ESP-DL User Guide

Release v3.2.0-6-g8e99095b8e
Espressif Systems
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	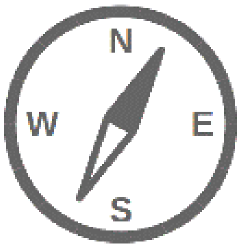	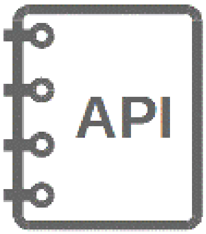
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Chapter 1

Introduction

1.1 Introduction

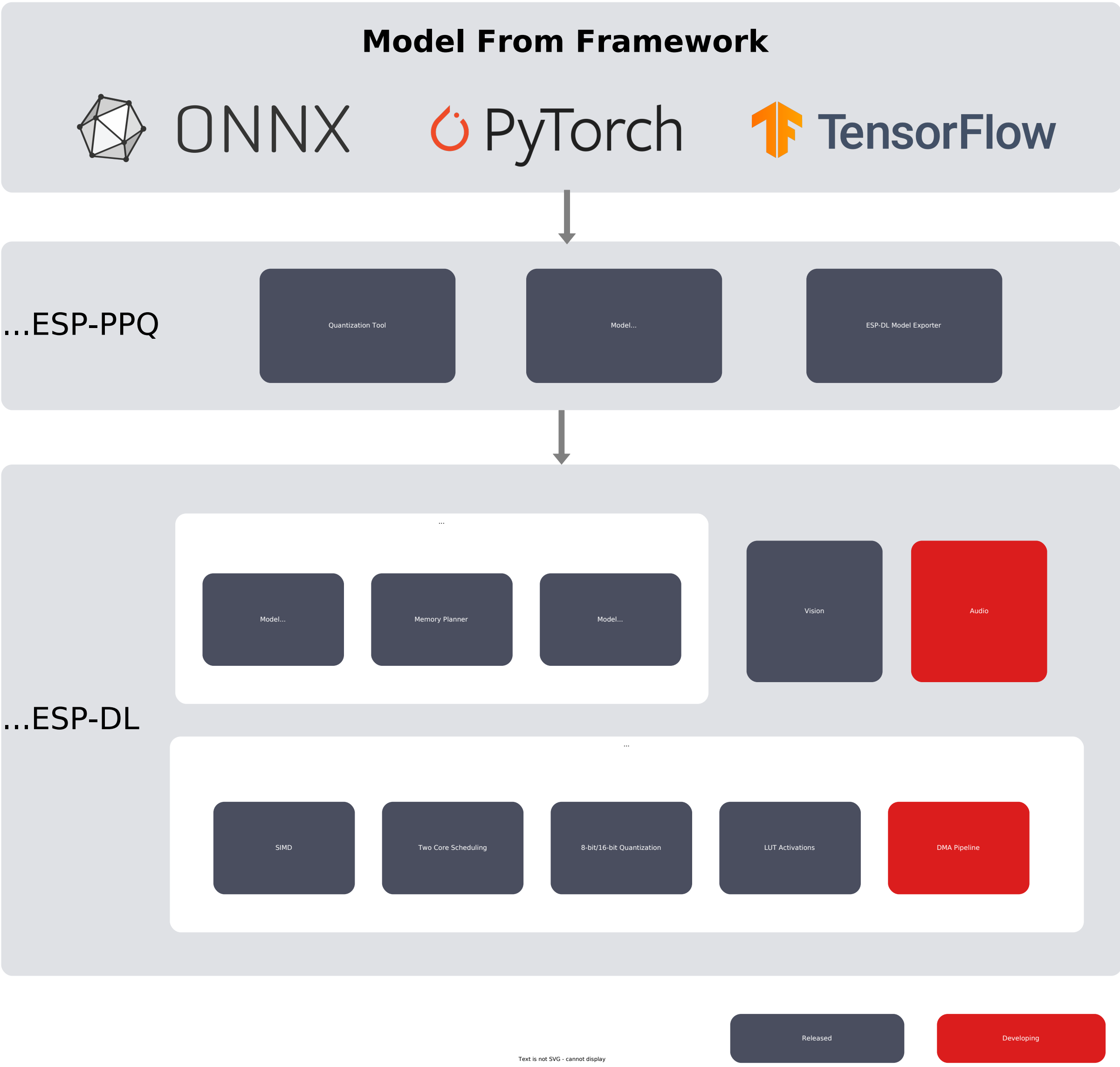
ESP-DL is a lightweight and efficient neural network inference framework designed specifically for ESP series chips. With ESP-DL, you can easily and quickly develop AI applications using Espressif's System on Chips (SoCs).

1.1.1 Overview

ESP-DL offers APIs to load, debug, and run AI models. The framework is easy to use and can be seamlessly integrated with other Espressif SDKs. ESP-PPQ serves as the quantization tool for ESP-DL, capable of quantizing models from ONNX, Pytorch, and TensorFlow, and exporting them into the ESP-DL standard model format.

- **ESP-DL Standard Model Format**: This format is similar to ONNX but uses FlatBuffers instead of Protobuf, making it more lightweight and supporting zero-copy deserialization, with a file extension of *.espdl*.
- **Efficient Operator Implementation**: ESP-DL efficiently implements common AI operators such as Conv, Gemm, Add, and Mul. The list of supported operators: operator_support_state.md
- **Static Memory Planner**: The memory planner automatically allocates different layers to the optimal memory location based on the user-specified internal RAM size, ensuring efficient overall running speed while minimizing memory usage.
- **Dual Core Scheduling**: Automatic dual-core scheduling allows computationally intensive operators to fully utilize the dual-core computing power. Currently, Conv2D and DepthwiseConv2D support dual-core scheduling.
- **8bit LUT Activation**: All activation functions except for ReLU and PReLU are implemented using an 8-bit LUT (Look Up Table) method in ESP-DL to accelerate inference. You can use any activation function, and their computational complexity remains the same.

The framework figures below illustrate the overall architecture of ESP-DL.



1.2 ESP-DL Project Organization

ESP-DL' s modular design enables efficient development, maintenance, and scalability. The project is organized as follows:

1.2.1 dl (Deep Learning)

Core deep learning modules and tools, divided into submodules:

- **model** Loads, manages, and allocates memory for deep learning models. Includes `dl_model_base` and `dl_memory_manager`.
- **module** Interfaces for operations (convolution, pooling, activation, etc.). Files: `dl_module_conv`, `dl_module_pool`, `dl_module_relu` etc.
- **base** Implements operations for chips (esp32s3/esp32p4) with assembly support.
- **math** Mathematical operations (matrix functions). Files: `dl_math.hpp` and `dl_math.cpp`.
- **tool** Auxiliary functions (utility tools). Files: `dl_tool.hpp` and `dl_tool.cpp`.
- **tensor** Tensor classes. Files: `dl_tensor_base.hpp`.

1.2.2 vision

Computer vision modules divided into submodules:

- **classification** Image classification (model inference). Inference: `dl_cls_base`. Post-processors: `imagenet_cls_postprocessor`, `dl_cls_postprocessor`.
- **recognition** Feature extract (model inference). Feature database management (Enroll, delete, query). Pre-processor: `dl_feat_image_preprocessor`. Inference: `dl_feat_base`. Post-processor: `dl_feat_postprocessor`. Database: `dl_recognition_database`
- **image** Image process(resize, crop, warp affine). Color conversion(pixel, img). Image preprocessor (pipeline of resize, crop, color conversion, normalization, quantization). Image decoding/encoding (JPEG/BMP). Draw utility (point, hollow rectangle).
  Image process: `dl_image_process`. Color conversion: `dl_image_color`. Image preprocessor: `dl_image_preprocessor`. Image decoding/encoding: `dl_image_jpeg`, `dl_image_bmp`. Draw utility: `dl_image_draw`.
- **detect** Object detection (model inference). Inference: `dl_detect_base`. Post-processors: `dl_detect_msr_postprocessor`, `dl_detect_mnp_postprocessor`, `dl_detect_pico_postprocessor`.

1.2.3 fbs_loader (FlatBuffers Loader)

Handles FlatBuffers models:

- **include** Headers: `fbs_loader.hpp`, `fbs_model.hpp`.
- **src** Implementations: `fbs_loader.cpp`.

1.2.4 Other Files

- **CMakeLists.txt** Project build configuration.
- **idf_component.yml** Component metadata (name, version, dependencies).
- **README.md** Project documentation and usage.
- **LICENSE** License terms.

Chapter 2

Getting Started

2.1 Hardware Requirements

- An ESP32-S3 or ESP32-P4 development board. Recommended: ESP32-S3-EYE or ESP32-P4-Function-EV-Board
- PC (Linux)

Note:

- Some boards currently use Type C connectors. Make sure you use the right cable to connect the board!
- ESP-DL also supports ESP32, but its operator implementations are written in C, so the execution speed on ESP32 will be significantly slower than on ESP32-S3 or ESP32-P4. If needed, you can manually add compilation configuration files to your project—the function interface calls in ESP-DL remain identical. Note:
  - When quantizing **ESP32** platform models using **ESP-PPQ**, set the target to `c`.
  - When deploying **ESP32** platform models using **ESP-DL**, set the project compilation target to `esp32`.

2.2 Software Requirements

2.2.1 ESP-IDF

ESP-DL runs based on ESP-IDF. For detailed instructions on how to get ESP-IDF, see the ESP-IDF Programming Guide.

Note: Please use `release/v5.3` or higher version of ESP-IDF.

2.2.2 ESP-PPQ

ESP-PPQ is a quantization tool based on ppq, and its source code is fully open-sourced. ESP-PPQ adds Espressif’s customized quantizer and exporter based on PPQ, which makes it convenient for users to select quantization rules that match ESP-DL according to different chip selections, and export them to standard model files that can be directly loaded by ESP-DL. ESP-PPQ is compatible with all PPQ APIs and quantization scripts. For more details, please refer to PPQ documents and videos. If you want to quantize your model, you can install esp-ppq using the following method:

Method 1: Install the package using pip

```
pip install torch torchvision torchaudio --index-url https://download.pytorch.org/
↪whl/cpu
pip install esp-ppq
```

Method 2: Install from source with pip to stay synchronized with the master branch

```
git clone https://github.com/espressif/esp-ppq.git
cd esp-ppq
pip install torch torchvision torchaudio --index-url https://download.pytorch.org/
↪whl/cpu
pip install -e .
```

Method 3: Install the package using uv

```
uv pip install "esp-ppq[cpu]" --torch-backend=cpu
# GPU
# uv pip install "esp-ppq[cpu]" --torch-backend=cu124
# AMD GPU
# uv pip install "esp-ppq[cpu]" --torch-backend=rocm6.2
# Intel XPU
# uv pip install "esp-ppq[cpu]" --torch-backend=xpu
```

Method 4: Install from source using uv to stay in sync with the master branch

```
git clone https://github.com/espressif/esp-ppq.git
cd esp-ppq
uv pip install torch torchvision torchaudio --index-url https://download.pytorch.
↪org/whl/cpu
uv pip install -e .
```

Method 5: Use esp-ppq with docker

```
docker build -t esp-ppq:your_tag https://github.com/espressif/esp-ppq.git
```

Note:

- The example code installs the Linux PyTorch CPU version. Please install the appropriate PyTorch version based on your actual needs.
- If installing the package with uv, simply modify the `--torch-backend` parameter, which will override the PyTorch URLs index configured in the project.

2.3 Quick Start

ESP-DL provides some out-of-the-box examples

2.3.1 Example Compile & Flash

```
idf.py set-target [Soc]
idf.py flash monitor -p [PORT]
```

Replace `[Soc]` with the specific chip, currently supports `esp32s3` and `esp32p4`. The example does not yet include the model and compilation configuration files for `esp32`.

2.3.2 Example Configuration

```
idf.py menuconfig
```

Some examples contain configurable options that can be configured using `idf.py menuconfig` after specifying the chip using `idf.py set-target`.

2.3.3 Trouble shooting

Check ESP-IDF doc

See ESP-IDF DOC

Erase FLASH & Clear Example

```
idf.py erase-flash -p [PORT]
```

Delete `build/`, `sdkconfig`, `dependencies.lock`, `managed_components/` and try again.

2.4 Model Quantization

First, please refer to operator_support_state.md to ensure that the operators in your model are supported.

ESP-DL must use the proprietary format `.espdl` for model deployment. Deep learning models need to be quantized and converted to the format before they can be used. ESP-PPQ provides two interfaces, `espdl_quantize_onnx` and `espdl_quantize_torch`, to support ONNX models and PyTorch models to be exported as `.espdl` models. Other deep learning frameworks, such as TensorfFlow, PaddlePaddle, etc., need to convert the model to ONNX first. So make sure your model can be converted to ONNX model. For more details, please refer to:

- *How to quantize model*
- *How to quantize MobileNetV2*
- *How to quantize YOLO11n*
- *How to quantize YOLO11n-pose*
- *How to quantize streaming model*

2.5 Model deployment

ESP-DL provides a series of APIs to quickly load and run models. For more details, see:

- *How to load & test & profile model*
- *How to run model*
- *How to deploy streaming model*

Chapter 3

Tutorials

3.1 How to quantize model

ESP-DL must use a proprietary format `.espdl` for model deployment. This is a quantized model format that supports 8bit and 16bit. In this tutorial, we will take quantize_sin_model as an example to show how to use ESP-PPQ to quantize and export a `.espdl` model. The quantization method is Post Training Quantization (PTQ).

3.1.1 Preparation

Install ESP_PPQ

3.1.2 Pre-trained model

```
python sin_model.py
```

Run sin_model.py . This script trains a simple Pytorch model to fit the sin function in the range [0, 2pi]. After training, the corresponding .pth weights will be saved and the ONNX model will be exported.

Note: ESP-PPQ provides two interfaces, `espdl_quantize_onnx` and `espdl_quantize_torch`, to support ONNX models and PyTorch models. Other deep learning frameworks, such as TensorfFlow, PaddlePaddle, etc., need to be converted to ONNX first.

- Convert TensorFlow to ONNX tf2onnx
- Convert TFLite to ONNX tflite2onnx
- Convert TFLite to TensorFlow tflite2tensorflow

- Convert PaddlePaddle to ONNX paddle2onnx

3.1.3 Quantize and export `.espdl`

Reference quantize_torch_model.py and quantize_onnx_model.py , learn how to use the `espdl_quantize_onnx` and `espdl_quantize_torch` interfaces to quantize and export the `.espdl` model.

After executing the script, three files will be exported:

- `**.espdl`: ESPDL model binary file, which can be directly used for chip reasoning.
- `**.info`: ESPDL model text file, used to debug and determine whether the `.espdl` model is exported correctly. Contains model structure, quantized model weights, test input/output and other information.
- `**.json`: Quantization information file, used to save and load quantization information.

Note:

1. The `.espdl` models of different platforms cannot be mixed, otherwise the inference results will be inaccurate.
   - The `ESP32` uses `ROUND_HALF_UP` as its rounding strategy.
     - When quantizing **ESP32** platform models using **ESP-PPQ**, set the target to `c`. Because ESP-DL implements its operators in C.
     - When deploying **ESP32** platform models using **ESP-DL**, set the project compilation target to `esp32`.
   - The ROUND strategy used by `ESP32S3` is `ROUND_HALF_UP`.
   - The ROUND strategy used by `ESP32P4` is `ROUND_HALF_EVEN`.
2. The quantization strategy currently used by ESP-DL is symmetric quantization + POWER OF TWO.

Add test input/output

To verify whether the inference results of the model on the board are correct, you first need to record a set of test input/output on the PC. By turning on the `export_test_values` option in the api, a set of test input/output can be saved in the `.espdl` model. One of the `input_shape` and `inputs` parameters must be specified. The `input_shape` parameter uses a random test input, while `inputs` can use a specific test input. The values of the test input/output can be viewed in the `.info` file. Search for `test inputs value` and `test outputs value` to view them.

Quantized model inference & accuracy evaluation

`espdl_quantize_onnx` and `espdl_quantize_torch` APIs will return `BaseGraph`. Use `BaseGraph` to build the corresponding `TorchExecutor` to use the quantized model for inference on the PC side.

```
executor = TorchExecutor(graph=quanted_graph, device=device)
output = executor(input)
```

The output obtained by quantized model inference can be used to calculate various accuracy metrics. Since the board-side `esp-dl` inference result can be aligned with `esp-ppq`, these metrics can be used directly to evaluate the accuracy of the quantized model.

Note:

1. Currently esp-dl only supports batch_size of 1, and does not support multi-batch or dynamic batch.
2. The test input/output and the quantized model weights in the `.info` file are all 16-byte aligned. If the length is less than 16 bytes, it will be padded with 0.

3.1.4 Advanced Quantization Methods

If you want to further improve the performance of the quantized model, please try the the following advanced quantization methods:

Post Training Quantization (PTQ)

- *Mixed precision quantization*
- *Layerwise equalization quantization*
- *Horizontal Layer Split Quantization*

Quantization Aware Training (QAT)

- *YOLO11n Quantization-Aware Training*
- *YOLO11n-pose Quantization-Aware Training*

3.2 How to load & test & profile model

In this tutorial, we will show you how to load, test, profile an espdl model. example

3.2.1 Preparation

1. *Install ESP_IDF*
2. *how_to_quantize_model*

3.2.2 Load model from `rodata`

1. **Add model file in** `CMakeLists.txt`
   If you want to put the `.espdl` model file into the `.rodata` section of the FLASH chip, you need to add the following code in `CMakeLists.txt`. The first few lines should be placed before `idf_component_register()` and the last line should be placed after `idf_component_register()`.

```
idf_build_get_property(component_targets __COMPONENT_TARGETS)
if ("___idf_espressif__esp-dl" IN_LIST component_targets)
idf_component_get_property(espdl_dir espressif__esp-dl COMPONENT_DIR)
elseif("___idf_esp-dl" IN_LIST component_targets)
idf_component_get_property(espdl_dir esp-dl COMPONENT_DIR)
endif()
set(cmake_dir ${espdl_dir}/fbs_loader/cmake)
include(${cmake_dir}/utilities.cmake)
set(embed_files your_model_path/model_name.espdl) idf_component_register(...)
```

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```
target_add_aligned_binary_data(${COMPONENT_LIB} ${embed_files} BINARY)
```

2. **Load the model in the program**

```
// "_binary_model_espdl_start" is composed of three parts: the prefix "binary",
↪ the filename "model_espdl", and the suffix "_start".
extern const uint8_t model_espdl[] asm("_binary_model_espdl_start");

dl::Model *model = new dl::Model((const char *)model_espdl, fbs::MODEL_
↪LOCATION_IN_FLASH_RODATA);

// Keep parameter in FLASH, saves PSRAM/internal RAM, lower performance.
// dl::Model *model = new dl::Model((const char *)model_espdl, fbs::MODEL_
↪LOCATION_IN_FLASH_RODATA, 0, dl::MEMORY_MANAGER_GREEDY, nullptr, false);
```

Note:

1. When using *Load model from rodata*, since the `.rodata` section belongs to the app partition, the model file will be flashed every time the code is modified. If the model file is large, you may need to adjust the size of the app partition. Using *Load model from partition* or *Load model from sdcard* can avoid repeatedly flashing the model, which helps to reduce the flashing time.
2. When using *Load model from rodata* or *Load model from partition*, turning off the param_copy option in the Model constructor can avoid copying the model weights in PSRAM or internal RAM to FLASH. This can reduce the use of PSRAM or internal RAM. However, since the frequency of PSRAM or internal RAM is higher than FLASH, the inference performance of the model will decrease.

3.2.3 Load model from `partition`

1. **Add model information in** `partition.csv`

About `partition.csv`, please refer to the partition table documentation.

