloNode::HelloNode(const std::string& node_name) : Node(node_name){
    RCLCPP_INFO(this->get_logger(), "HelloNode constructor called");
    print_hello();
}

void HelloNode::print_hello(){
    RCLCPP_INFO_STREAM(this->get_logger(),
                       "Hello from " << this->get_name() << "!");
}

}  // namespace first_package
```

Step 3: Update main.cpp

```cpp
#include "first_package/hello_node.hpp"

int main(int argc, char **argv){
    rclcpp::init(argc, argv);
    auto node = std::make_shared<first_package::HelloNode>("hello_oop");
    rclcpp::shutdown();
}
```

Step 4: Update CMakeLists.txt

Update the build configuration in CMakeLists.txt:

Step 5: Build and Test

1. Build: `colcon build --packages-select first_package`
2. Run: `ros2 run first_package hello_oop`

Useful Colcon Build Options

- `colcon build --symlink-install`: Create symbolic links instead of copying files
  - Changes to Python files take effect immediately
  - Useful during development for faster iteration
- `colcon build --packages-select <pkg1> <pkg2>`: Build only specific packages
  - Faster builds when working on specific packages
  - Useful in large workspaces with many packages
- `colcon build --packages-up-to <pkg>`: Build package and its dependencies
  - Ensures all dependencies are built before target package
  - Good for dependency troubleshooting
- `colcon build --continue-on-error`: Build all packages, don't stop on first error
  - Useful for finding multiple build issues at once
  - Good for CI/CD pipelines

Pro Tip: Add alias build='colcon build –symlink-install' to your shell function for faster development cycles.

Node Lifecycle Management

- **Initialization**: `rclcpp::init()` sets up ROS 2 context
- **Node Creation**: Constructor runs, initializes publishers/subscribers
- **Execution**: `rclcpp::spin()` keeps node alive (we will cover this next)
- **Shutdown**: `rclcpp::shutdown()` cleans up resources

Logging Best Practices

- **Use appropriate levels**: DEBUG → INFO → WARN → ERROR → FATAL
- **Include context**: Node name, function name, relevant data
- **Be concise but informative**: "Camera initialized with resolution 640x480"
- **Use stream syntax for complex messages**:

```
RCLCPP_INFO_STREAM(logger, "Value: " << value)
```

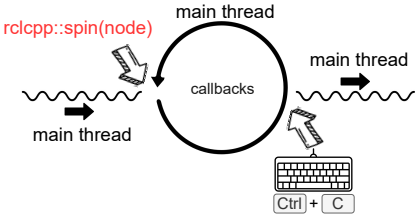
Common Pitfalls to Avoid

- Forgetting to source workspace after builds
- Not updating **CMakeLists.txt** when adding new files
- Using the same node name for multiple instances
- Not calling `rclcpp::init()` before creating nodes

Node Spinning

Spinning keeps a node alive and responsive by processing callbacks for incoming messages, service requests, and timer events.

Node Spinning



- **Why Spin?**
  - Process incoming messages
  - Execute timer callbacks
  - Handle service requests
  - Respond to actions
  - Keep the node alive
- **Spinning Methods**
  - `rclcpp::spin(node)` - Blocks forever
  - `rclcpp::spin_some(node)` - Process available work
  - `rclcpp::spin_until_future_complete()` - Conditional spinning
  - Executor-based spinning (advanced)

Without spinning, your node will exit immediately after initialization, and callbacks won't be processed!

Basic Node Spinning Pattern

```cpp
int main(int argc, char **argv){
    // Initialize ROS 2
    rclcpp::init(argc, argv);
    // Create node
    auto node = std::make_shared<MyNode>("my_node");
    // Spin the node - blocks until shutdown
    rclcpp::spin(node);
    // Clean up
    rclcpp::shutdown();
}
```

What Happens During Spin?

1. **Event Loop**: Continuously checks for new messages, timer events, service calls
2. **Callback Execution**: Invokes appropriate callbacks when events occur
3. **Thread Management**: Handles single or multi-threaded callback execution
4. **Signal Handling**: Responds to shutdown signals (Ctrl+C)

Spinning Alternatives

- **Spin Some**: Process available callbacks without blocking

```
while (rclcpp::ok()) {
    rclcpp::spin_some(node);
    // Do other work here
    std::this_thread::sleep_for(std::chrono::milliseconds(100));
}
```

- **Spin Until Future Complete**: Wait for specific condition

```
auto future = std::async(std::launch::async, some_async_operation);
rclcpp::spin_until_future_complete(node, future);
```

- **Executor-based Spinning**: More control over execution

```
rclcpp::executors::SingleThreadedExecutor executor;
executor.add_node(node);
executor.spin();
```

Use `rclcpp::spin()` for simple nodes. Use executors when you need fine-grained control over multiple nodes or threading.

ROS 2 Messages

Messages are the fundamental data structures used for communication between nodes in ROS 2.

Key Characteristics

- **Strongly Typed**: Each field has a specific data type
- **Language Agnostic**: Same message works in C++, Python, etc.
- **Serializable**: Automatically converted to/from bytes for transport
- **Versioned**: Changes require new message types
- **Efficient**: Optimized for real-time communication

Resources

- About ROS 2 Interfaces
- Common Interfaces Repository

Message Categories

- **Standard Messages** (***std_msgs***): Basic data types
- **Common Messages** (***geometry_msgs***, ***sensor_msgs***): Robotics-specific
- **Package-Specific**: Custom messages for specific packages

Think of messages as “contracts” between nodes: both publisher and subscriber must agree on the message structure.

Standard Messages Package

The ***std_msgs*** package provides basic message types for common data.

- **Primitive Types**
  - **Bool** - Boolean value
  - **Byte** - Single byte
  - **Char** - Character
  - **String** - Text string
  - **Empty** - No data (events)
- **Numeric Types**
  - **Int8**, **Int16**, **Int32**, **Int64**
  - **UInt8**, **UInt16**, **UInt32**, **UInt64**
  - **Float32**, **Float64**
- **Array Types**
  - **Int32MultiArray** - Multi-dimensional int32
  - **Float32MultiArray** - Multi-dimensional float32
  - **ByteMultiArray** - Multi-dimensional bytes
- **Special Types**
  - **Header** - Timestamp and frame ID
  - **ColorRGBA** - Color with alpha

ROS 2 CLI for Messages

The `ros2 interface` command provides powerful message introspection capabilities.

List All Available Messages

- All interfaces: `ros2 interface list`
- Only messages: `ros2 interface list -m`
- From specific package: `ros2 interface package std_msgs`

Try the following:

- [ ] `ros2 interface show std_msgs/msg/String`
- [ ] `ros2 interface show std_msgs/msg/Header`

Find Messages by Type

Search for all messages containing “String” in their name: `ros2 interface list | grep String`

Show Message Package

Find which package provides a message: `ros2 interface package std_msgs/msg/String`

Proto Format

Get message definition in proto format (useful for code generation):
`ros2 interface proto std_msgs/msg/String`

Development Workflow: Always check the exact message structure with `ros2 interface show` before using it in your code to ensure field names and types are correct.

Including Messages in C++

Each message type has a corresponding C++ header file:

```cpp
// Include format: <package>/msg/<message_name>.hpp
#include <std_msgs/msg/string.hpp>
#include <std_msgs/msg/int32.hpp>
#include <std_msgs/msg/float64.hpp>
#include <std_msgs/msg/bool.hpp>
#include <std_msgs/msg/header.hpp>
#include <std_msgs/msg/empty.hpp>
```

Message Type Names

- Full type: `std_msgs::msg::String`
- With SharedPtr: `std_msgs::msg::String::SharedPtr`
- Const SharedPtr: `std_msgs::msg::String::ConstSharedPtr`

Creating and Populating Messages

```cpp
// String message
auto string_msg = std_msgs::msg::String();
string_msg.data = "Hello ROS 2";

// Numeric messages
auto int_msg = std_msgs::msg::Int32();
int_msg.data = 42;

// Header message (with timestamp)
auto header_msg = std_msgs::msg::Header();
header_msg.stamp = this->now();  // Current ROS time
header_msg.frame_id = "base_link";
```

Messages are simple **structs**: access fields directly with the dot operator.

Adding Message Dependencies

To use messages in your package, declare dependencies properly:

In package.xml