```
# Name, Type, SubType, Offset, Size, Flags
factory, app, factory, 0x010000, 4000K,
model, data, spiffs, , 4000K,
```

The `Name` field of the model can be any meaningful name, but cannot exceed 16 bytes, including a null byte (the content after that will be truncated). The `SubType` field must be spiffs. The `Offset` can be left blank after other partitions and will be automatically calculated. `Size` must be larger than the size of the model file.

2. **Add model flashing information in** `CMakeLists.txt`

```
idf_component_register(...)
set(image_file your_model_path)
esptool_py_flash_to_partition(flash "model" "${image_file}")
```

The second parameter in `esptool_py_flash_to_partition` must be consistent with the `Name` field in `partition.csv`.

3. **Load the model in the program**

```
dl::Model *model = new dl::Model("model", fbs::MODEL_LOCATION_IN_FLASH_PARTITION);

// Keep parameter in flash, saves PSRAM/internal RAM, lower performance.
// dl::Model *model = new dl::Model("model", fbs::MODEL_LOCATION_IN_FLASH_
↪PARTITION, 0, dl::MEMORY_MANAGER_GREEDY,
// nullptr, false);
```

The first parameter of the constructor must be consistent with the `Name` field in `partition.csv`.

Note: Use `idf.py app-flash` instead of `idf.py flash` to flash only the app partition without flashing the model partition, this can reduce the flashing time.

3.2.4 Load model from `sdcard`

1. **Check if sdcard is in the correct format**
   Back up the data first, then try to mount it on the board. If the sdcard is not in the correct format, it will be automatically formatted to the correct format.

- If using BSP(Board Support Package)
  Enable `CONFIG_BSP_SD_FORMAT_ON_MOUNT_FAIL` option in menuconfig.

```
ESP_ERROR_CHECK(bsp_sdcard_mount());
```

- If not using BSP(Board Support Package)
  Set format_if_mount_failed in esp_vfs_fat_sdmmc_mount_config_t structure to true.

```
esp_vfs_fat_sdmmc_mount_config_t mount_config = {
      .format_if_mount_failed = true,
      .max_files = 5,
      .allocation_unit_size = 16 * 1024
};
// Mount sdcard.
```

2. **Copy model to sdcard**
   Copy .espdl model to sdcard.
3. **Load the model in the program**

- If using BSP(Board Support Package)

```
ESP_ERROR_CHECK(bsp_sdcard_mount());
const char *model_path = "/your_sdcard_mount_point/your_model_path/model_name.
↪espdl";
Model *model = new Model(model_path, fbs::MODEL_LOCATION_IN_SDCARD);
```

- If not using BSP(Board Support Package)

```
// Mount sdcard.
const char *model_path = "/your_sdcard_mount_point/your_model_path/model_name.
↪espdl";
Model *model = new Model(model_path, fbs::MODEL_LOCATION_IN_SDCARD);
```

Note: When using *load model from sdcard*, the model loading process will take longer because the model data needs to be copied from sdcard to PSRAM or internal RAM. This method is useful if your FLASH is tight.

3.2.5 Test whether on-board model inference is correct

In order to test whether on-board model inference is correct, the `.espdl` model needs to *add test input/output* when exporting. When actually deploying, you can export a version without test input and output to reduce the size of the model file.

```
ESP_ERROR_CHECK(model->test());
```

3.2.6 Profile model memory usage

```
model->profile_memory();
```

Name	Explanation
fbs_model parameter	Flatbuffers model, contains a sub-item `parameter`. In addition to the model parameters, the flatbuffers model also contains test input/output, test input and output, model parameter/variable shape, model structure etc.
`parameter_copy`	Copied Model parameter, when the flatbuffers model locates in FLASH, parameters are copied to PSRAM or internal RAM by default to improve inference performance.
`variable`	Memory allocated by the memory manager. Model input/output and intermediate calculation results will use this space.
`others`	Space required for class member variables, extra part for alignment during `heap_caps_aligned_alloc` / `heap_caps_aligned_calloc` (very small).

3.2.7 Profile model inference latency

```
model->profile_module();
```

By default, the model modules are printed in ONNX topological sort. If you want to sort by the latency of each module, you can set the input parameter of `profile_module` to `True`.

```
model->profile_module(true);
```

3.3 How to run model

In this tutorial, we will introduce the most basic model inference process. example

3.3.1 Preparation

Install ESP_IDF

3.3.2 Load model

How to load model

3.3.3 Get model input/output.

```
std::map<std::string, dl::TensorBase *> model_inputs = model->get_inputs();
dl::TensorBase *model_input = model_inputs.begin()->second;
std::map<std::string, dl::TensorBase *> model_outputs = model->get_outputs();
dl::TensorBase *model_output = model_outputs.begin()->second;
```

You can get the input/output names and the corresponding `dl::TensorBase` with `get_inputs()` and `get_outputs()` api. For more information, see *dl::TensorBase documentation*.

Note: ESP-DL's memory manager allocates a whole block of memory for each model's input/intermediate result/output. Since they share this memory, when the model is inferencing, the later results will overwrite the previous results. In other words, the data in `model_input` may be overwritten by `model_output` or other intermediate results after the model inference is completed.

3.3.4 Quantize Input

8-bit and 16-bit quantized models accept inputs of type `int8_t` and `int16_t` respectively. `float` inputs must be quantized to the one of them according to `exponent` before being fed into the model. Calculation formula:

$$Q = \text{Clip}\left(\text{Round}\left(\frac{R}{\text{Scale}}\right), \text{MIN}, \text{MAX}\right)$$

$$\text{Scale} = 2^{\text{Exp}}$$

Where:

- R is the floating point number to be quantized.
- Q is the integer value after quantization, which needs to be clipped within the range [MIN, MAX].
- MIN is the minimum integer value, when 8bit, MIN = -128, when 16bit, MIN = -32768.
- MAX is the maximum integer value, when 8bit, MAX = 127, when 16bit, MAX = 32767.

Quantize a single value

```
float input_v = VALUE;
// Note that dl::quantize accepts inverse of scale as the second input, so we use
↪DL_RESCALE here.
int8_t quant_input_v = dl::quantize<int8_t>(input_v, DL_RESCALE(model_input->
↪exponent));
```

Quantize `dl::TensorBase`

```
// assume that input_tensor already contains the float input data.
dl::TensorBase *input_tensor;
model_input->assign(input_tensor);
```

3.3.5 Dequantize output

8bit and 16bit quantized model, get `int8_t` and `int16_t` type output respectively. Must be dequantized according to `exponent` to get floating point output. Calculation formula:

$$R' = Q \times \text{Scale}$$

$$\text{Scale} = 2^{\text{Exp}}$$

Where:

- R' is the approximate floating point value recovered after dequantization.
- Q is the integer value after quantization.

Dequantize a single value

```
int8_t quant_output_v = VALUE;
float output_v = dl::dequantize(quant_output_v, DL_SCALE(model_output->exponent));
```

Dequantize `dl::TensorBase`

```
// create a TensorBase filled with 0 of shape [1, 1]
dl::TensorBase *output_tensor = new dl::TensorBase({1, 1}, nullptr, 0, dl::DATA_
↪TYPE_FLOAT);
output_tensor->assign(model_output);
```

3.3.6 Model Inference

See:

- example
- *void dl::Model::run(runtime_mode_t mode)*
- *void dl::Model::run(TensorBase *input, runtime_mode_t mode)*
- *void dl::Model::run(std::map<std::string, TensorBase*> &user_inputs, runtime_mode_t mode, std::map<std::string, TensorBase*> user_outputs)*

3.4 Creating a New Module (Operator)

This tutorial guides you through the process of creating a new module in the `dl::module` namespace. The `Module` class serves as the base class for all modules, and you can extend this base class to create your custom module.

Note: The interface of modules in ESP-DL should be aligned with ONNX.

3.4.1 Understand the Base `Module` Class

The base class provides several virtual methods that must be overridden in your derived class.

- **Methods:**
  - *dl::module::Module::Module()*: Constructor to initialize the module.
  - *dl::module::Module::~Module()*: Destructor to release resources.

- *dl::module::Module::get_output_shape()*: Calculates the output shape based on the input shape.
- *dl::module::Module::forward()*: Runs the module, high-level interface.
- *dl::module::Module::forward_args()*: Runs the module, low-level interface.
- *dl::module::Module::deserialize()*: Creates a module instance from serialized information.
- *dl::module::Module::print()*: Prints module information.

For more information, please refer to Module Class Reference.

3.4.2 Create a New Module Class

To create a new module, you need to derive a new class from the `Module` base class and override the necessary methods.

Example: Creating a `MyCustomModule` Class

For more examples, please refer to esp-dl/dl/module.

```
#include "module.h" // Include the header file where the Module class is defined

namespace dl {
namespace module {

class MyCustomModule : public Module {
public:
    // Constructor
    MyCustomModule(const char *name = "MyCustomModule",
                   module_inplace_t inplace = MODULE_NON_INPLACE,
                   quant_type_t quant_type = QUANT_TYPE_NONE)
        : Module(name, inplace, quant_type) {}

   // Destructor
    virtual ~MyCustomModule() {}

    // Override the get_output_shape method
    std::vector<std::vector<int>> get_output_shape(std::vector<std::vector<int>> &
↪input_shapes) override {
        // Implement the logic to calculate the output shape based on input shapes
        std::vector<std::vector<int>> output_shapes;
        // Example: Assume the output shape is the same as the input shape
        output_shapes.push_back(input_shapes[0]);
        return output_shapes;
    }

    // Override the forward method
    void forward(std::vector<dl::TensorBase *> &tensors, runtime_mode_t mode =␣
↪RUNTIME_MODE_AUTO) override {
       // Implement the logic to run the module
        // Example: Perform some operation on the tensors
        for (auto &tensor : tensors) {
           // Perform some operation on each tensor
        }
    }

    // Override the forward_args method
    void forward_args(void *args) override {
        // Implement the low-level interface logic
        // Example: Perform some operation based on the arguments
    }
```

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```
    // Deserialize module instance by serialization information
    static Module *deserialize(fbs::FbsModel *fbs_model, std::string node_name){
        // Implement the logic to deserialize the module instance
        // The interface shoud be align with ONNX
    }

    // Override the print method
    void print() override {
        // Print module information
        ESP_LOGI("MyCustomModule", "Module Name: %s, Quant type: %d", name.c_str(),
↪ quant_type);
    }
};

} // namespace module
} // namespace dl
```

Register `MyCustomModule` Class

Once you have implemented `MyCustomModule` Class, register your module in dl_module_creator as a globally available module.

```
void register_dl_modules()
{
    if (creators.empty()) {
        ...
        this->register_module("MyCustomModule", MyCustomModule::deserialize);
    }
}
```

3.5 How to deploy MobileNetV2

In this tutorial, we will introduce how to quantize a pre-trained MobileNetV2 model using ESP-PPQ and deploy the quantized MobileNetV2 model using ESP-DL.

3.5.1 Preparation

1. *Install ESP_IDF*
2. *Install ESP_PPQ*

3.5.2 Model quantization

Quantization script

Pre-trained model

Load the pre-trained model of MobileNet_v2 from torchvision. You can also download it from ONNX models or TensorFlow models:

```
import torchvision
from torchvision.models.mobilenetv2 import MobileNet_V2_Weights

model = torchvision.models.mobilenet.mobilenet_v2(weights=MobileNet_V2_Weights.
↪IMAGENET1K_V1)
```

Calibration dataset

The calibration dataset needs to be consistent with your model input format. The calibration dataset needs to cover all possible situations of your model input as much as possible to better quantize the model. Here we take the ImageNet dataset as an example to demonstrate how to prepare the calibration dataset.

Use torchvision to load the ImageNet dataset:

```
import torchvision.datasets as datasets
from torch.utils.data.dataset import Subset
dataset = datasets.ImageFolder(
    CALIB_DIR,
    transforms.Compose(
            [
                transforms.Resize(256),
                transforms.CenterCrop(224),
                transforms.ToTensor(),
                transforms.Normalize(
                    mean=[0.485, 0.456, 0.406], std=[0.229, 0.224, 0.225]
                ),
            ]
    ),
)
dataset = Subset(dataset, indices=[_ for _ in range(0, 1024)])
dataloader = DataLoader(
    dataset=dataset,
    batch_size=BATCH_SIZE,
    shuffle=False,
    num_workers=4,
    pin_memory=False,
    collate_fn=collate_fn1,
)
```

8bit default configuration quantization

Quantization settings

```
target="esp32p4"
num_of_bits=8
batch_size=32
quant_setting = QuantizationSettingFactory.espdl_setting() # default setting
```

Quantization results

```
Analysing Graphwise Quantization Error::
Layer                                            | NOISE:SIGNAL POWER RATIO
/features/features.16/conv/conv.2/Conv:          | ████████████████████ | 48.831%
/features/features.15/conv/conv.2/Conv:          | ███████████████████  | 45.268%
/features/features.17/conv/conv.2/Conv:          | ██████████████████   | 43.112%
/features/features.18/features.18.0/Conv:        | █████████████████    | 41.586%
/features/features.14/conv/conv.2/Conv:          | █████████████████    | 41.135%
/features/features.13/conv/conv.2/Conv:          | ██████████████       | 35.090%
/features/features.17/conv/conv.0/conv.0.0/Conv: | █████████████        | 32.895%
/features/features.16/conv/conv.1/conv.1.0/Conv: | ████████████         | 29.226%
/features/features.12/conv/conv.2/Conv:          | ████████████         | 28.895%
/features/features.16/conv/conv.0/conv.0.0/Conv: | ███████████          | 27.808%
/features/features.7/conv/conv.2/Conv:           | ███████████          | 27.675%
/features/features.10/conv/conv.2/Conv:          | ███████████          | 26.292%
/features/features.11/conv/conv.2/Conv:          | ███████████          | 26.085%
/features/features.6/conv/conv.2/Conv:           | ███████████          | 25.892%
/classifier/classifier.1/Gemm:                   | ██████████           | 25.591%
/features/features.15/conv/conv.0/conv.0.0/Conv: | ██████████           | 25.323%
/features/features.4/conv/conv.2/Conv:           | ██████████           | 24.787%
/features/features.15/conv/conv.1/conv.1.0/Conv: | ██████████           | 24.354%
/features/features.14/conv/conv.1/conv.1.0/Conv: | ████████             | 20.207%
/features/features.9/conv/conv.2/Conv:           | ████████             | 19.808%
/features/features.14/conv/conv.0/conv.0.0/Conv: | ████████             | 18.465%
/features/features.5/conv/conv.2/Conv:           | ███████              | 17.868%
/features/features.12/conv/conv.1/conv.1.0/Conv: | ███████              | 16.589%
/features/features.13/conv/conv.1/conv.1.0/Conv: | ███████              | 16.143%
/features/features.11/conv/conv.1/conv.1.0/Conv: | ██████               | 15.382%
/features/features.3/conv/conv.2/Conv:           | ██████               | 15.105%
/features/features.13/conv/conv.0/conv.0.0/Conv: | ██████               | 15.029%
/features/features.10/conv/conv.1/conv.1.0/Conv: | ██████               | 14.875%
/features/features.2/conv/conv.2/Conv:           | ██████               | 14.869%
/features/features.11/conv/conv.0/conv.0.0/Conv: | ██████               | 14.552%
/features/features.9/conv/conv.1/conv.1.0/Conv:  | ██████               | 14.050%
/features/features.8/conv/conv.1/conv.1.0/Conv:  | ██████               | 13.929%
/features/features.8/conv/conv.2/Conv:           | ██████               | 13.833%
/features/features.12/conv/conv.0/conv.0.0/Conv: | ██████               | 13.684%
/features/features.7/conv/conv.0/conv.0.0/Conv:  | █████                | 12.942%
/features/features.6/conv/conv.1/conv.1.0/Conv:  | █████                | 12.765%
/features/features.10/conv/conv.0/conv.0.0/Conv: | █████                | 12.251%
/features/features.5/conv/conv.1/conv.1.0/Conv:  | █████                | 11.186%
/features/features.17/conv/conv.1/conv.1.0/Conv: | ████                 | 11.070%
/features/features.9/conv/conv.0/conv.0.0/Conv:  | ████                 | 10.371%
/features/features.4/conv/conv.1/conv.1.0/Conv:  | ████                 | 10.356%
/features/features.6/conv/conv.0/conv.0.0/Conv:  | ████                 | 10.149%
/features/features.4/conv/conv.0/conv.0.0/Conv:  | ████                 | 9.472%
/features/features.8/conv/conv.0/conv.0.0/Conv:  | ████                 | 9.232%
/features/features.3/conv/conv.1/conv.1.0/Conv:  | ████                 | 9.187%
/features/features.1/conv/conv.1/Conv:           | ████                 | 8.770%
/features/features.5/conv/conv.0/conv.0.0/Conv:  | ███                  | 8.408%
/features/features.7/conv/conv.1/conv.1.0/Conv:  | ███                  | 8.151%
/features/features.2/conv/conv.1/conv.1.0/Conv:  | ███                  | 7.156%
/features/features.3/conv/conv.0/conv.0.0/Conv:  | ███                  | 6.328%
/features/features.2/conv/conv.0/conv.0.0/Conv:  | ██                   | 5.392%
/features/features.1/conv/conv.0/conv.0.0/Conv:  |                      | 0.875%
/features/features.0/features.0.0/Conv:          |                      | 0.119%
Analysing Layerwise quantization error:: 100
↪%|████████████████████████████████████████████████████████████████████████████████████████████
↪53/53 [08:44<00:00,  9.91s/it]
Layer                                            | NOISE:SIGNAL POWER RATIO
/features/features.1/conv/conv.0/conv.0.0/Conv:  | ████████████████████ | 14.303%
/features/features.0/features.0.0/Conv:          | █                    | 0.844%
/features/features.1/conv/conv.1/Conv:           | █                    | 0.667%
```