```
<depend>std_msgs</depend>
<depend>geometry_msgs</depend>  <!-- If using geometry messages -->
<depend>sensor_msgs</depend>     <!-- If using sensor messages -->
```

In CMakeLists.txt

```
find_package(ament_cmake REQUIRED)
find_package(rclcpp REQUIRED)
find_package(std_msgs REQUIRED)

# For your node
ament_target_dependencies(my_node
  rclcpp
  std_msgs
)
```

Testing with Command Line

You can publish messages directly from the terminal for testing:

Basic Publishing

- String: `ros2 topic pub /chatter std_msgs/msg/String "data: 'Hello World'"`
- Integer: `ros2 topic pub /number std_msgs/msg/Int32 "data: 42"`
- Float: `ros2 topic pub /temperature std_msgs/msg/Float64 "data: 23.5"`
- Boolean: `ros2 topic pub /enabled std_msgs/msg/Bool "data: true"`

Publishing Options

- Once: `ros2 topic pub --once /topic std_msgs/msg/String "data: 'test'"`
- Rate: `ros2 topic pub --rate 10 /topic std_msgs/msg/String "data: 'test'"`
- Count: `ros2 topic pub --times 5 /topic std_msgs/msg/String "data: 'test'"`

Message Format Guidelines

When publishing from CLI, use YAML format:

Message Type	CLI Format	Example
String	`"data: '<text>'"`	`"data: 'Hello'"`
Numeric	`"data: <number>"`	`"data: 3.14"`
Boolean	`"data: true/false"`	`"data: false"`
Empty	`""`	`""`
Arrays	`"data: [1, 2, 3]"`	`"data: [1.0, 2.0]"`
Nested	Use indentation	See geometry_msgs

Complex Message Example

For messages with multiple fields:

```
ros2 topic pub /header std_msgs/msg/Header{"stamp: {sec: 0, nanosec: 0}, frame_id: 'map'"}
```

Publishers

Publishers send messages to topics, enabling one-to-many communication between nodes.

Publisher Workflow

1. **Create Publisher**: Specify message type, topic name, and QoS
2. **Create Message**: Instantiate and populate message object
3. **Publish**: Send message to all subscribers
4. **Repeat**: Often done periodically using timers

Common Use Cases

- Sensor data streaming (cameras, lidar, IMU)
- Robot state broadcasting (position, velocity, battery)
- Control commands (velocity commands, joint positions)
- Status updates and heartbeats

Resources

- Writing a Simple Publisher and Subscriber (C++)
- About Topics

Create a node with a publisher component that publishes string messages.

Package	*publisher_demo*
Header	include/publisher_demo/publisher_demo.hpp
Source	src/publisher_demo.cpp
Node	publisher_demo
Executable	*publisher_demo*

```
ros2 pkg create publisher_demo --build-type ament_cmake --dependencies rclcpp std_msgs
```

Don't forget to update package.xml with proper metadata and CMakeLists.txt with build instructions!

Publisher Node Header

Create include/publisher_demo/publisher_demo.hpp:

```cpp
#pragma once

#include <rclcpp/rclcpp.hpp>
#include <std_msgs/msg/string.hpp>
#include <chrono>
#include <memory>

class PublisherDemo : public rclcpp::Node{
public:
    explicit PublisherDemo(const std::string& node_name);

private:
    void timer_callback();

    rclcpp::Publisher<std_msgs::msg::String>::SharedPtr publisher_;
    rclcpp::TimerBase::SharedPtr timer_;
    size_t count_;
};
```

Publisher Implementation

Create src/publisher_demo.cpp:

```cpp
#include "publisher_demo/publisher_demo.hpp"

PublisherDemo::PublisherDemo(const std::string& node_name)
    : Node(node_name), count_{0}{
    // Create publisher with message type, topic name, and QoS depth
    publisher_ = this->create_publisher<std_msgs::msg::String>("leia", 10);

    // Create timer for periodic publishing (2Hz = 500ms)
    timer_ = this->create_wall_timer(
        std::chrono::milliseconds(500),
        std::bind(&PublisherDemo::timer_callback, this));