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```
/features/features.2/conv/conv.1/conv.1.0/Conv:  | █                     | 0.574%
/features/features.3/conv/conv.1/conv.1.0/Conv:  | █                     | 0.419%
/features/features.15/conv/conv.1/conv.1.0/Conv: |                       | 0.272%
/features/features.9/conv/conv.1/conv.1.0/Conv:  |                       | 0.238%
/features/features.17/conv/conv.1/conv.1.0/Conv: |                       | 0.214%
/features/features.4/conv/conv.1/conv.1.0/Conv:  |                       | 0.180%
/features/features.11/conv/conv.1/conv.1.0/Conv: |                       | 0.151%
/features/features.12/conv/conv.1/conv.1.0/Conv: |                       | 0.148%
/features/features.16/conv/conv.1/conv.1.0/Conv: |                       | 0.146%
/features/features.14/conv/conv.2/Conv:          |                       | 0.136%
/features/features.13/conv/conv.1/conv.1.0/Conv: |                       | 0.105%
/features/features.6/conv/conv.1/conv.1.0/Conv:  |                       | 0.105%
/features/features.8/conv/conv.1/conv.1.0/Conv:  |                       | 0.083%
/features/features.7/conv/conv.2/Conv:           |                       | 0.076%
/features/features.5/conv/conv.1/conv.1.0/Conv:  |                       | 0.076%
/features/features.3/conv/conv.2/Conv:           |                       | 0.075%
/features/features.16/conv/conv.2/Conv:          |                       | 0.074%
/features/features.13/conv/conv.0/conv.0.0/Conv: |                       | 0.072%
/features/features.15/conv/conv.2/Conv:          |                       | 0.066%
/features/features.4/conv/conv.2/Conv:           |                       | 0.065%
/features/features.11/conv/conv.2/Conv:          |                       | 0.063%
/classifier/classifier.1/Gemm:                   |                       | 0.063%
/features/features.2/conv/conv.0/conv.0.0/Conv:  |                       | 0.054%
/features/features.13/conv/conv.2/Conv:          |                       | 0.050%
/features/features.10/conv/conv.1/conv.1.0/Conv: |                       | 0.042%
/features/features.17/conv/conv.0/conv.0.0/Conv: |                       | 0.040%
/features/features.2/conv/conv.2/Conv:           |                       | 0.038%
/features/features.4/conv/conv.0/conv.0.0/Conv:  |                       | 0.034%
/features/features.17/conv/conv.2/Conv:          |                       | 0.030%
/features/features.14/conv/conv.0/conv.0.0/Conv: |                       | 0.025%
/features/features.16/conv/conv.0/conv.0.0/Conv: |                       | 0.024%
/features/features.10/conv/conv.2/Conv:          |                       | 0.022%
/features/features.11/conv/conv.0/conv.0.0/Conv: |                       | 0.021%
/features/features.9/conv/conv.2/Conv:           |                       | 0.021%
/features/features.14/conv/conv.1/conv.1.0/Conv: |                       | 0.020%
/features/features.7/conv/conv.1/conv.1.0/Conv:  |                       | 0.020%
/features/features.5/conv/conv.2/Conv:           |                       | 0.019%
/features/features.8/conv/conv.2/Conv:           |                       | 0.018%
/features/features.12/conv/conv.2/Conv:          |                       | 0.017%
/features/features.6/conv/conv.2/Conv:           |                       | 0.014%
/features/features.7/conv/conv.0/conv.0.0/Conv:  |                       | 0.014%
/features/features.3/conv/conv.0/conv.0.0/Conv:  |                       | 0.013%
/features/features.12/conv/conv.0/conv.0.0/Conv: |                       | 0.009%
/features/features.15/conv/conv.0/conv.0.0/Conv: |                       | 0.008%
/features/features.5/conv/conv.0/conv.0.0/Conv:  |                       | 0.006%
/features/features.6/conv/conv.0/conv.0.0/Conv:  |                       | 0.005%
/features/features.9/conv/conv.0/conv.0.0/Conv:  |                       | 0.003%
/features/features.18/features.18.0/Conv:        |                       | 0.002%
/features/features.10/conv/conv.0/conv.0.0/Conv: |                       | 0.002%
/features/features.8/conv/conv.0/conv.0.0/Conv:  |                       | 0.002%

* Prec@1 60.500 Prec@5 83.275*
```

Quantization error analysis

The top1 accuracy after quantization is only 60.5%, which is far from the accuracy of the float model (71.878%). The quantization model has a large loss in accuracy, including:

- **Graphwise Error**
  The last layer of the model is /classifier/classifier.1/Gemm, and the cumulative error of this layer is 25.591%. In experience, the cumulative error of the last layer is less than 10%, and the accuracy loss of the quantization model is small.

- **Layerwise error**
  Observing the Layerwise error, it is found that the errors of most layers are less than 1%, indicating that the quantization errors of most layers are small, and only a few layers have large errors. We can choose to quantize the layers with large errors using int16. For details, please see mixed precision quantization.

Mixed precision quantization

esp-dl supports mixed precision quantization, which can be used to quantize some layers using int16 and some layers using int8. The quantization error of the model can be reduced by using mixed precision quantization.

Quantization settings

```python
from esp_ppq.api import get_target_platform
target="esp32p4"
num_of_bits=8
batch_size=32

# The following layers are quantized using int16
quant_setting = QuantizationSettingFactory.espdl_setting()
quant_setting.dispatching_table.append("/features/features.1/conv/conv.0/conv.0.0/
↪Conv", get_target_platform(TARGET, 16))
quant_setting.dispatching_table.append("/features/features.1/conv/conv.0/conv.0.2/
↪Clip", get_target_platform(TARGET, 16))
```

Quantization results

```
Layer                                            | NOISE:SIGNAL POWER RATIO
/features/features.16/conv/conv.2/Conv:          | ████████████████████ | 31.585%
/features/features.15/conv/conv.2/Conv:          | ███████████████████  | 29.253%
/features/features.17/conv/conv.0/conv.0.0/Conv: | ████████████████     | 25.077%
/features/features.14/conv/conv.2/Conv:          | ████████████████     | 24.819%
/features/features.17/conv/conv.2/Conv:          | ████████████         | 19.546%
/features/features.13/conv/conv.2/Conv:          | ████████████         | 19.283%
/features/features.16/conv/conv.0/conv.0.0/Conv: | ████████████         | 18.764%
/features/features.16/conv/conv.1/conv.1.0/Conv: | ████████████         | 18.596%
/features/features.18/features.18.0/Conv:        | ████████████         | 18.541%
/features/features.15/conv/conv.0/conv.0.0/Conv: | ██████████           | 15.633%
/features/features.12/conv/conv.2/Conv:          | █████████            | 14.784%
/features/features.15/conv/conv.1/conv.1.0/Conv: | █████████            | 14.773%
/features/features.14/conv/conv.1/conv.1.0/Conv: | █████████            | 13.700%
/features/features.6/conv/conv.2/Conv:           | ████████             | 12.824%
/features/features.10/conv/conv.2/Conv:          | ███████              | 11.727%
/features/features.14/conv/conv.0/conv.0.0/Conv: | ███████              | 10.612%
/features/features.11/conv/conv.2/Conv:          | ██████               | 10.262%
/features/features.9/conv/conv.2/Conv:           | ██████               | 9.967%
/classifier/classifier.1/Gemm:                   | ██████               | 9.117%
/features/features.5/conv/conv.2/Conv:           | ██████               | 8.915%
/features/features.7/conv/conv.2/Conv:           | █████                | 8.690%
/features/features.3/conv/conv.2/Conv:           | █████                | 8.586%
/features/features.4/conv/conv.2/Conv:           | █████                | 7.525%
/features/features.13/conv/conv.1/conv.1.0/Conv: | █████                | 7.432%
/features/features.12/conv/conv.1/conv.1.0/Conv: | █████                | 7.317%
/features/features.13/conv/conv.0/conv.0.0/Conv: | ████                 | 6.848%
/features/features.8/conv/conv.2/Conv:           | ████                 | 6.711%
/features/features.10/conv/conv.1/conv.1.0/Conv: | ████                 | 6.100%
/features/features.8/conv/conv.1/conv.1.0/Conv:  | ████                 | 6.043%
/features/features.11/conv/conv.1/conv.1.0/Conv: | ████                 | 5.962%
/features/features.9/conv/conv.1/conv.1.0/Conv:  | ████                 | 5.873%
/features/features.12/conv/conv.0/conv.0.0/Conv: | ████                 | 5.833%
/features/features.7/conv/conv.0/conv.0.0/Conv:  | ████                 | 5.832%
/features/features.11/conv/conv.0/conv.0.0/Conv: | ████                 | 5.736%
```

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```
/features/features.6/conv/conv.1/conv.1.0/Conv:  | ████                 | 5.639%
/features/features.5/conv/conv.1/conv.1.0/Conv:  | ███                  | 5.017%
/features/features.10/conv/conv.0/conv.0.0/Conv: | ███                  | 4.963%
/features/features.17/conv/conv.1/conv.1.0/Conv: | ███                  | 4.870%
/features/features.3/conv/conv.1/conv.1.0/Conv:  | ███                  | 4.655%
/features/features.2/conv/conv.2/Conv:           | ███                  | 4.650%
/features/features.4/conv/conv.0/conv.0.0/Conv:  | ███                  | 4.648%
/features/features.1/conv/conv.1/Conv:           | ███                  | 4.318%
/features/features.9/conv/conv.0/conv.0.0/Conv:  | ██                   | 3.849%
/features/features.6/conv/conv.0/conv.0.0/Conv:  | ██                   | 3.712%
/features/features.4/conv/conv.1/conv.1.0/Conv:  | ██                   | 3.394%
/features/features.8/conv/conv.0/conv.0.0/Conv:  | ██                   | 3.391%
/features/features.7/conv/conv.1/conv.1.0/Conv:  | ██                   | 2.713%
/features/features.2/conv/conv.1/conv.1.0/Conv:  | ██                   | 2.637%
/features/features.2/conv/conv.0/conv.0.0/Conv:  | ██                   | 2.602%
/features/features.5/conv/conv.0/conv.0.0/Conv:  | █                    | 2.397%
/features/features.3/conv/conv.0/conv.0.0/Conv:  | █                    | 1.759%
/features/features.1/conv/conv.0/conv.0.0/Conv:  |                      | 0.433%
/features/features.0/features.0.0/Conv:          |                      | 0.119%
Analysing Layerwise quantization error:: 100
↪%|█████████████████████████████████████████████████████████████████████████████████████████████
↪53/53 [08:27<00:00,  9.58s/it]
*
Layer                                            | NOISE:SIGNAL POWER RATIO
/features/features.1/conv/conv.1/Conv:           | ████████████████████ | 1.096%
/features/features.0/features.0.0/Conv:          | ███████████████      | 0.844%
/features/features.2/conv/conv.1/conv.1.0/Conv:  | ██████████           | 0.574%
/features/features.3/conv/conv.1/conv.1.0/Conv:  | ████████             | 0.425%
/features/features.15/conv/conv.1/conv.1.0/Conv: | █████                | 0.272%
/features/features.9/conv/conv.1/conv.1.0/Conv:  | ████                 | 0.238%
/features/features.17/conv/conv.1/conv.1.0/Conv: | ████                 | 0.214%
/features/features.4/conv/conv.1/conv.1.0/Conv:  | ███                  | 0.180%
/features/features.11/conv/conv.1/conv.1.0/Conv: | ███                  | 0.151%
/features/features.12/conv/conv.1/conv.1.0/Conv: | ███                  | 0.148%
/features/features.16/conv/conv.1/conv.1.0/Conv: | ███                  | 0.146%
/features/features.14/conv/conv.2/Conv:          | ██                   | 0.136%
/features/features.13/conv/conv.1/conv.1.0/Conv: | ██                   | 0.105%
/features/features.6/conv/conv.1/conv.1.0/Conv:  | ██                   | 0.105%
/features/features.8/conv/conv.1/conv.1.0/Conv:  | █                    | 0.083%
/features/features.5/conv/conv.1/conv.1.0/Conv:  | █                    | 0.076%
/features/features.3/conv/conv.2/Conv:           | █                    | 0.075%
/features/features.16/conv/conv.2/Conv:          | █                    | 0.074%
/features/features.13/conv/conv.0/conv.0.0/Conv: | █                    | 0.072%
/features/features.7/conv/conv.2/Conv:           | █                    | 0.071%
/features/features.15/conv/conv.2/Conv:          | █                    | 0.066%
/features/features.4/conv/conv.2/Conv:           | █                    | 0.065%
/features/features.11/conv/conv.2/Conv:          | █                    | 0.063%
/classifier/classifier.1/Gemm:                   | █                    | 0.063%
/features/features.13/conv/conv.2/Conv:          | █                    | 0.059%
/features/features.2/conv/conv.0/conv.0.0/Conv:  | █                    | 0.054%
/features/features.10/conv/conv.1/conv.1.0/Conv: | █                    | 0.042%
/features/features.17/conv/conv.0/conv.0.0/Conv: | █                    | 0.040%
/features/features.2/conv/conv.2/Conv:           | █                    | 0.038%
/features/features.4/conv/conv.0/conv.0.0/Conv:  | █                    | 0.034%
/features/features.17/conv/conv.2/Conv:          | █                    | 0.030%
/features/features.14/conv/conv.0/conv.0.0/Conv: |                      | 0.025%
/features/features.16/conv/conv.0/conv.0.0/Conv: |                      | 0.024%
/features/features.10/conv/conv.2/Conv:          |                      | 0.022%
/features/features.11/conv/conv.0/conv.0.0/Conv: |                      | 0.021%
/features/features.9/conv/conv.2/Conv:           |                      | 0.021%
/features/features.14/conv/conv.1/conv.1.0/Conv: |                      | 0.020%
```

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```
/features/features.7/conv/conv.1/conv.1.0/Conv:  |                      | 0.020%
/features/features.5/conv/conv.2/Conv:           |                      | 0.019%
/features/features.8/conv/conv.2/Conv:           |                      | 0.018%
/features/features.12/conv/conv.2/Conv:          |                      | 0.017%
/features/features.1/conv/conv.0/conv.0.0/Conv:  |                      | 0.017%
/features/features.6/conv/conv.2/Conv:           |                      | 0.014%
/features/features.7/conv/conv.0/conv.0.0/Conv:  |                      | 0.014%
/features/features.3/conv/conv.0/conv.0.0/Conv:  |                      | 0.013%
/features/features.12/conv/conv.0/conv.0.0/Conv: |                      | 0.009%
/features/features.15/conv/conv.0/conv.0.0/Conv: |                      | 0.008%
/features/features.5/conv/conv.0/conv.0.0/Conv:  |                      | 0.006%
/features/features.6/conv/conv.0/conv.0.0/Conv:  |                      | 0.005%
/features/features.9/conv/conv.0/conv.0.0/Conv:  |                      | 0.003%
/features/features.18/features.18.0/Conv:        |                      | 0.002%
/features/features.10/conv/conv.0/conv.0.0/Conv: |                      | 0.002%
/features/features.8/conv/conv.0/conv.0.0/Conv:  |                      | 0.002%

* Prec@1 69.550 Prec@5 88.450*
```

Quantization Error Analysis

After replacing the layer with the largest error with 16-bit quantization, it can be observed that the model accuracy is significantly improved. The top1 accuracy after quantization is 69.550%, which is close to the accuracy of the float model (71.878%). The cumulative error of the last layer of the model `/classifier/classifier.1/Gemm` is 9.117%.

Layerwise equalization quantization

This method is proposed in the paper Data-Free Quantization Through Weight Equalization and Bias Correction. When using this method, the original ReLU6 in the MobilenetV2 model needs to be replaced with ReLU.

Quantization Settings

```python
import torch.nn as nn
def convert_relu6_to_relu(model):
   for child_name, child in model.named_children():
      if isinstance(child, nn.ReLU6):
            setattr(model, child_name, nn.ReLU())
      else:
            convert_relu6_to_relu(child)
   return model

# Replace ReLU6 with ReLU
model = convert_relu6_to_relu(model)
# Use layerwise equalization
quant_setting = QuantizationSettingFactory.espdl_setting()
quant_setting.equalization = True
quant_setting.equalization_setting.iterations = 4
quant_setting.equalization_setting.value_threshold = .4
quant_setting.equalization_setting.opt_level = 2
quant_setting.equalization_setting.interested_layers = None
```

```
Layer                                            | NOISE:SIGNAL POWER RATIO
/features/features.16/conv/conv.2/Conv:          | ████████████████████ | 34.497%
/features/features.15/conv/conv.2/Conv:          | ██████████████████   | 30.813%
/features/features.14/conv/conv.2/Conv:          | ███████████████      | 25.876%
/features/features.17/conv/conv.0/conv.0.0/Conv: | ██████████████       | 24.498%
/features/features.17/conv/conv.2/Conv:          | ████████████         | 20.290%
/features/features.13/conv/conv.2/Conv:          | ████████████         | 20.177%
/features/features.16/conv/conv.0/conv.0.0/Conv: | ████████████         | 19.993%
```

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```
/features/features.18/features.18.0/Conv:        | ███████████          | 19.536%
/features/features.16/conv/conv.1/conv.1.0/Conv: | ██████████           | 17.879%
/features/features.12/conv/conv.2/Conv:          | ██████████           | 17.150%
/features/features.15/conv/conv.0/conv.0.0/Conv: | █████████            | 15.970%
/features/features.15/conv/conv.1/conv.1.0/Conv: | █████████            | 15.254%
/features/features.1/conv/conv.1/Conv:           | █████████            | 15.122%
/features/features.10/conv/conv.2/Conv:          | █████████            | 14.917%
/features/features.6/conv/conv.2/Conv:           | ████████             | 13.446%
/features/features.11/conv/conv.2/Conv:          | ███████              | 12.533%
/features/features.9/conv/conv.2/Conv:           | ███████              | 11.479%
/features/features.14/conv/conv.1/conv.1.0/Conv: | ███████              | 11.470%
/features/features.5/conv/conv.2/Conv:           | ██████               | 10.669%
/features/features.3/conv/conv.2/Conv:           | ██████               | 10.526%
/features/features.14/conv/conv.0/conv.0.0/Conv: | ██████               | 9.529%
/features/features.7/conv/conv.2/Conv:           | █████                | 9.500%
/classifier/classifier.1/Gemm:                   | █████                | 8.965%
/features/features.4/conv/conv.2/Conv:           | █████                | 8.674%
/features/features.12/conv/conv.1/conv.1.0/Conv: | █████                | 8.349%
/features/features.13/conv/conv.1/conv.1.0/Conv: | █████                | 8.068%
/features/features.8/conv/conv.2/Conv:           | █████                | 7.961%
/features/features.13/conv/conv.0/conv.0.0/Conv: | ████                 | 7.451%
/features/features.10/conv/conv.1/conv.1.0/Conv: | ████                 | 6.714%
/features/features.9/conv/conv.1/conv.1.0/Conv:  | ████                 | 6.399%
/features/features.8/conv/conv.1/conv.1.0/Conv:  | ████                 | 6.369%
/features/features.11/conv/conv.1/conv.1.0/Conv: | ████                 | 6.222%
/features/features.2/conv/conv.2/Conv:           | ███                  | 5.867%
/features/features.5/conv/conv.1/conv.1.0/Conv:  | ███                  | 5.719%
/features/features.12/conv/conv.0/conv.0.0/Conv: | ███                  | 5.546%
/features/features.6/conv/conv.1/conv.1.0/Conv:  | ███                  | 5.414%
/features/features.10/conv/conv.0/conv.0.0/Conv: | ███                  | 5.093%
/features/features.17/conv/conv.1/conv.1.0/Conv: | ███                  | 4.951%
/features/features.11/conv/conv.0/conv.0.0/Conv: | ███                  | 4.941%
/features/features.2/conv/conv.1/conv.1.0/Conv:  | ███                  | 4.825%
/features/features.7/conv/conv.0/conv.0.0/Conv:  | ██                   | 4.330%
/features/features.2/conv/conv.0/conv.0.0/Conv:  | ██                   | 4.299%
/features/features.3/conv/conv.1/conv.1.0/Conv:  | ██                   | 4.283%
/features/features.4/conv/conv.0/conv.0.0/Conv:  | ██                   | 3.477%
/features/features.4/conv/conv.1/conv.1.0/Conv:  | ██                   | 3.287%
/features/features.8/conv/conv.0/conv.0.0/Conv:  | ██                   | 2.787%
/features/features.9/conv/conv.0/conv.0.0/Conv:  | ██                   | 2.774%
/features/features.6/conv/conv.0/conv.0.0/Conv:  | ██                   | 2.705%
/features/features.7/conv/conv.1/conv.1.0/Conv:  | ██                   | 2.636%
/features/features.5/conv/conv.0/conv.0.0/Conv:  | █                    | 1.846%
/features/features.3/conv/conv.0/conv.0.0/Conv:  | █                    | 1.170%
/features/features.1/conv/conv.0/conv.0.0/Conv:  |                      | 0.389%
/features/features.0/features.0.0/Conv:          |                      | 0.025%
Analysing Layerwise quantization error:: 100%|██████████| 53/53 [07:46<00:00,  8.80s/it]
Layer                                            | NOISE:SIGNAL POWER RATIO
/features/features.1/conv/conv.0/conv.0.0/Conv:  | ████████████████████ | 0.989%
/features/features.0/features.0.0/Conv:          | █████████████████    | 0.845%
/features/features.16/conv/conv.2/Conv:          | █████                | 0.238%
/features/features.17/conv/conv.2/Conv:          | ████                 | 0.202%
/features/features.14/conv/conv.2/Conv:          | ████                 | 0.198%
/features/features.1/conv/conv.1/Conv:           | ████                 | 0.192%
/features/features.15/conv/conv.2/Conv:          | ███                  | 0.145%
/features/features.4/conv/conv.2/Conv:           | ██                   | 0.120%
/features/features.2/conv/conv.2/Conv:           | ██                   | 0.111%
/features/features.2/conv/conv.1/conv.1.0/Conv:  | ██                   | 0.079%
/classifier/classifier.1/Gemm:                   | █                    | 0.062%
/features/features.13/conv/conv.2/Conv:          | █                    | 0.050%
```

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```
/features/features.3/conv/conv.2/Conv:                  | █                     | 0.050%
/features/features.12/conv/conv.2/Conv:                 | █                     | 0.050%
/features/features.5/conv/conv.1/conv.1.0/Conv:         | █                     | 0.047%
/features/features.3/conv/conv.1/conv.1.0/Conv:         | █                     | 0.046%
/features/features.7/conv/conv.2/Conv:                  | █                     | 0.045%
/features/features.5/conv/conv.2/Conv:                  | █                     | 0.030%
/features/features.11/conv/conv.2/Conv:                 | █                     | 0.028%
/features/features.6/conv/conv.2/Conv:                  | █                     | 0.027%
/features/features.6/conv/conv.1/conv.1.0/Conv:         | █                     | 0.026%
/features/features.4/conv/conv.0/conv.0.0/Conv:         |                       | 0.025%
/features/features.15/conv/conv.1/conv.1.0/Conv:        |                       | 0.023%
/features/features.8/conv/conv.1/conv.1.0/Conv:         |                       | 0.021%
/features/features.10/conv/conv.2/Conv:                 |                       | 0.020%
/features/features.11/conv/conv.1/conv.1.0/Conv:        |                       | 0.020%
/features/features.16/conv/conv.1/conv.1.0/Conv:        |                       | 0.017%
/features/features.14/conv/conv.0/conv.0.0/Conv:        |                       | 0.016%
/features/features.4/conv/conv.1/conv.1.0/Conv:         |                       | 0.012%
/features/features.13/conv/conv.1/conv.1.0/Conv:        |                       | 0.012%
/features/features.13/conv/conv.0/conv.0.0/Conv:        |                       | 0.012%
/features/features.12/conv/conv.1/conv.1.0/Conv:        |                       | 0.012%
/features/features.17/conv/conv.0/conv.0.0/Conv:        |                       | 0.011%
/features/features.12/conv/conv.0/conv.0.0/Conv:        |                       | 0.011%
/features/features.2/conv/conv.0/conv.0.0/Conv:         |                       | 0.010%
/features/features.9/conv/conv.2/Conv:                  |                       | 0.008%
/features/features.8/conv/conv.2/Conv:                  |                       | 0.008%
/features/features.10/conv/conv.1/conv.1.0/Conv:        |                       | 0.008%
/features/features.16/conv/conv.0/conv.0.0/Conv:        |                       | 0.008%
/features/features.7/conv/conv.0/conv.0.0/Conv:         |                       | 0.008%
/features/features.10/conv/conv.0/conv.0.0/Conv:        |                       | 0.006%
/features/features.15/conv/conv.0/conv.0.0/Conv:        |                       | 0.005%
/features/features.3/conv/conv.0/conv.0.0/Conv:         |                       | 0.004%
/features/features.11/conv/conv.0/conv.0.0/Conv:        |                       | 0.004%
/features/features.18/features.18.0/Conv:               |                       | 0.003%
/features/features.5/conv/conv.0/conv.0.0/Conv:         |                       | 0.003%
/features/features.9/conv/conv.1/conv.1.0/Conv:         |                       | 0.003%
/features/features.6/conv/conv.0/conv.0.0/Conv:         |                       | 0.003%
/features/features.7/conv/conv.1/conv.1.0/Conv:         |                       | 0.003%
/features/features.17/conv/conv.1/conv.1.0/Conv:        |                       | 0.002%
/features/features.14/conv/conv.1/conv.1.0/Conv:        |                       | 0.002%
/features/features.8/conv/conv.0/conv.0.0/Conv:         |                       | 0.001%
/features/features.9/conv/conv.0/conv.0.0/Conv:         |                       | 0.001%

* Prec@1 69.800 Prec@5 88.550
```

Quantization Error Analysis

Note that applying layerwise equalization to 8-bit quantization helps reduce quantization loss. The cumulative error of the last layer of the model `/classifier/classifier.1/Gemm` is 8.965%. The top1 accuracy after quantization is 69.800%, which is closer to the accuracy of the float model (71.878%) and higher than the quantization accuracy of mixed precision quantization.

Note: To further reduce the quantization error, you can try using QAT (Auantization Aware Training). For specific methods, please refer to PPQ QAT example.

3.5.3 Model deployment

examples

Image classification base class

- dl_cls_base.hpp
- dl_cls_base.cpp

Pre-process

`ImagePreprocessor` class contains the common pre-precoess pipeline, `color conversion`, `crop`, `resize`, `normalization`, `quantize`。

- dl_image_preprocessor.hpp
- dl_image_preprocessor.cpp

Post-process

- dl_cls_postprocessor.hpp
- dl_cls_postprocessor.cpp
- imagenet_cls_postprocessor.hpp
- imagenet_cls_postprocessor.cpp

3.6 How to deploy YOLO11n

In this tutorial, we will introduce how to quantize a pre-trained YOLO11n model using ESP-PPQ and deploy the quantized YOLO11n model using ESP-DL.

3.6.1 Preparation

1. *安装 ESP_IDF*
2. *安装 ESP_PPQ*

3.6.2 Model quantization

Pre-trained Model

You can download pre-trained yolo11n model from Ultralytics release.

Currently, ESP-PPQ supports ONNX, PyTorch, and TensorFlow models. During the quantization process, PyTorch and TensorFlow models are first converted to ONNX models, so the pre-trained yolo11n model needs to be converted to an ONNX model.

Specifically, refer to the script export_onnx.py to convert the pre-trained yolo11n model to an ONNX model.

In the srcipt, we have overridden the forward method of the Detect class, which offers following advantages:

- Faster inference. Compared to the original yolo11n model, operations related to decoding bounding boxes in Detect head are moved from the inference pass to the post-processing phase, resulting in a significant reduction in inference latency. On one hand, operations like `Conv`, `Transpose`, `Slice`, `Split` and `Concat` are time-consuming when applied during inference pass. On the other hand, the inference outputs are first filtered using a score threshold before decoding the boxes in the post-processing pass, which significantly reduces the number of calculations, thereby acclerating the overall inference speed.
- Lower quantization Error. The `Concat` and `Add` operators adopt joint quantization in ESP-PPQ. To reduce quantization errors, the box and score are output by separate branches, rather than being concatenated, due to the significant difference in their ranges. Similarly, since the ranges of the two inputs of `Add` and `Sub` differ significantly, the calculations are performed in the post-processing phase to avoid quantization errors.

Calibration Dataset

The calibration dataset needs to match the input format of the model. The calibration dataset should cover all possible input scenarios to better quantize the model. Here, the calibration dataset used in this example is calib_yolo11n.

8bit default configuration quantization

Quantization settings

```
target="esp32p4"
num_of_bits=8
batch_size=32
quant_setting = QuantizationSettingFactory.espdl_setting() # default setting
```

Quantization results

```
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.10/m/m.0/ffn/ffn.1/conv/Conv:         | ████████████████████ | 36.008%
/model.10/m/m.0/attn/proj/conv/Conv:         | ████████████████     | 28.705%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv: | █████████████        | 22.865%
/model.23/cv2.2/cv2.2.0/conv/Conv:           | ████████████         | 21.718%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv: | ████████████         | 21.624%
/model.23/cv2.2/cv2.2.1/conv/Conv:           | ████████████         | 21.392%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv: | ████████████         | 21.224%
/model.22/m.0/cv2/conv/Conv:                 | ███████████          | 19.763%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv: | ███████████          | 19.436%
/model.22/m.0/cv3/conv/Conv:                 | ███████████          | 19.378%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv: | ██████████           | 18.913%
/model.22/m.0/m/m.1/cv2/conv/Conv:           | ██████████           | 18.645%
/model.22/cv2/conv/Conv:                     | ██████████           | 18.628%
/model.23/cv2.1/cv2.1.1/conv/Conv:           | ██████████           | 17.980%
/model.8/m.0/cv2/conv/Conv:                  | █████████            | 16.247%
/model.23/cv2.0/cv2.0.1/conv/Conv:           | █████████            | 15.602%
/model.10/m/m.0/attn/qkv/conv/Conv:          | ████████             | 14.666%
/model.10/m/m.0/attn/pe/conv/Conv:           | ████████             | 14.556%
/model.23/cv2.1/cv2.1.0/conv/Conv:           | ████████             | 14.302%
/model.22/cv1/conv/Conv:                     | ████████             | 13.921%
/model.10/m/m.0/attn/MatMul_1:               | ████████             | 13.905%
/model.10/cv1/conv/Conv:                     | ███████              | 13.494%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv: | ██████               | 11.800%
/model.19/m.0/cv2/conv/Conv:                 | ██████               | 11.515%
/model.22/m.0/m/m.0/cv2/conv/Conv:           | ██████               | 11.286%
/model.20/conv/Conv:                         | ██████               | 10.930%
/model.13/m.0/cv2/conv/Conv:                 | ██████               | 10.882%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv: | ██████               | 10.692%
```

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```
/model.23/cv2.2/cv2.2.2/Conv:                | ██████               | 10.113%
/model.10/cv2/conv/Conv:                     | █████                | 9.720%
/model.8/cv2/conv/Conv:                      | █████                | 9.598%
/model.8/m.0/cv1/conv/Conv:                  | █████                | 9.470%
/model.19/cv2/conv/Conv:                     | █████                | 9.314%
/model.22/m.0/m/m.0/cv1/conv/Conv:           | █████                | 9.068%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv: | █████                | 9.065%
/model.8/cv1/conv/Conv:                      | █████                | 9.051%
/model.8/m.0/cv3/conv/Conv:                  | █████                | 9.044%
/model.6/m.0/cv2/conv/Conv:                  | █████                | 8.811%
/model.22/m.0/m/m.1/cv1/conv/Conv:           | █████                | 8.781%
/model.13/cv2/conv/Conv:                     | █████                | 8.687%
/model.8/m.0/m/m.0/cv1/conv/Conv:            | █████                | 8.503%
/model.8/m.0/m/m.0/cv2/conv/Conv:            | █████                | 8.470%
/model.19/cv1/conv/Conv:                     | ████                 | 8.199%
/model.10/m/m.0/attn/MatMul:                 | ████                 | 8.117%
/model.8/m.0/m/m.1/cv1/conv/Conv:            | ████                 | 7.964%
/model.13/cv1/conv/Conv:                     | ████                 | 7.734%
/model.19/m.0/cv1/conv/Conv:                 | ████                 | 7.661%
/model.22/m.0/cv1/conv/Conv:                 | ████                 | 7.490%
/model.13/m.0/cv1/conv/Conv:                 | ████                 | 7.162%
/model.8/m.0/m/m.1/cv2/conv/Conv:            | ████                 | 7.145%
/model.23/cv2.0/cv2.0.0/conv/Conv:           | ████                 | 7.041%
/model.23/cv2.1/cv2.1.2/Conv:                | ████                 | 6.917%
/model.23/cv2.0/cv2.0.2/Conv:                | ████                 | 6.778%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv: | ████                 | 6.641%
/model.17/conv/Conv:                         | ███                  | 6.125%
/model.16/m.0/cv2/conv/Conv:                 | ███                  | 5.937%
/model.6/cv2/conv/Conv:                      | ███                  | 5.838%
/model.6/m.0/cv3/conv/Conv:                  | ███                  | 5.832%
/model.6/cv1/conv/Conv:                      | ███                  | 5.688%
/model.7/conv/Conv:                          | ███                  | 5.612%
/model.9/cv2/conv/Conv:                      | ███                  | 5.367%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:         | ███                  | 5.158%
/model.6/m.0/m/m.0/cv1/conv/Conv:            | ███                  | 5.143%
/model.16/m.0/cv1/conv/Conv:                 | ███                  | 5.137%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv: | ███                  | 5.087%
/model.16/cv2/conv/Conv:                     | ███                  | 4.989%
/model.2/cv2/conv/Conv:                      | ██                   | 4.547%
/model.6/m.0/m/m.0/cv2/conv/Conv:            | ██                   | 4.441%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv: | ██                   | 4.343%
/model.3/conv/Conv:                          | ██                   | 4.304%
/model.6/m.0/m/m.1/cv1/conv/Conv:            | ██                   | 4.006%
/model.5/conv/Conv:                          | ██                   | 3.932%
/model.6/m.0/cv1/conv/Conv:                  | ██                   | 3.837%
/model.4/cv1/conv/Conv:                      | ██                   | 3.687%
/model.2/cv1/conv/Conv:                      | ██                   | 3.565%
/model.4/cv2/conv/Conv:                      | ██                   | 3.559%
/model.16/cv1/conv/Conv:                     | ██                   | 3.107%
/model.2/m.0/cv2/conv/Conv:                  | ██                   | 2.882%
/model.6/m.0/m/m.1/cv2/conv/Conv:            | █                    | 2.758%
/model.4/m.0/cv1/conv/Conv:                  | █                    | 2.564%
/model.9/cv1/conv/Conv:                      | █                    | 2.017%
/model.4/m.0/cv2/conv/Conv:                  | █                    | 1.785%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv: | █                    | 1.327%
/model.1/conv/Conv:                          | █                    | 1.313%
/model.23/cv3.2/cv3.2.2/Conv:                | █                    | 1.155%
/model.2/m.0/cv1/conv/Conv:                  |                      | 0.727%
/model.23/cv3.1/cv3.1.2/Conv:                |                      | 0.493%
/model.23/cv3.0/cv3.0.2/Conv:                |                      | 0.282%
/model.0/conv/Conv:                          |                      | 0.159%
```