    RCLCPP_INFO(this->get_logger(), "Publisher initialized");
}
```

Key Components

- `create_publisher<MessageType>()`: Creates publisher object
- Topic name: `"leia"`: Where messages will be published
- QoS depth: `10` - Message queue size
- Timer: Triggers callback every 500ms (2Hz)

Understanding QoS (Quality of Service)

When you pass an integer to `create_publisher()`, it sets the queue depth with default QoS settings:

```
// Simple integer parameter
publisher_ = create_publisher<std_msgs::msg::String>("topic", 10);

// Equivalent explicit QoS
rclcpp::QoS qos(10);  // Queue depth of 10
qos.reliability(rclcpp::ReliabilityPolicy::Reliable);
qos.durability(rclcpp::DurabilityPolicy::Volatile);
qos.history(rclcpp::HistoryPolicy::KeepLast);
publisher_ = create_publisher<std_msgs::msg::String>("topic", qos);
```

Queue Behavior

Scenario	Queue Behavior
Subscribers keep up	Messages delivered immediately, queue stays empty
Slow/disconnected subscriber	Messages queued up to depth limit
Queue full	Oldest messages dropped (KeepLast policy)

Timer Callback Implementation

```cpp
void PublisherDemo::timer_callback(){
    // Create message
    auto message = std_msgs::msg::String();

    // Populate message data
    message.data = "Help me Obi-Wan Kenobi, you're my only hope #" +
                   std::to_string(count_++);

    // Log what we're publishing (optional)
    RCLCPP_INFO(this->get_logger(), "Publishing: '%s'", message.data.c_str());

    // Publish the message
    publisher_->publish(message);
}
```

Main Function

```cpp
int main(int argc, char **argv){
    rclcpp::init(argc, argv);
    auto node = std::make_shared<PublisherDemo>("publisher_demo");
    rclcpp::spin(node);
    rclcpp::shutdown();
}
```

Build and Run

- `cd ~/ros702_ws  colcon build --packages-select publisher_demo`
- `source install/setup.<bash|zsh>`
- `ros2 run publisher_demo publisher_demo`

Subscribers

Subscribers receive messages from topics, enabling nodes to react to data published by other nodes.

Subscriber Workflow

1. **Create Subscriber**: Specify message type, topic, callback, and QoS
2. **Define Callback**: Function to process received messages
3. **Spin Node**: Keep node alive to receive messages
4. **Process**: Handle messages as they arrive asynchronously

Common Use Cases

- Processing sensor data for navigation
- Reacting to control commands
- Monitoring system status
- Data logging and visualization
- Triggering actions based on events

ToDo

Create a subscriber node that receives messages from the `t` leia topic.

Package	*subscriber_demo*
Header	include/subscriber_demo/subscriber_demo.hpp
Source	src/subscriber_demo.cpp
Node	`n` subscriber_demo
Executable	*subscriber_demo*

```
ros2 pkg create subscriber_demo --build-type ament_cmake --dependencies rclcpp std_msgs
```

Subscriber Node Header

Create include/subscriber_demo/subscriber_demo.hpp:

```cpp
#pragma once

#include <rclcpp/rclcpp.hpp>
#include <std_msgs/msg/string.hpp>
#include <memory>

class SubscriberDemo : public rclcpp::Node{
public:
    explicit SubscriberDemo(const std::string& node_name);

private:
    void topic_callback(const std_msgs::msg::String::SharedPtr msg);

    rclcpp::Subscription<std_msgs::msg::String>::SharedPtr subscription_;
};
```

Subscriber Implementation

Create **src/subscriber_demo.cpp**:

```cpp
#include "subscriber_demo/subscriber_demo.hpp"

SubscriberDemo::SubscriberDemo(const std::string& node_name)
    : Node(node_name){
    subscription_ = this->create_subscription<std_msgs::msg::String>(
        "leia",  // Topic name
        10,      // QoS queue depth
        std::bind(&SubscriberDemo::topic_callback, this, std::placeholders::_1));

    RCLCPP_INFO(this->get_logger(), "Subscriber initialized, listening to 'leia'");
}
```

Key Components

- `create_subscription<MessageType>()`: Creates subscriber
- Topic: `"leia"`: Must match publisher's topic
- QoS: `10` - Subscriber's message queue size
- Callback: `std::bind()` - Links callback method

Callback Implementation