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```
Analysing Layerwise quantization error:: 100%|██████████| 89/89 [03:39<00:00,  2.46s/it]
Layer                                         | NOISE:SIGNAL POWER RATIO
/model.1/conv/Conv:                           | ████████████████████ | 0.384%
/model.22/cv1/conv/Conv:                      | █████████████        | 0.247%
/model.4/cv2/conv/Conv:                       | ████████████         | 0.233%
/model.2/cv2/conv/Conv:                       | ██████████           | 0.201%
/model.0/conv/Conv:                           | ██████████           | 0.192%
/model.9/cv2/conv/Conv:                       | ████████             | 0.156%
/model.10/cv1/conv/Conv:                      | ███████              | 0.132%
/model.3/conv/Conv:                           | ██████               | 0.108%
/model.4/cv1/conv/Conv:                       | ████                 | 0.074%
/model.16/cv1/conv/Conv:                      | ███                  | 0.066%
/model.2/cv1/conv/Conv:                       | ███                  | 0.060%
/model.23/cv2.0/cv2.0.0/conv/Conv:            | ███                  | 0.052%
/model.2/m.0/cv1/conv/Conv:                   | ██                   | 0.044%
/model.6/cv1/conv/Conv:                       | ██                   | 0.033%
/model.10/m/m.0/attn/pe/conv/Conv:            | ██                   | 0.029%
/model.2/m.0/cv2/conv/Conv:                   | █                    | 0.028%
/model.22/m.0/m/m.0/cv1/conv/Conv:            | █                    | 0.023%
/model.16/cv2/conv/Conv:                      | █                    | 0.021%
/model.16/m.0/cv2/conv/Conv:                  | █                    | 0.020%
/model.19/m.0/cv1/conv/Conv:                  | █                    | 0.020%
/model.4/m.0/cv1/conv/Conv:                   | █                    | 0.018%
/model.19/cv2/conv/Conv:                      | █                    | 0.017%
/model.4/m.0/cv2/conv/Conv:                   | █                    | 0.016%
/model.10/m/m.0/attn/qkv/conv/Conv:           | █                    | 0.016%
/model.19/cv1/conv/Conv:                      | █                    | 0.015%
/model.13/cv2/conv/Conv:                      | █                    | 0.015%
/model.8/cv1/conv/Conv:                       | █                    | 0.013%
/model.23/cv2.1/cv2.1.0/conv/Conv:            | █                    | 0.013%
/model.23/cv2.2/cv2.2.1/conv/Conv:            | █                    | 0.012%
/model.13/cv1/conv/Conv:                      | █                    | 0.012%
/model.10/cv2/conv/Conv:                      | █                    | 0.011%
/model.13/m.0/cv1/conv/Conv:                  | █                    | 0.011%
/model.6/cv2/conv/Conv:                       | █                    | 0.011%
/model.13/m.0/cv2/conv/Conv:                  | █                    | 0.010%
/model.5/conv/Conv:                           |                      | 0.010%
/model.19/m.0/cv2/conv/Conv:                  |                      | 0.009%
/model.6/m.0/m/m.1/cv1/conv/Conv:             |                      | 0.009%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv:  |                      | 0.008%
/model.23/cv2.2/cv2.2.0/conv/Conv:            |                      | 0.008%
/model.23/cv2.1/cv2.1.1/conv/Conv:            |                      | 0.008%
/model.9/cv1/conv/Conv:                       |                      | 0.008%
/model.23/cv2.0/cv2.0.1/conv/Conv:            |                      | 0.007%
/model.16/m.0/cv1/conv/Conv:                  |                      | 0.007%
/model.17/conv/Conv:                          |                      | 0.007%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv:  |                      | 0.007%
/model.10/m/m.0/ffn/ffn.1/conv/Conv:          |                      | 0.007%
/model.23/cv2.0/cv2.0.2/Conv:                 |                      | 0.006%
/model.8/m.0/cv1/conv/Conv:                   |                      | 0.006%
/model.23/cv2.2/cv2.2.2/Conv:                 |                      | 0.005%
/model.23/cv2.1/cv2.1.2/Conv:                 |                      | 0.005%
/model.22/m.0/cv3/conv/Conv:                  |                      | 0.005%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv:  |                      | 0.005%
/model.7/conv/Conv:                           |                      | 0.005%
/model.8/cv2/conv/Conv:                       |                      | 0.004%
/model.22/cv2/conv/Conv:                      |                      | 0.004%
/model.6/m.0/cv3/conv/Conv:                   |                      | 0.004%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:          |                      | 0.004%
/model.8/m.0/m/m.1/cv2/conv/Conv:             |                      | 0.004%
```

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```
/model.22/m.0/m/m.1/cv1/conv/Conv:               |                        | 0.004%
/model.8/m.0/m/m.1/cv1/conv/Conv:                |                        | 0.004%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv:     |                        | 0.003%
/model.10/m/m.0/attn/proj/conv/Conv:             |                        | 0.003%
/model.22/m.0/m/m.0/cv2/conv/Conv:               |                        | 0.003%
/model.22/m.0/cv1/conv/Conv:                     |                        | 0.003%
/model.8/m.0/cv3/conv/Conv:                      |                        | 0.003%
/model.6/m.0/m/m.0/cv1/conv/Conv:                |                        | 0.003%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv:     |                        | 0.003%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv:     |                        | 0.002%
/model.6/m.0/m/m.1/cv2/conv/Conv:                |                        | 0.002%
/model.8/m.0/m/m.0/cv2/conv/Conv:                |                        | 0.002%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv:     |                        | 0.002%
/model.10/m/m.0/attn/MatMul_1:                   |                        | 0.002%
/model.22/m.0/m/m.1/cv2/conv/Conv:               |                        | 0.001%
/model.6/m.0/m/m.0/cv2/conv/Conv:                |                        | 0.001%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv:     |                        | 0.001%
/model.8/m.0/m/m.0/cv1/conv/Conv:                |                        | 0.001%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv:     |                        | 0.001%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv:     |                        | 0.001%
/model.6/m.0/cv1/conv/Conv:                      |                        | 0.001%
/model.23/cv3.2/cv3.2.2/Conv:                    |                        | 0.001%
/model.20/conv/Conv:                             |                        | 0.001%
/model.23/cv3.1/cv3.1.2/Conv:                    |                        | 0.001%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv:     |                        | 0.001%
/model.6/m.0/cv2/conv/Conv:                      |                        | 0.001%
/model.23/cv3.0/cv3.0.2/Conv:                    |                        | 0.000%
/model.10/m/m.0/attn/MatMul:                     |                        | 0.000%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv:     |                        | 0.000%
/model.8/m.0/cv2/conv/Conv:                      |                        | 0.000%
/model.22/m.0/cv2/conv/Conv:                     |                        | 0.000%
```

Quantization error analysis

With the same inputs, The mAP50:95 on COCO val2017 after quantization is only 30.7%, which is lower than that of the float model. There is a accuracy loss with:

- **Graphwise Error**
  The output layers of the model are /model.23/cv3.2/cv3.2.2/Conv, /model.23/cv2.2/cv2.2.2/Conv, /model.23/cv3.1/cv3.1.2/Conv, /model.23/cv2.1/cv2.1.2/Conv, /model.23/cv3.0/cv3.0.2/Conv and /model.23/cv2.0/cv2.0.2/Conv. The cumulative error for these layers are 1.155%, 10.113%, 0.493%, 6.917%, 0.282% and 6.778% respectively. Generally, if the cumulative error of the output layer is less than 10%, the loss in accuracy of the quantized model is minimal.
- **Layerwise error**
  Observing the Layerwise error, it is found that the errors for all layers are below 1%, indicating that the quantization errors for all layers are small.

We noticed that although the layer-wise errors for all layers are small, the cumulative errors in some layers are relatively large. This may be related to the complex CSP structure in the yolo11n model, where the inputs to the `Concat` or `Add` layers may have different distributions or scales. We can choose to quantize certain layers using int16 and optimize the quantization with horizontal layer split pass. For more details, please refer to the mixed-precision + horizontal layer split pass quantization test.

Mixed-Precision + Horizontal Layer Split Quantization

Spliting convolution layers or GEMM layers can reduce quantization error for better performance.

Quantization settings

```python
from esp_ppq.api import get_target_platform
target="esp32p4"
num_of_bits=8
batch_size=32

# Quantize the following layers with 16-bits
quant_setting = QuantizationSettingFactory.espdl_setting()
quant_setting.dispatching_table.append("/model.2/cv2/conv/Conv", get_target_platform(TARGET, 16))
quant_setting.dispatching_table.append("/model.3/conv/Conv", get_target_platform(TARGET, 16))
quant_setting.dispatching_table.append("/model.4/cv2/conv/Conv", get_target_platform(TARGET, 16))

# Horizontal Layer Split Pass
quant_setting.weight_split = True
quant_setting.weight_split_setting.method = 'balance'
quant_setting.weight_split_setting.value_threshold = 1.5
quant_setting.weight_split_setting.interested_layers = ['/model.0/conv/Conv', '/model.1/conv/Conv']
```

Quantization results

```
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.10/m/m.0/ffn/ffn.1/conv/Conv:         | ████████████████████ | 24.835%
/model.10/m/m.0/attn/proj/conv/Conv:         | ███████████████      | 18.632%
/model.23/cv2.2/cv2.2.1/conv/Conv:           | ██████████████       | 17.908%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv: | ██████████████       | 16.922%
/model.23/cv2.2/cv2.2.0/conv/Conv:           | █████████████        | 16.754%
/model.22/m.0/cv3/conv/Conv:                 | ████████████         | 15.404%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv: | ████████████         | 15.042%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv: | ████████████         | 14.948%
/model.22/m.0/m/m.1/cv2/conv/Conv:           | ████████████         | 14.702%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv: | ███████████          | 13.683%
/model.22/cv2/conv/Conv:                     | ███████████          | 13.654%
/model.22/m.0/cv2/conv/Conv:                 | ███████████          | 13.514%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv: | ██████████           | 12.885%
/model.23/cv2.1/cv2.1.1/conv/Conv:           | █████████            | 10.865%
/model.23/cv2.0/cv2.0.1/conv/Conv:           | ████████             | 9.875%
/model.23/cv2.1/cv2.1.0/conv/Conv:           | ████████             | 9.658%
/model.22/cv1/conv/Conv:                     | ███████              | 8.917%
/model.10/m/m.0/attn/MatMul_1:               | ███████              | 8.368%
/model.23/cv2.2/cv2.2.2/Conv:                | ███████              | 8.156%
/model.22/m.0/m/m.0/cv2/conv/Conv:           | ██████               | 8.056%
/model.10/m/m.0/attn/qkv/conv/Conv:          | ██████               | 7.948%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv: | ██████               | 7.824%
/model.13/m.0/cv2/conv/Conv:                 | ██████               | 7.504%
/model.19/m.0/cv2/conv/Conv:                 | ██████               | 7.290%
/model.20/conv/Conv:                         | ██████               | 6.986%
/model.10/m/m.0/attn/pe/conv/Conv:           | ██████               | 6.926%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv: | █████                | 6.771%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv: | █████                | 6.756%
/model.22/m.0/m/m.1/cv1/conv/Conv:           | █████                | 6.465%
/model.22/m.0/m/m.0/cv1/conv/Conv:           | █████                | 6.274%
/model.19/cv2/conv/Conv:                     | █████                | 6.116%
/model.10/cv1/conv/Conv:                     | █████                | 5.868%
/model.13/cv2/conv/Conv:                     | █████                | 5.815%
/model.10/cv2/conv/Conv:                     | ████                 | 5.664%
/model.19/cv1/conv/Conv:                     | ████                 | 5.178%
/model.8/m.0/cv2/conv/Conv:                  | ████                 | 4.970%
/model.19/m.0/cv1/conv/Conv:                 | ████                 | 4.919%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv: | ████                 | 4.864%
```

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```
/model.22/m.0/cv1/conv/Conv:                 | ████                 | 4.844%
/model.10/m/m.0/attn/MatMul:                 | ████                 | 4.650%
/model.13/cv1/conv/Conv:                     | ████                 | 4.564%
/model.23/cv2.0/cv2.0.0/conv/Conv:           | ███                  | 4.389%
/model.13/m.0/cv1/conv/Conv:                 | ███                  | 4.243%
/model.23/cv2.0/cv2.0.2/Conv:                | ███                  | 4.232%
/model.23/cv2.1/cv2.1.2/Conv:                | ███                  | 4.222%
/model.6/m.0/cv2/conv/Conv:                  | ███                  | 4.023%
/model.17/conv/Conv:                         | ███                  | 3.754%
/model.16/m.0/cv2/conv/Conv:                 | ███                  | 3.511%
/model.8/m.0/cv1/conv/Conv:                  | ███                  | 3.277%
/model.16/m.0/cv1/conv/Conv:                 | ██                   | 3.158%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv: | ██                   | 3.155%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv: | ██                   | 3.152%
/model.8/cv2/conv/Conv:                      | ██                   | 3.119%
/model.8/m.0/m/m.1/cv1/conv/Conv:            | ██                   | 3.106%
/model.8/m.0/cv3/conv/Conv:                  | ██                   | 3.083%
/model.6/m.0/cv3/conv/Conv:                  | ██                   | 3.068%
/model.8/cv1/conv/Conv:                      | ██                   | 3.035%
/model.16/cv2/conv/Conv:                     | ██                   | 3.002%
/model.2/cv2/conv/Conv:                      | ██                   | 2.992%
/model.8/m.0/m/m.0/cv2/conv/Conv:            | ██                   | 2.971%
/model.6/cv1/conv/Conv:                      | ██                   | 2.819%
/model.8/m.0/m/m.0/cv1/conv/Conv:            | ██                   | 2.809%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:         | ██                   | 2.760%
/model.2/cv1/conv/Conv:                      | ██                   | 2.683%
/model.6/cv2/conv/Conv:                      | ██                   | 2.630%
/model.8/m.0/m/m.1/cv2/conv/Conv:            | ██                   | 2.615%
/model.9/cv2/conv/Conv:                      | ██                   | 2.540%
/model.3/conv/Conv:                          | ██                   | 2.503%
/model.2/m.0/cv2/conv/Conv:                  | ██                   | 2.474%
/model.6/m.0/m/m.0/cv1/conv/Conv:            | ██                   | 2.273%
/model.6/m.0/m/m.0/cv2/conv/Conv:            | ██                   | 2.246%
/model.4/cv2/conv/Conv:                      | ██                   | 2.141%
/model.7/conv/Conv:                          | ██                   | 2.120%
/model.6/m.0/m/m.1/cv1/conv/Conv:            | ██                   | 2.069%
/model.5/conv/Conv:                          | ██                   | 2.015%
/model.16/cv1/conv/Conv:                     | █                    | 1.894%
/model.4/cv1/conv/Conv:                      | █                    | 1.793%
/model.4/m.0/cv1/conv/Conv:                  | █                    | 1.776%
/model.6/m.0/cv1/conv/Conv:                  | █                    | 1.731%
/model.6/m.0/m/m.1/cv2/conv/Conv:            | █                    | 1.550%
/model.4/m.0/cv2/conv/Conv:                  | █                    | 1.257%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv: | █                    | 0.886%
/model.1/conv/Conv:                          | █                    | 0.775%
/model.23/cv3.2/cv3.2.2/Conv:                | █                    | 0.771%
PPQ_Operation_2:                             |                      | 0.696%
/model.9/cv1/conv/Conv:                      |                      | 0.695%
/model.2/m.0/cv1/conv/Conv:                  |                      | 0.534%
/model.23/cv3.1/cv3.1.2/Conv:                |                      | 0.339%
/model.23/cv3.0/cv3.0.2/Conv:                |                      | 0.190%
PPQ_Operation_0:                             |                      | 0.110%
/model.0/conv/Conv:                          |                      | 0.099%
Analysing Layerwise quantization error:: 100%|██████████| 91/91 [04:13<00:00,  2.
↪79s/it]
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.22/cv1/conv/Conv:                     | ████████████████████ | 0.244%
/model.9/cv2/conv/Conv:                      | █████████████        | 0.156%
/model.10/cv1/conv/Conv:                     | ███████████          | 0.132%
/model.1/conv/Conv:                          | ██████               | 0.077%
/model.4/cv1/conv/Conv:                      | ██████               | 0.074%
```

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```
/model.16/cv1/conv/Conv:                      | █████                | 0.066%
/model.0/conv/Conv:                           | █████                | 0.061%
/model.2/cv1/conv/Conv:                       | █████                | 0.060%
/model.23/cv2.0/cv2.0.0/conv/Conv:            | ████                 | 0.052%
PPQ_Operation_0:                              | ████                 | 0.047%
/model.2/m.0/cv1/conv/Conv:                   | ████                 | 0.045%
/model.10/m/m.0/attn/pe/conv/Conv:            | ██                   | 0.029%
/model.2/m.0/cv2/conv/Conv:                   | ██                   | 0.029%
/model.10/m/m.0/attn/MatMul:                  | ██                   | 0.025%
/model.6/cv1/conv/Conv:                       | ██                   | 0.025%
/model.22/m.0/m/m.0/cv1/conv/Conv:            | ██                   | 0.023%
/model.16/cv2/conv/Conv:                      | ██                   | 0.021%
/model.16/m.0/cv2/conv/Conv:                  | ██                   | 0.020%
/model.19/m.0/cv1/conv/Conv:                  | ██                   | 0.020%
/model.4/m.0/cv1/conv/Conv:                   | █                    | 0.018%
/model.19/cv2/conv/Conv:                      | █                    | 0.017%
/model.4/m.0/cv2/conv/Conv:                   | █                    | 0.016%
/model.10/m/m.0/attn/qkv/conv/Conv:           | █                    | 0.016%
/model.19/cv1/conv/Conv:                      | █                    | 0.015%
/model.13/cv2/conv/Conv:                      | █                    | 0.015%
/model.23/cv2.1/cv2.1.0/conv/Conv:            | █                    | 0.013%
/model.23/cv2.2/cv2.2.1/conv/Conv:            | █                    | 0.012%
/model.13/cv1/conv/Conv:                      | █                    | 0.012%
/model.6/cv2/conv/Conv:                       | █                    | 0.011%
/model.13/m.0/cv1/conv/Conv:                  | █                    | 0.011%
/model.8/cv1/conv/Conv:                       | █                    | 0.010%
/model.13/m.0/cv2/conv/Conv:                  | █                    | 0.010%
/model.5/conv/Conv:                           | █                    | 0.010%
/model.6/m.0/m/m.1/cv1/conv/Conv:             | █                    | 0.009%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv:  | █                    | 0.008%
/model.23/cv2.2/cv2.2.0/conv/Conv:            | █                    | 0.008%
/model.23/cv2.1/cv2.1.1/conv/Conv:            | █                    | 0.008%
/model.19/m.0/cv2/conv/Conv:                  | █                    | 0.008%
/model.8/cv2/conv/Conv:                       | █                    | 0.008%
/model.9/cv1/conv/Conv:                       | █                    | 0.008%
/model.23/cv2.0/cv2.0.1/conv/Conv:            | █                    | 0.007%
/model.16/m.0/cv1/conv/Conv:                  | █                    | 0.007%
/model.17/conv/Conv:                          | █                    | 0.007%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv:  | █                    | 0.007%
/model.10/m/m.0/ffn/ffn.1/conv/Conv:          | █                    | 0.007%
/model.22/m.0/cv1/conv/Conv:                  |                      | 0.006%
/model.10/cv2/conv/Conv:                      |                      | 0.006%
/model.23/cv2.0/cv2.0.2/Conv:                 |                      | 0.006%
/model.23/cv2.2/cv2.2.2/Conv:                 |                      | 0.005%
/model.23/cv2.1/cv2.1.2/Conv:                 |                      | 0.005%
/model.22/m.0/cv3/conv/Conv:                  |                      | 0.005%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv:  |                      | 0.005%
/model.22/cv2/conv/Conv:                      |                      | 0.005%
/model.7/conv/Conv:                           |                      | 0.004%
/model.6/m.0/cv3/conv/Conv:                   |                      | 0.004%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:          |                      | 0.004%
/model.8/m.0/m/m.1/cv2/conv/Conv:             |                      | 0.004%
/model.22/m.0/m/m.1/cv1/conv/Conv:            |                      | 0.004%
/model.8/m.0/m/m.1/cv1/conv/Conv:             |                      | 0.004%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv:  |                      | 0.003%
/model.8/m.0/cv1/conv/Conv:                   |                      | 0.003%
/model.10/m/m.0/attn/proj/conv/Conv:          |                      | 0.003%
/model.22/m.0/m/m.0/cv2/conv/Conv:            |                      | 0.003%
PPQ_Operation_2:                              |                      | 0.003%
/model.8/m.0/cv3/conv/Conv:                   |                      | 0.003%
/model.6/m.0/m/m.0/cv1/conv/Conv:             |                      | 0.003%
```

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```
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv: |                       | 0.002%
/model.6/m.0/m/m.1/cv2/conv/Conv:            |                       | 0.002%
/model.8/m.0/m/m.0/cv2/conv/Conv:            |                       | 0.002%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv: |                       | 0.002%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv: |                       | 0.002%
/model.10/m/m.0/attn/MatMul_1:               |                       | 0.002%
/model.22/m.0/m/m.1/cv2/conv/Conv:           |                       | 0.001%
/model.6/m.0/m/m.0/cv2/conv/Conv:            |                       | 0.001%
/model.8/m.0/m/m.0/cv1/conv/Conv:            |                       | 0.001%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv: |                       | 0.001%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv: |                       | 0.001%
/model.2/cv2/conv/Conv:                      |                       | 0.001%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv: |                       | 0.001%
/model.6/m.0/cv1/conv/Conv:                  |                       | 0.001%
/model.23/cv3.2/cv3.2.2/Conv:                |                       | 0.001%
/model.20/conv/Conv:                         |                       | 0.001%
/model.23/cv3.1/cv3.1.2/Conv:                |                       | 0.001%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv: |                       | 0.001%
/model.6/m.0/cv2/conv/Conv:                  |                       | 0.001%
/model.23/cv3.0/cv3.0.2/Conv:                |                       | 0.000%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv: |                       | 0.000%
/model.8/m.0/cv2/conv/Conv:                  |                       | 0.000%
/model.22/m.0/cv2/conv/Conv:                 |                       | 0.000%
/model.3/conv/Conv:                          |                       | 0.000%
/model.4/cv2/conv/Conv:                      |                       | 0.000%
```

Quantization error analysis

After using 16-bits quantization on layers with higher layer-wise error and employing horizontal layer split pass, the quantized model's mAP50:95 on COCO val2017 improves to 33.4% with the same inputs. Additionally, a noticeable decrease in cumulative error of output layers can be observed.

The graphwise error for the output layers of the model, /model.23/cv3.2/cv3.2.2/Conv, /model.23/cv2.2/cv2.2.2/Conv, /model.23/cv3.1/cv3.1.2/Conv, /model.23/cv2.1/cv2.1.2/Conv, /model.23/cv3.0/cv3.0.2/Conv and /model.23/cv2.0/cv2.0.2/Conv, are 0.771%, 8.156%, 0.339%, 4.222%, 0.190% and 4.232% respectively.

Quantization-Aware Training

To further improve the accuracy of the quantized model, we adopt the quantization-aware training(QAT) strategy. Here, QAT is performed based on 8-bit quantization.

Quantization settings

- yolo11n_qat.py
- trainer.py

Quantization results

```
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.10/m/m.0/ffn/ffn.1/conv/Conv:         | ████████████████████    | 29.837%
/model.10/m/m.0/attn/proj/conv/Conv:         | ████████████████        | 23.397%
/model.10/m/m.0/attn/pe/conv/Conv:           | ██████████              | 15.253%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv: | ██████████              | 14.819%
/model.10/m/m.0/attn/MatMul_1:               | ██████████              | 14.725%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv: | ██████████              | 14.315%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv: | █████████               | 14.212%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv: | █████████               | 14.187%
/model.10/m/m.0/attn/qkv/conv/Conv:          | █████████               | 13.797%
/model.23/cv2.2/cv2.2.0/conv/Conv:           | █████████               | 13.721%
/model.22/m.0/cv2/conv/Conv:                 | █████████               | 13.540%
```

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```
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv: | █████████            | 13.408%
/model.8/m.0/cv2/conv/Conv:                  | █████████            | 12.809%
/model.22/m.0/cv3/conv/Conv:                 | ████████             | 12.623%
/model.23/cv2.1/cv2.1.1/conv/Conv:           | ████████             | 12.472%
/model.23/cv2.1/cv2.1.0/conv/Conv:           | ████████             | 12.177%
/model.22/m.0/m/m.1/cv2/conv/Conv:           | ████████             | 11.719%
/model.23/cv2.2/cv2.2.1/conv/Conv:           | ████████             | 11.711%
/model.10/cv1/conv/Conv:                     | ████████             | 11.589%
/model.22/cv2/conv/Conv:                     | ████████             | 11.551%
/model.23/cv2.0/cv2.0.1/conv/Conv:           | ████████             | 11.505%
/model.10/m/m.0/attn/MatMul:                 | ████████             | 11.346%
/model.22/cv1/conv/Conv:                     | ███████              | 10.201%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv: | ██████               | 9.710%
/model.13/m.0/cv2/conv/Conv:                 | ██████               | 9.538%
/model.20/conv/Conv:                         | ██████               | 8.870%
/model.19/m.0/cv2/conv/Conv:                 | ██████               | 8.713%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv: | █████                | 8.157%
/model.22/m.0/m/m.0/cv2/conv/Conv:           | █████                | 8.005%
/model.8/cv2/conv/Conv:                      | █████                | 7.952%
/model.8/m.0/cv1/conv/Conv:                  | █████                | 7.697%
/model.13/cv2/conv/Conv:                     | █████                | 7.557%
/model.19/cv2/conv/Conv:                     | █████                | 7.443%
/model.10/cv2/conv/Conv:                     | █████                | 7.403%
/model.6/m.0/cv2/conv/Conv:                  | █████                | 7.099%
/model.8/cv1/conv/Conv:                      | █████                | 6.996%
/model.19/cv1/conv/Conv:                     | █████                | 6.912%
/model.8/m.0/m/m.0/cv1/conv/Conv:            | █████                | 6.908%
/model.8/m.0/cv3/conv/Conv:                  | ████                 | 6.755%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv: | ████                 | 6.746%
/model.8/m.0/m/m.0/cv2/conv/Conv:            | ████                 | 6.743%
/model.8/m.0/m/m.1/cv1/conv/Conv:            | ████                 | 6.638%
/model.13/cv1/conv/Conv:                     | ████                 | 6.361%
/model.2/m.0/cv2/conv/Conv:                  | ████                 | 6.274%
/model.13/m.0/cv1/conv/Conv:                 | ████                 | 6.261%
/model.19/m.0/cv1/conv/Conv:                 | ████                 | 6.191%
/model.22/m.0/m/m.0/cv1/conv/Conv:           | ████                 | 6.036%
/model.23/cv2.2/cv2.2.2/Conv:                | ████                 | 5.999%
/model.22/m.0/m/m.1/cv1/conv/Conv:           | ████                 | 5.899%
/model.23/cv2.0/cv2.0.0/conv/Conv:           | ████                 | 5.618%
/model.8/m.0/m/m.1/cv2/conv/Conv:            | ████                 | 5.560%
/model.22/m.0/cv1/conv/Conv:                 | ███                  | 5.336%
/model.16/m.0/cv2/conv/Conv:                 | ███                  | 5.316%
/model.17/conv/Conv:                         | ███                  | 5.113%
/model.6/m.0/cv3/conv/Conv:                  | ███                  | 5.103%
/model.16/m.0/cv1/conv/Conv:                 | ███                  | 5.101%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv: | ███                  | 5.052%
/model.2/cv2/conv/Conv:                      | ███                  | 5.003%
/model.6/cv2/conv/Conv:                      | ███                  | 4.968%
/model.6/cv1/conv/Conv:                      | ███                  | 4.792%
/model.23/cv2.1/cv2.1.2/Conv:                | ███                  | 4.543%
/model.7/conv/Conv:                          | ███                  | 4.520%
/model.3/conv/Conv:                          | ███                  | 4.362%
/model.16/cv2/conv/Conv:                     | ███                  | 4.028%
/model.23/cv2.0/cv2.0.2/Conv:                | ███                  | 4.001%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv: | ███                  | 3.954%
/model.9/cv2/conv/Conv:                      | ███                  | 3.901%
/model.6/m.0/m/m.0/cv1/conv/Conv:            | ███                  | 3.891%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:         | ██                   | 3.791%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv: | ██                   | 3.711%
/model.4/cv1/conv/Conv:                      | ██                   | 3.673%
/model.6/m.0/m/m.0/cv2/conv/Conv:            | ██                   | 3.620%
```

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```
/model.6/m.0/m/m.1/cv1/conv/Conv:            | ██                   | 3.513%
/model.4/cv2/conv/Conv:                      | ██                   | 3.421%
/model.5/conv/Conv:                          | ██                   | 3.320%
/model.6/m.0/cv1/conv/Conv:                  | ██                   | 3.073%
/model.2/cv1/conv/Conv:                      | ██                   | 3.021%
/model.16/cv1/conv/Conv:                     | ██                   | 2.764%
/model.6/m.0/m/m.1/cv2/conv/Conv:            | ██                   | 2.454%
/model.4/m.0/cv1/conv/Conv:                  | ██                   | 2.408%
/model.4/m.0/cv2/conv/Conv:                  | █                    | 1.689%
/model.2/m.0/cv1/conv/Conv:                  | █                    | 1.602%
/model.9/cv1/conv/Conv:                      | █                    | 1.568%
/model.1/conv/Conv:                          | █                    | 1.205%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv: | █                    | 1.091%
/model.23/cv3.2/cv3.2.2/Conv:                |                      | 0.746%
/model.23/cv3.1/cv3.1.2/Conv:                |                      | 0.480%
/model.23/cv3.0/cv3.0.2/Conv:                |                      | 0.386%
/model.0/conv/Conv:                          |                      | 0.163%
Analysing Layerwise quantization error:: 100%|██████████| 89/89 [04:01<00:00,  2.
↪72s/it]
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.2/cv2/conv/Conv:                      | ████████████████████ | 0.935%
/model.9/cv2/conv/Conv:                      | ██████████████████   | 0.826%
/model.2/m.0/cv1/conv/Conv:                  | ███████████████      | 0.698%
/model.3/conv/Conv:                          | █████████████        | 0.611%
/model.4/cv2/conv/Conv:                      | ██████████           | 0.491%
/model.10/cv2/conv/Conv:                     | █████████            | 0.408%
/model.23/cv2.2/cv2.2.2/Conv:                | ██████               | 0.283%
/model.2/cv1/conv/Conv:                      | ██████               | 0.261%
/model.4/cv1/conv/Conv:                      | █████                | 0.249%
/model.1/conv/Conv:                          | █████                | 0.217%
/model.22/cv1/conv/Conv:                     | ████                 | 0.201%
/model.10/cv1/conv/Conv:                     | ███                  | 0.143%
/model.5/conv/Conv:                          | ███                  | 0.136%
/model.16/cv1/conv/Conv:                     | ███                  | 0.128%
/model.10/m/m.0/attn/pe/conv/Conv:           | ███                  | 0.120%
/model.0/conv/Conv:                          | ███                  | 0.118%
/model.16/m.0/cv1/conv/Conv:                 | ██                   | 0.105%
/model.16/cv2/conv/Conv:                     | ██                   | 0.094%
/model.16/m.0/cv2/conv/Conv:                 | ██                   | 0.092%
/model.23/cv2.0/cv2.0.0/conv/Conv:           | ██                   | 0.089%
/model.4/m.0/cv1/conv/Conv:                  | ██                   | 0.071%
/model.22/m.0/cv1/conv/Conv:                 | █                    | 0.067%
/model.19/cv2/conv/Conv:                     | █                    | 0.063%
/model.6/cv2/conv/Conv:                      | █                    | 0.061%
/model.4/m.0/cv2/conv/Conv:                  | █                    | 0.059%
/model.17/conv/Conv:                         | █                    | 0.054%
/model.13/cv2/conv/Conv:                     | █                    | 0.053%
/model.8/m.0/cv3/conv/Conv:                  | █                    | 0.051%
/model.6/cv1/conv/Conv:                      | █                    | 0.047%
/model.23/cv2.2/cv2.2.0/conv/Conv:           | █                    | 0.042%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv: | █                    | 0.041%
/model.13/cv1/conv/Conv:                     | █                    | 0.040%
/model.7/conv/Conv:                          | █                    | 0.038%
/model.10/m/m.0/attn/qkv/conv/Conv:          | █                    | 0.038%
/model.13/m.0/cv1/conv/Conv:                 | █                    | 0.033%
/model.23/cv2.1/cv2.1.0/conv/Conv:           | █                    | 0.031%
/model.6/m.0/m/m.1/cv1/conv/Conv:            | █                    | 0.028%
/model.19/m.0/cv2/conv/Conv:                 | █                    | 0.027%
/model.8/m.0/m/m.1/cv1/conv/Conv:            | █                    | 0.026%
/model.2/m.0/cv2/conv/Conv:                  | █                    | 0.026%
/model.19/m.0/cv1/conv/Conv:                 |                      | 0.022%
```

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```
/model.6/m.0/cv3/conv/Conv:                       |                          | 0.021%
/model.19/cv1/conv/Conv:                          |                          | 0.021%
/model.9/cv1/conv/Conv:                           |                          | 0.016%
/model.22/m.0/m/m.1/cv1/conv/Conv:                |                          | 0.016%
/model.13/m.0/cv2/conv/Conv:                      |                          | 0.015%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv:      |                          | 0.015%
/model.22/m.0/m/m.0/cv1/conv/Conv:                |                          | 0.014%
/model.8/cv1/conv/Conv:                           |                          | 0.013%
/model.23/cv2.0/cv2.0.2/Conv:                     |                          | 0.013%
/model.23/cv2.2/cv2.2.1/conv/Conv:                |                          | 0.012%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:              |                          | 0.011%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv:      |                          | 0.011%
/model.8/cv2/conv/Conv:                           |                          | 0.011%
/model.23/cv2.1/cv2.1.2/Conv:                     |                          | 0.010%
/model.22/m.0/cv3/conv/Conv:                      |                          | 0.010%
/model.23/cv2.1/cv2.1.1/conv/Conv:                |                          | 0.008%
/model.10/m/m.0/ffn/ffn.1/conv/Conv:              |                          | 0.008%
/model.23/cv2.0/cv2.0.1/conv/Conv:                |                          | 0.007%
/model.10/m/m.0/attn/proj/conv/Conv:              |                          | 0.007%
/model.8/m.0/cv1/conv/Conv:                       |                          | 0.007%
/model.22/m.0/m/m.0/cv2/conv/Conv:                |                          | 0.006%
/model.8/m.0/m/m.1/cv2/conv/Conv:                 |                          | 0.005%
/model.22/cv2/conv/Conv:                          |                          | 0.005%
/model.20/conv/Conv:                              |                          | 0.005%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv:      |                          | 0.005%
/model.6/m.0/m/m.0/cv1/conv/Conv:                 |                          | 0.005%
/model.8/m.0/m/m.0/cv1/conv/Conv:                 |                          | 0.004%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv:      |                          | 0.003%
/model.8/m.0/m/m.0/cv2/conv/Conv:                 |                          | 0.003%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv:      |                          | 0.003%
/model.6/m.0/cv1/conv/Conv:                       |                          | 0.003%
/model.23/cv3.2/cv3.2.2/Conv:                     |                          | 0.003%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv:      |                          | 0.003%
/model.6/m.0/m/m.1/cv2/conv/Conv:                 |                          | 0.003%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv:      |                          | 0.002%
/model.22/m.0/m/m.1/cv2/conv/Conv:                |                          | 0.002%
/model.6/m.0/m/m.0/cv2/conv/Conv:                 |                          | 0.002%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv:      |                          | 0.002%
/model.10/m/m.0/attn/MatMul_1:                    |                          | 0.002%
/model.23/cv3.0/cv3.0.2/Conv:                     |                          | 0.001%
/model.23/cv3.1/cv3.1.2/Conv:                     |                          | 0.001%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv:      |                          | 0.001%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv:      |                          | 0.001%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv:      |                          | 0.001%
/model.6/m.0/cv2/conv/Conv:                       |                          | 0.000%
/model.10/m/m.0/attn/MatMul:                      |                          | 0.000%
/model.8/m.0/cv2/conv/Conv:                       |                          | 0.000%
/model.22/m.0/cv2/conv/Conv:                      |                          | 0.000%
```

Quantization error analysis

After applying QAT to 8-bit quantization, the quantized model's mAP50:95 on COCO val2017 improves to 36.0% with the same inputs, while cumulative errors of out layers are significantly reduced. Compared to the other two quantization methods, the 8-bit QAT quantized model achieves the highest quantization accuracy with the lowest inference latency.

The graphwise error for the output layers of the model, /model.23/cv3.2/cv3.2.2/Conv, /model.23/cv2.2/cv2.2.2/Conv, /model.23/cv3.1/cv3.1.2/Conv, /model.23/cv2.1/cv2.1.2/Conv, /model.23/cv3.0/cv3.0.2/Conv and /model.23/cv2.0/cv2.0.2/Conv, are 0.746%, 5.999%, 0.480%, 4.543%, 0.386% and 4.001% respectively.