```
void SubscriberDemo::topic_callback(const std_msgs::msg::String::SharedPtr msg){
    RCLCPP_INFO(this->get_logger(), "Received: '%s'", msg->data.c_str());

    // Process the message as needed:
    // - Store data for later use
    // - Trigger other actions
    // - Update internal state
    // - Publish transformed data
}
```

Main Function

```
int main(int argc, char **argv){
    rclcpp::init(argc, argv);
    auto node = std::make_shared<SubscriberDemo>("subscriber_demo");
    rclcpp::spin(node);
    rclcpp::shutdown();
}
```

The callback is executed asynchronously whenever a message arrives. Make sure callback execution is faster than message arrival rate to avoid queue overflow.

Build and Test Publisher-Subscriber System

Update **CMakeLists.txt** for subscriber (same pattern as publisher).

Run the Complete System

1. Terminal 1 - Start the publisher:
   - `ros2 run publisher_demo publisher_demo`
2. Terminal 2 - Start the subscriber:
   - `ros2 run subscriber_demo subscriber_demo`
3. Terminal 3 - Inspect the system:
   - `ros2 topic list`
   - `ros2 topic info /leia`
   - `ros2 topic echo /leia`
   - `ros2 topic hz /leia`

Always verify topic names match between publishers and subscribers. Use `ros2 topic list` to debug connection issues.

Communication Scenarios

Understanding how messages flow between publishers and subscribers under different conditions.

Scenario #1: No Subscriber

- Publisher rate: 2 Hz (1 message every 0.5s)
- **No subscriber present**
- QoS depth: 10 (publisher)

Time	Publisher Action	DDS Behavior	Result
t=0.0s	Publishes msg1	No matching DataReader	Message discarded
t=0.5s	Publishes msg2	No matching DataReader	Message discarded
t=1.0s	Publishes msg3	No matching DataReader	Message discarded

Key Points

- DDS is smart - doesn't waste resources on undeliverable messages
- Publisher continues running normally
- No performance impact from missing subscribers
- Messages are lost forever (unless using durability QoS)

Scenario #2: Fast Subscriber

- Publisher rate: 2 Hz (500ms period)
- Subscriber callback: **Fast - 100ms**
- QoS depth: 10 (both sides)

Time	Pub Action	Sub Queue	Callback	Notes
t=0.0s	Publish msg1	[msg1] → [ ]	Starts immediately	Quick processing
t=0.1s	—	[ ]	Completes	Ready for next
t=0.5s	Publish msg2	[msg2] → [ ]	Starts immediately	No queue buildup
t=0.6s	—	[ ]	Completes	System healthy

Analysis

- Ideal scenario - subscriber keeps pace with publisher
- Queue never builds up (always 0 or 1 message)
- Low latency between publish and process
- System remains responsive

Scenario #3: Slow Subscriber

- Publisher rate: 2 Hz (500ms period)
- Subscriber callback: **Slow - 1.7s**
- QoS depth: 3 (both sides)

Time	Pub	Sub Queue	Callback	Result
t=0.0s	msg1	[msg1]	Processing msg1	Queue: 0
t=0.5s	msg2	[msg2]	Still on msg1	Queue: 1
t=1.0s	msg3	[msg2, msg3]	Still on msg1	Queue: 2
t=1.5s	msg4	[msg2, msg3, msg4]	Still on msg1	Queue full!
t=1.7s	—	[msg3, msg4]	Done, starts msg2	—
t=2.0s	msg5	[msg3, msg4, msg5]	Processing msg2	msg3 dropped!

Consequences

- Message loss when queue overflows
- Increasing latency between publish and process
- Subscriber always behind real-time
- May need to increase queue size or optimize callback

Useful Commands

- Check if messages are being published:
  - `ros2 topic echo /topic_name`
  - `ros2 topic hz /topic_name`
- Analyze publisher-subscriber connections:
  - `ros2 topic info /topic_name -v`
  - `ros2 node info /node_name`
- Monitor system performance:
  - `ros2 doctor --report`
  - Use `RCLCPP_DEBUG` logging in callbacks

Performance Tips

- Keep callbacks fast - offload heavy processing
- Use appropriate queue sizes based on data rate
- Consider async processing for CPU-intensive tasks
- Profile your code to find bottlenecks

Next Class

- Lecture 10: ROS (Part 2).