Note: If the model inference speed is a higher priority and a certain degree of accuracy loss is acceptable, you may consider quantizing the model with an input size of 320x320 for the YOLO11N model. The model inference speed of different input resolutions can be found in README.md .

3.6.3 Model deployment

example

Object detection base class

- dl_detect_base.hpp
- dl_detect_base.cpp

Pre-process

`ImagePreprocessor` class contains the common pre-precoess pipeline, `color conversion`, `crop`, `resize`, `normalization`, `quantize`。

- dl_image_preprocessor.hpp
- dl_image_preprocessor.cpp

Post-process

- dl_detect_postprocessor.hpp
- dl_detect_postprocessor.cpp
- dl_detect_yolo11_postprocessor.hpp
- dl_detect_yolo11_postprocessor.cpp

3.7 How to deploy YOLO11n-pose

In this tutorial, we will introduce how to quantize a pre-trained YOLO11n-pose model using ESP-PPQ and deploy the quantized YOLO11n-pose model using ESP-DL.

3.7.1 Preparation

1. *安装 ESP_IDF*
2. *安装 ESP_PPQ*

3.7.2 Model quantization

Pre-trained Model

You can download pre-trained yolo11n-pose model from Ultralytics release.

Currently, ESP-PPQ supports ONNX, PyTorch, and TensorFlow models. During the quantization process, PyTorch and TensorFlow models are first converted to ONNX models, so the pre-trained yolo11n-pose model needs to be converted to an ONNX model.

Specifically, refer to the script export_onnx.py to convert the pre-trained yolo11n-pose model to an ONNX model.

In the srcipt, we have overridden the forward method of the Pose class, which offers following advantages:

- Faster inference. Compared to the original yolo11n-pose model, operations related to decoding bounding boxes and keypoints in Pose head are moved from the inference pass to the post-processing phase, resulting in a significant reduction in inference latency. On one hand, operations like `Conv`, `Transpose`, `Slice`, `Split` and `Concat` are time-consuming when applied during inference pass. On the other hand, the inference outputs are first filtered using a score threshold before decoding the boxes in the post-processing pass, which significantly reduces the number of calculations, thereby acclerating the overall inference speed.
- Lower quantization Error. The `Concat` and `Add` operators adopt joint quantization in ESP-PPQ. To reduce quantization errors, the box and score are output by separate branches, rather than being concatenated, due to the significant difference in their ranges. Similarly, since the ranges of the two inputs of `Add` and `Sub` differ significantly, the calculations are performed in the post-processing phase to avoid quantization errors.

Calibration Dataset

The calibration dataset needs to match the input format of the model. The calibration dataset should cover all possible input scenarios to better quantize the model. Here, the calibration dataset used in this example is calib_yolo11n-pose.

8bit default configuration quantization

Quantization settings

```
target="esp32p4"
num_of_bits=8
batch_size=32
quant_setting = QuantizationSettingFactory.espdl_setting() # default setting
```

Quantization results

```
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.22/m.0/cv2/conv/Conv:                 | ████████████████████ | 29.305%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv: | ██████████████████   | 26.959%
/model.23/cv4.1/cv4.1.0/conv/Conv:           | ██████████████████   | 26.555%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv: | █████████████████    | 25.611%
/model.20/conv/Conv:                         | █████████████████    | 24.738%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv: | ████████████████     | 24.122%
/model.23/cv4.1/cv4.1.1/conv/Conv:           | ███████████████      | 22.512%
/model.19/m.0/cv2/conv/Conv:                 | ███████████████      | 22.397%
/model.23/cv2.0/cv2.0.1/conv/Conv:           | ███████████████      | 22.174%
/model.23/cv4.0/cv4.0.0/conv/Conv:           | ███████████████      | 21.621%
/model.23/cv2.1/cv2.1.1/conv/Conv:           | ███████████████      | 21.489%
/model.23/cv4.0/cv4.0.1/conv/Conv:           | ███████████████      | 21.445%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv: | ██████████████       | 20.528%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv: | ██████████████       | 20.083%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv: | ██████████████       | 20.066%
/model.13/m.0/cv2/conv/Conv:                 | ██████████████       | 20.042%
/model.22/m.0/cv3/conv/Conv:                 | █████████████        | 19.737%
/model.10/m/m.0/ffn/ffn.1/conv/Conv:         | █████████████        | 19.585%
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```
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv: | █████████████        | 19.392%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv: | █████████████        | 18.773%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv: | █████████████        | 18.688%
/model.22/cv1/conv/Conv:                     | █████████████        | 18.579%
/model.19/cv2/conv/Conv:                     | █████████████        | 18.494%
/model.22/m.0/m/m.1/cv2/conv/Conv:           | ████████████         | 17.576%
/model.17/conv/Conv:                         | ████████████         | 17.224%
/model.19/cv1/conv/Conv:                     | ████████████         | 17.140%
/model.22/cv2/conv/Conv:                     | ███████████          | 16.785%
/model.23/cv4.2/cv4.2.1/conv/Conv:           | ███████████          | 16.375%
/model.23/cv4.2/cv4.2.0/conv/Conv:           | ███████████          | 16.167%
/model.23/cv2.1/cv2.1.0/conv/Conv:           | ███████████          | 15.655%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv: | ███████████          | 15.504%
/model.23/cv2.2/cv2.2.0/conv/Conv:           | ███████████          | 15.431%
/model.10/m/m.0/attn/proj/conv/Conv:         | ██████████           | 15.251%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv: | ██████████           | 15.171%
/model.22/m.0/m/m.0/cv2/conv/Conv:           | ██████████           | 15.006%
/model.19/m.0/cv1/conv/Conv:                 | ██████████           | 14.692%
/model.23/cv2.2/cv2.2.1/conv/Conv:           | ██████████           | 14.548%
/model.22/m.0/m/m.0/cv1/conv/Conv:           | █████████            | 13.065%
/model.16/m.0/cv2/conv/Conv:                 | █████████            | 12.980%
/model.22/m.0/m/m.1/cv1/conv/Conv:           | █████████            | 12.921%
/model.10/m/m.0/attn/pe/conv/Conv:           | █████████            | 12.745%
/model.23/cv4.1/cv4.1.2/Conv:                | ████████             | 12.498%
/model.13/cv2/conv/Conv:                     | ████████             | 11.932%
/model.23/cv4.2/cv4.2.2/Conv:                | ████████             | 11.797%
/model.13/m.0/cv1/conv/Conv:                 | ████████             | 11.777%
/model.16/cv2/conv/Conv:                     | ███████              | 10.892%
/model.13/cv1/conv/Conv:                     | ███████              | 10.760%
/model.23/cv2.0/cv2.0.0/conv/Conv:           | ███████              | 10.352%
/model.23/cv4.0/cv4.0.2/Conv:                | ███████              | 10.325%
/model.22/m.0/cv1/conv/Conv:                 | ███████              | 10.257%
/model.8/m.0/cv2/conv/Conv:                  | ███████              | 9.687%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:         | ██████               | 8.997%
/model.10/cv1/conv/Conv:                     | ██████               | 8.787%
/model.16/m.0/cv1/conv/Conv:                 | ██████               | 8.629%
/model.10/m/m.0/attn/qkv/conv/Conv:          | ██████               | 8.600%
/model.8/m.0/cv3/conv/Conv:                  | ██████               | 8.328%
/model.10/m/m.0/attn/MatMul_1:               | ██████               | 8.293%
/model.16/cv1/conv/Conv:                     | █████                | 7.947%
/model.10/cv2/conv/Conv:                     | █████                | 7.824%
/model.8/cv2/conv/Conv:                      | █████                | 7.696%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv: | █████                | 7.615%
/model.8/m.0/m/m.1/cv2/conv/Conv:            | █████                | 7.145%
/model.8/m.0/m/m.0/cv2/conv/Conv:            | █████                | 7.033%
/model.10/m/m.0/attn/MatMul:                 | █████                | 6.707%
/model.8/m.0/m/m.1/cv1/conv/Conv:            | ████                 | 6.376%
/model.23/cv2.1/cv2.1.2/Conv:                | ████                 | 6.321%
/model.8/cv1/conv/Conv:                      | ████                 | 6.296%
/model.6/m.0/cv2/conv/Conv:                  | ████                 | 5.605%
/model.23/cv3.2/cv3.2.2/Conv:                | ████                 | 5.599%
/model.6/m.0/m/m.0/cv2/conv/Conv:            | ████                 | 5.559%
/model.23/cv2.0/cv2.0.2/Conv:                | ████                 | 5.262%
/model.23/cv2.2/cv2.2.2/Conv:                | ████                 | 5.207%
/model.6/m.0/cv3/conv/Conv:                  | ███                  | 4.840%
/model.8/m.0/cv1/conv/Conv:                  | ███                  | 4.667%
/model.6/cv1/conv/Conv:                      | ███                  | 4.523%
/model.9/cv1/conv/Conv:                      | ███                  | 4.038%
/model.9/cv2/conv/Conv:                      | ██                   | 3.733%
/model.7/conv/Conv:                          | ██                   | 3.605%
/model.6/cv2/conv/Conv:                      | ██                   | 3.478%
```

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```
/model.3/conv/Conv:                          | ██                   | 3.352%
/model.2/cv2/conv/Conv:                      | ██                   | 3.230%
/model.8/m.0/m/m.0/cv1/conv/Conv:            | ██                   | 3.136%
/model.4/cv1/conv/Conv:                      | ██                   | 2.913%
/model.6/m.0/m/m.1/cv1/conv/Conv:            | ██                   | 2.830%
/model.6/m.0/m/m.1/cv2/conv/Conv:            | ██                   | 2.692%
/model.6/m.0/m/m.0/cv1/conv/Conv:            | ██                   | 2.557%
/model.6/m.0/cv1/conv/Conv:                  | ██                   | 2.475%
/model.5/conv/Conv:                          | ██                   | 2.413%
/model.2/cv1/conv/Conv:                      | █                    | 2.267%
/model.4/cv2/conv/Conv:                      | █                    | 2.135%
/model.2/m.0/cv2/conv/Conv:                  | █                    | 2.104%
/model.4/m.0/cv1/conv/Conv:                  | █                    | 1.910%
/model.1/conv/Conv:                          | █                    | 1.708%
/model.2/m.0/cv1/conv/Conv:                  | █                    | 1.658%
/model.23/cv3.1/cv3.1.2/Conv:                | █                    | 1.455%
/model.4/m.0/cv2/conv/Conv:                  | █                    | 1.056%
/model.23/cv3.0/cv3.0.2/Conv:                |                      | 0.364%
/model.0/conv/Conv:                          |                      | 0.087%
Analysing Layerwise quantization error:: 100%|██████████| 98/98 [16:09<00:00,  9.89s/it]
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.0/conv/Conv:                          | ████████████████████ | 1.017%
/model.9/cv2/conv/Conv:                      | ██████████           | 0.493%
/model.8/cv1/conv/Conv:                      | ████████             | 0.410%
/model.2/cv2/conv/Conv:                      | ██████               | 0.287%
/model.1/conv/Conv:                          | ████                 | 0.228%
/model.2/cv1/conv/Conv:                      | ███                  | 0.163%
/model.16/cv2/conv/Conv:                     | ███                  | 0.130%
/model.4/cv2/conv/Conv:                      | ██                   | 0.096%
/model.3/conv/Conv:                          | █                    | 0.070%
/model.4/cv1/conv/Conv:                      | █                    | 0.068%
/model.10/cv1/conv/Conv:                     | █                    | 0.049%
/model.2/m.0/cv2/conv/Conv:                  | █                    | 0.047%
/model.2/m.0/cv1/conv/Conv:                  | █                    | 0.043%
/model.4/m.0/cv2/conv/Conv:                  | █                    | 0.041%
/model.13/cv2/conv/Conv:                     | █                    | 0.037%
/model.16/cv1/conv/Conv:                     | █                    | 0.030%
/model.22/cv2/conv/Conv:                     | █                    | 0.027%
/model.8/cv2/conv/Conv:                      | █                    | 0.027%
/model.13/cv1/conv/Conv:                     |                      | 0.025%
/model.5/conv/Conv:                          |                      | 0.025%
/model.19/m.0/cv2/conv/Conv:                 |                      | 0.025%
/model.6/cv2/conv/Conv:                      |                      | 0.024%
/model.4/m.0/cv1/conv/Conv:                  |                      | 0.022%
/model.6/cv1/conv/Conv:                      |                      | 0.021%
/model.19/cv1/conv/Conv:                     |                      | 0.020%
/model.23/cv2.1/cv2.1.1/conv/Conv:           |                      | 0.018%
/model.23/cv4.1/cv4.1.0/conv/Conv:           |                      | 0.017%
/model.9/cv1/conv/Conv:                      |                      | 0.015%
/model.23/cv4.2/cv4.2.1/conv/Conv:           |                      | 0.014%
/model.10/m/m.0/attn/qkv/conv/Conv:          |                      | 0.014%
/model.19/cv2/conv/Conv:                     |                      | 0.014%
/model.16/m.0/cv2/conv/Conv:                 |                      | 0.014%
/model.23/cv4.2/cv4.2.0/conv/Conv:           |                      | 0.014%
/model.6/m.0/m/m.0/cv1/conv/Conv:            |                      | 0.013%
/model.22/m.0/cv3/conv/Conv:                 |                      | 0.013%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv: |                      | 0.013%
/model.23/cv4.0/cv4.0.0/conv/Conv:           |                      | 0.013%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv: |                      | 0.013%
/model.22/m.0/m/m.1/cv1/conv/Conv:           |                      | 0.012%
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/model.6/m.0/cv3/conv/Conv:                 |                          | 0.012%
/model.10/m/m.0/attn/pe/conv/Conv:          |                          | 0.012%
/model.23/cv4.1/cv4.1.1/conv/Conv:          |                          | 0.011%
/model.8/m.0/m/m.1/cv1/conv/Conv:           |                          | 0.011%
/model.13/m.0/cv1/conv/Conv:                |                          | 0.011%
/model.22/m.0/m/m.0/cv1/conv/Conv:          |                          | 0.011%
/model.6/m.0/m/m.1/cv1/conv/Conv:           |                          | 0.011%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv: |                         | 0.011%
/model.8/m.0/cv3/conv/Conv:                 |                          | 0.010%
/model.7/conv/Conv:                         |                          | 0.010%
/model.17/conv/Conv:                        |                          | 0.009%
/model.8/m.0/m/m.0/cv1/conv/Conv:           |                          | 0.009%
/model.13/m.0/cv2/conv/Conv:                |                          | 0.009%
/model.10/m/m.0/attn/MatMul:                |                          | 0.009%
/model.19/m.0/cv1/conv/Conv:                |                          | 0.008%
/model.16/m.0/cv1/conv/Conv:                |                          | 0.008%
/model.23/cv2.2/cv2.2.1/conv/Conv:          |                          | 0.008%
/model.8/m.0/m/m.1/cv2/conv/Conv:           |                          | 0.008%
/model.8/m.0/cv1/conv/Conv:                 |                          | 0.008%
/model.10/cv2/conv/Conv:                    |                          | 0.007%
/model.23/cv2.0/cv2.0.2/Conv:               |                          | 0.007%
/model.22/m.0/cv1/conv/Conv:                |                          | 0.007%
/model.6/m.0/cv1/conv/Conv:                 |                          | 0.007%
/model.23/cv2.0/cv2.0.0/conv/Conv:          |                          | 0.006%
/model.23/cv2.1/cv2.1.0/conv/Conv:          |                          | 0.006%
/model.22/m.0/m/m.1/cv2/conv/Conv:          |                          | 0.006%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv: |                         | 0.005%
/model.8/m.0/m/m.0/cv2/conv/Conv:           |                          | 0.005%
/model.23/cv2.1/cv2.1.2/Conv:               |                          | 0.005%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv: |                         | 0.005%
/model.23/cv2.2/cv2.2.2/Conv:               |                          | 0.005%
/model.22/cv1/conv/Conv:                    |                          | 0.004%
/model.10/m/m.0/attn/proj/conv/Conv:        |                          | 0.004%
/model.23/cv4.2/cv4.2.2/Conv:               |                          | 0.004%
/model.23/cv4.1/cv4.1.2/Conv:               |                          | 0.004%
/model.22/m.0/m/m.0/cv2/conv/Conv:          |                          | 0.004%
/model.23/cv2.2/cv2.2.0/conv/Conv:          |                          | 0.003%
/model.6/m.0/m/m.1/cv2/conv/Conv:           |                          | 0.003%
/model.23/cv4.0/cv4.0.1/conv/Conv:          |                          | 0.003%
/model.6/m.0/m/m.0/cv2/conv/Conv:           |                          | 0.003%
/model.10/m/m.0/attn/MatMul_1:              |                          | 0.002%
/model.23/cv4.0/cv4.0.2/Conv:               |                          | 0.002%
/model.10/m/m.0/ffn/ffn.1/conv/Conv:        |                          | 0.002%
/model.20/conv/Conv:                        |                          | 0.002%
/model.23/cv2.0/cv2.0.1/conv/Conv:          |                          | 0.002%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:        |                          | 0.001%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv: |                         | 0.001%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv: |                         | 0.001%
/model.23/cv3.2/cv3.2.2/Conv:               |                          | 0.001%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv: |                         | 0.001%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv: |                         | 0.001%
/model.23/cv3.1/cv3.1.2/Conv:               |                          | 0.000%
/model.23/cv3.0/cv3.0.2/Conv:               |                          | 0.000%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv: |                         | 0.000%
/model.6/m.0/cv2/conv/Conv:                 |                          | 0.000%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv: |                         | 0.000%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv: |                         | 0.000%
/model.8/m.0/cv2/conv/Conv:                 |                          | 0.000%
/model.22/m.0/cv2/conv/Conv:                |                          | 0.000%
```

Quantization error analysis

With the same inputs, The Pose mAP50:95 on COCO after quantization is only 43.1%, which is lower than that of the float model（50.0%）.

Quantization-Aware Training

To further improve the accuracy of the quantized model, we adopt the quantization-aware training(QAT) strategy. Here, QAT is performed based on 8-bit quantization.

Quantization settings

- yolo11n-pose_qat.py
- trainer.py

Quantization results

```
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.22/m.0/cv2/conv/Conv:                 | ████████████████████ | 27.739%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv: | ███████████████████  | 26.872%
/model.23/cv4.1/cv4.1.0/conv/Conv:           | ███████████████████  | 26.229%
/model.23/cv2.1/cv2.1.1/conv/Conv:           | ██████████████████   | 25.300%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv: | ██████████████████   | 24.625%
/model.23/cv2.0/cv2.0.1/conv/Conv:           | █████████████████    | 23.751%
/model.20/conv/Conv:                         | █████████████████    | 23.320%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv: | █████████████████    | 22.901%
/model.23/cv4.1/cv4.1.1/conv/Conv:           | ████████████████     | 22.516%
/model.10/m/m.0/ffn/ffn.1/conv/Conv:         | ████████████████     | 22.035%
/model.19/m.0/cv2/conv/Conv:                 | ████████████████     | 21.569%
/model.23/cv4.0/cv4.0.0/conv/Conv:           | ███████████████      | 21.199%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv: | ███████████████      | 20.785%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv: | ███████████████      | 20.597%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv: | ███████████████      | 20.329%
/model.23/cv4.0/cv4.0.1/conv/Conv:           | ███████████████      | 20.179%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv: | ██████████████       | 19.983%
/model.22/m.0/cv3/conv/Conv:                 | ██████████████       | 19.919%
/model.13/m.0/cv2/conv/Conv:                 | ██████████████       | 19.424%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv: | ██████████████       | 18.893%
/model.19/cv2/conv/Conv:                     | █████████████        | 18.055%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv: | █████████████        | 17.915%
/model.22/m.0/m/m.1/cv2/conv/Conv:           | █████████████        | 17.796%
/model.22/cv1/conv/Conv:                     | █████████████        | 17.777%
/model.23/cv4.2/cv4.2.1/conv/Conv:           | █████████████        | 17.573%
/model.19/cv1/conv/Conv:                     | ████████████         | 17.116%
/model.17/conv/Conv:                         | ████████████         | 16.869%
/model.22/cv2/conv/Conv:                     | ████████████         | 16.750%
/model.23/cv2.2/cv2.2.1/conv/Conv:           | ████████████         | 16.540%
/model.10/m/m.0/attn/proj/conv/Conv:         | ████████████         | 16.491%
/model.23/cv2.2/cv2.2.0/conv/Conv:           | ████████████         | 16.421%
/model.23/cv2.1/cv2.1.0/conv/Conv:           | ████████████         | 16.205%
/model.23/cv4.2/cv4.2.0/conv/Conv:           | ████████████         | 16.116%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv: | ███████████          | 15.400%
/model.22/m.0/m/m.0/cv2/conv/Conv:           | ███████████          | 15.251%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv: | ███████████          | 14.851%
/model.10/m/m.0/attn/pe/conv/Conv:           | ███████████          | 14.659%
/model.19/m.0/cv1/conv/Conv:                 | ██████████           | 14.289%
/model.22/m.0/m/m.1/cv1/conv/Conv:           | █████████            | 13.038%
/model.16/m.0/cv2/conv/Conv:                 | █████████            | 12.941%
/model.22/m.0/m/m.0/cv1/conv/Conv:           | █████████            | 12.791%
/model.23/cv4.2/cv4.2.2/Conv:                | █████████            | 12.508%
/model.23/cv4.1/cv4.1.2/Conv:                | █████████            | 12.226%
/model.13/cv1/conv/Conv:                     | ████████             | 11.821%
/model.13/cv2/conv/Conv:                     | ████████             | 11.612%
/model.13/m.0/cv1/conv/Conv:                 | ████████             | 11.515%
```

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```
/model.10/m/m.0/attn/MatMul_1:               | ████████             | 11.303%
/model.16/cv2/conv/Conv:                     | ████████             | 11.028%
/model.10/m/m.0/attn/qkv/conv/Conv:          | ████████             | 10.951%
/model.10/cv1/conv/Conv:                     | ████████             | 10.755%
/model.23/cv2.0/cv2.0.0/conv/Conv:           | ████████             | 10.684%
/model.22/m.0/cv1/conv/Conv:                 | ███████              | 10.164%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:         | ███████              | 9.968%
/model.16/m.0/cv1/conv/Conv:                 | ███████              | 9.656%
/model.23/cv4.0/cv4.0.2/Conv:                | ███████              | 9.566%
/model.8/m.0/cv2/conv/Conv:                  | ███████              | 9.521%
/model.10/cv2/conv/Conv:                     | ██████               | 8.068%
/model.16/cv1/conv/Conv:                     | ██████               | 7.989%
/model.23/cv2.1/cv2.1.2/Conv:                | ██████               | 7.969%
/model.8/m.0/cv3/conv/Conv:                  | ██████               | 7.725%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv: | █████                | 7.570%
/model.8/m.0/m/m.0/cv2/conv/Conv:            | █████                | 7.339%
/model.8/m.0/m/m.1/cv2/conv/Conv:            | █████                | 7.283%
/model.8/cv2/conv/Conv:                      | █████                | 7.092%
/model.10/m/m.0/attn/MatMul:                 | █████                | 6.654%
/model.8/cv1/conv/Conv:                      | █████                | 6.492%
/model.8/m.0/m/m.1/cv1/conv/Conv:            | █████                | 6.451%
/model.23/cv2.0/cv2.0.2/Conv:                | ████                 | 5.990%
/model.23/cv2.2/cv2.2.2/Conv:                | ████                 | 5.902%
/model.6/m.0/m/m.0/cv2/conv/Conv:            | ████                 | 5.898%
/model.6/m.0/cv2/conv/Conv:                  | ████                 | 5.881%
/model.6/m.0/cv3/conv/Conv:                  | ████                 | 5.402%
/model.8/m.0/cv1/conv/Conv:                  | ████                 | 5.210%
/model.23/cv3.2/cv3.2.2/Conv:                | ████                 | 5.126%
/model.6/cv1/conv/Conv:                      | ████                 | 4.983%
/model.9/cv2/conv/Conv:                      | ███                  | 4.616%
/model.9/cv1/conv/Conv:                      | ███                  | 3.934%
/model.7/conv/Conv:                          | ███                  | 3.906%
/model.3/conv/Conv:                          | ███                  | 3.654%
/model.6/cv2/conv/Conv:                      | ██                   | 3.429%
/model.8/m.0/m/m.0/cv1/conv/Conv:            | ██                   | 3.319%
/model.2/cv2/conv/Conv:                      | ██                   | 3.220%
/model.6/m.0/m/m.1/cv1/conv/Conv:            | ██                   | 3.191%
/model.6/m.0/m/m.0/cv1/conv/Conv:            | ██                   | 3.157%
/model.4/cv1/conv/Conv:                      | ██                   | 2.893%
/model.6/m.0/m/m.1/cv2/conv/Conv:            | ██                   | 2.792%
/model.6/m.0/cv1/conv/Conv:                  | ██                   | 2.761%
/model.5/conv/Conv:                          | ██                   | 2.629%
/model.4/cv2/conv/Conv:                      | ██                   | 2.298%
/model.2/cv1/conv/Conv:                      | █                    | 2.107%
/model.2/m.0/cv2/conv/Conv:                  | █                    | 2.095%
/model.4/m.0/cv1/conv/Conv:                  | █                    | 2.069%
/model.23/cv3.1/cv3.1.2/Conv:                | █                    | 1.744%
/model.1/conv/Conv:                          | █                    | 1.631%
/model.2/m.0/cv1/conv/Conv:                  | █                    | 1.583%
/model.4/m.0/cv2/conv/Conv:                  | █                    | 1.126%
/model.23/cv3.0/cv3.0.2/Conv:                |                      | 0.535%
/model.0/conv/Conv:                          |                      | 0.067%
Analysing Layerwise quantization error:: 100%|██████████| 98/98 [10:49<00:00,  6.
↪63s/it]
Layer                                        | NOISE:SIGNAL POWER RATIO
/model.9/cv2/conv/Conv:                      | ████████████████████ | 2.976%
/model.2/cv2/conv/Conv:                      | ███████████          | 1.610%
/model.3/conv/Conv:                          | ██████               | 0.854%
/model.2/cv1/conv/Conv:                      | ████                 | 0.543%
/model.1/conv/Conv:                          | ███                  | 0.487%
/model.8/cv1/conv/Conv:                      | ███                  | 0.414%
```

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```
/model.4/cv2/conv/Conv:                       | ███                  | 0.397%
/model.0/conv/Conv:                           | ██                   | 0.364%
/model.6/m.0/cv3/conv/Conv:                   | ██                   | 0.230%
/model.5/conv/Conv:                           | █                    | 0.181%
/model.2/m.0/cv2/conv/Conv:                   | █                    | 0.144%
/model.13/cv2/conv/Conv:                      | █                    | 0.140%
/model.2/m.0/cv1/conv/Conv:                   | █                    | 0.138%
/model.4/cv1/conv/Conv:                       | █                    | 0.129%
/model.16/cv2/conv/Conv:                      | █                    | 0.122%
/model.23/cv4.2/cv4.2.0/conv/Conv:            | █                    | 0.120%
/model.4/m.0/cv1/conv/Conv:                   | █                    | 0.107%
/model.23/cv4.1/cv4.1.0/conv/Conv:            | █                    | 0.096%
/model.19/cv2/conv/Conv:                      | █                    | 0.078%
/model.23/cv2.2/cv2.2.2/Conv:                 | █                    | 0.076%
/model.4/m.0/cv2/conv/Conv:                   |                      | 0.071%
/model.8/m.0/m/m.1/cv1/conv/Conv:             |                      | 0.071%
/model.6/cv2/conv/Conv:                       |                      | 0.067%
/model.6/cv1/conv/Conv:                       |                      | 0.066%
/model.17/conv/Conv:                          |                      | 0.060%
/model.23/cv4.2/cv4.2.1/conv/Conv:            |                      | 0.057%
/model.22/m.0/m/m.1/cv1/conv/Conv:            |                      | 0.056%
/model.16/cv1/conv/Conv:                      |                      | 0.051%
/model.10/cv1/conv/Conv:                      |                      | 0.050%
/model.23/cv4.2/cv4.2.2/Conv:                 |                      | 0.046%
/model.22/cv2/conv/Conv:                      |                      | 0.044%
/model.7/conv/Conv:                           |                      | 0.043%
/model.10/m/m.0/attn/pe/conv/Conv:            |                      | 0.043%
/model.10/cv2/conv/Conv:                      |                      | 0.037%
/model.19/cv1/conv/Conv:                      |                      | 0.037%
/model.8/cv2/conv/Conv:                       |                      | 0.036%
/model.13/cv1/conv/Conv:                      |                      | 0.036%
/model.6/m.0/m/m.1/cv1/conv/Conv:             |                      | 0.033%
/model.22/m.0/cv3/conv/Conv:                  |                      | 0.031%
/model.19/m.0/cv1/conv/Conv:                  |                      | 0.027%
/model.23/cv3.2/cv3.2.0/cv3.2.0.1/conv/Conv:  |                      | 0.026%
/model.8/m.0/cv1/conv/Conv:                   |                      | 0.025%
/model.19/m.0/cv2/conv/Conv:                  |                      | 0.025%
/model.8/m.0/cv3/conv/Conv:                   |                      | 0.024%
/model.10/m/m.0/attn/qkv/conv/Conv:           |                      | 0.023%
/model.8/m.0/m/m.0/cv1/conv/Conv:             |                      | 0.023%
/model.22/m.0/cv1/conv/Conv:                  |                      | 0.021%
/model.6/m.0/m/m.0/cv1/conv/Conv:             |                      | 0.021%
/model.23/cv2.0/cv2.0.0/conv/Conv:            |                      | 0.020%
/model.6/m.0/cv1/conv/Conv:                   |                      | 0.020%
/model.23/cv4.0/cv4.0.0/conv/Conv:            |                      | 0.019%
/model.9/cv1/conv/Conv:                       |                      | 0.018%
/model.23/cv4.1/cv4.1.2/Conv:                 |                      | 0.018%
/model.23/cv2.1/cv2.1.1/conv/Conv:            |                      | 0.018%
/model.13/m.0/cv1/conv/Conv:                  |                      | 0.016%
/model.23/cv2.1/cv2.1.0/conv/Conv:            |                      | 0.016%
/model.23/cv4.1/cv4.1.1/conv/Conv:            |                      | 0.016%
/model.16/m.0/cv2/conv/Conv:                  |                      | 0.015%
/model.10/m/m.0/attn/proj/conv/Conv:          |                      | 0.013%
/model.23/cv3.1/cv3.1.1/cv3.1.1.1/conv/Conv:  |                      | 0.013%
/model.8/m.0/m/m.0/cv2/conv/Conv:             |                      | 0.013%
/model.16/m.0/cv1/conv/Conv:                  |                      | 0.012%
/model.23/cv2.2/cv2.2.0/conv/Conv:            |                      | 0.011%
/model.20/conv/Conv:                          |                      | 0.011%
/model.22/m.0/m/m.0/cv1/conv/Conv:            |                      | 0.011%
/model.23/cv3.2/cv3.2.1/cv3.2.1.1/conv/Conv:  |                      | 0.011%
/model.8/m.0/m/m.1/cv2/conv/Conv:             |                      | 0.010%
```

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```
/model.23/cv2.0/cv2.0.2/Conv:                 |                                             | 0.009%
/model.10/m/m.0/attn/MatMul:                  |                                             | 0.009%
/model.22/cv1/conv/Conv:                      |                                             | 0.009%
/model.13/m.0/cv2/conv/Conv:                  |                                             | 0.008%
/model.23/cv2.2/cv2.2.1/conv/Conv:            |                                             | 0.008%
/model.23/cv2.1/cv2.1.2/Conv:                 |                                             | 0.007%
/model.23/cv3.2/cv3.2.1/cv3.2.1.0/conv/Conv:  |                                             | 0.007%
/model.22/m.0/m/m.1/cv2/conv/Conv:            |                                             | 0.007%
/model.6/m.0/m/m.0/cv2/conv/Conv:             |                                             | 0.006%
/model.22/m.0/m/m.0/cv2/conv/Conv:            |                                             | 0.006%
/model.23/cv4.0/cv4.0.1/conv/Conv:            |                                             | 0.005%
/model.23/cv3.2/cv3.2.0/cv3.2.0.0/conv/Conv:  |                                             | 0.005%
/model.23/cv4.0/cv4.0.2/Conv:                 |                                             | 0.004%
/model.6/m.0/m/m.1/cv2/conv/Conv:             |                                             | 0.004%
/model.23/cv3.0/cv3.0.0/cv3.0.0.1/conv/Conv:  |                                             | 0.004%
/model.10/m/m.0/ffn/ffn.1/conv/Conv:          |                                             | 0.003%
/model.23/cv3.2/cv3.2.2/Conv:                 |                                             | 0.003%
/model.10/m/m.0/attn/MatMul_1:                |                                             | 0.002%
/model.10/m/m.0/ffn/ffn.0/conv/Conv:          |                                             | 0.002%
/model.23/cv3.1/cv3.1.0/cv3.1.0.1/conv/Conv:  |                                             | 0.002%
/model.23/cv2.0/cv2.0.1/conv/Conv:            |                                             | 0.002%
/model.23/cv3.1/cv3.1.1/cv3.1.1.0/conv/Conv:  |                                             | 0.001%
/model.23/cv3.0/cv3.0.2/Conv:                 |                                             | 0.001%
/model.23/cv3.1/cv3.1.2/Conv:                 |                                             | 0.001%
/model.23/cv3.0/cv3.0.1/cv3.0.1.0/conv/Conv:  |                                             | 0.001%
/model.23/cv3.1/cv3.1.0/cv3.1.0.0/conv/Conv:  |                                             | 0.001%
/model.23/cv3.0/cv3.0.0/cv3.0.0.0/conv/Conv:  |                                             | 0.000%
/model.6/m.0/cv2/conv/Conv:                   |                                             | 0.000%
/model.23/cv3.0/cv3.0.1/cv3.0.1.1/conv/Conv:  |                                             | 0.000%
/model.8/m.0/cv2/conv/Conv:                   |                                             | 0.000%
/model.22/m.0/cv2/conv/Conv:                  |                                             | 0.000%
```

Quantization error analysis

After applying QAT to 8-bit quantization, the quantized model’s Pose mAP50:95 on COCO improves to 44.9% with the same inputs, while cumulative errors of out layers are significantly reduced. Compared to the other two quantization methods, the 8-bit QAT quantized model achieves the highest quantization accuracy with the lowest inference latency.

3.7.3 Model deployment

example

Object detection base class

- dl_detect_base.hpp
- dl_detect_base.cpp

Pre-process

`ImagePreprocessor` class contains the common pre-precoess pipeline, `color conversion`, `crop`, `resize`, `normalization`, `quantize`。

- dl_image_preprocessor.hpp
- dl_image_preprocessor.cpp

Post-process

- dl_detect_postprocessor.hpp
- dl_detect_postprocessor.cpp
- dl_pose_yolo11_postprocessor.hpp
- dl_pose_yolo11_postprocessor.cpp

3.8 How to Deploy Streaming Models

Time series models are now widely applied in various fields, such as audio processing. Audio models typically have two deployment modes when deployed:

- Offline mode: The model receives the complete audio data (e.g., an entire speech file) at once and processes it as a whole.
- Streaming mode: In streaming mode, the model receives audio data frame by frame (or block by block) in real-time, processes it, and outputs intermediate results.

In this tutorial, we will introduce how to quantize a streaming model using ESP-PPQ and deploy the quantized streaming model with ESP-DL.

3.8.1 Prerequisites

1. *Install ESP-IDF*
2. *Install ESP-PPQ*

3.8.2 Model Quantization

Reference example

How to Convert to a Streaming Model

There are numerous types of time series models. Here, we take the Temporal Convolutional Network (TCN) as an example. If you are unfamiliar with TCNs, please refer to relevant resources for details; we won't elaborate further. Other models should be customized based on their specific structures.

The example code constructs a TCN model: test_model.py (the model is incomplete and used only for demonstration). The demonstration model splits a complete model into three parts: `TestModel_0`, `TestModel_1`, and `TestModel_2`. This represents that a single frame of data sequentially flows through one module at a time, with the data flow being: `frame_data -> TestModel_0 -> TestModel_1 -> TestModel_2`.

Note: There is no fixed convention for splitting models; it depends on the model's structure. The more modules you split, the lower the CPU load, but the output latency of the final computation increases. Conversely, fewer splits reduce latency but increase CPU load.

For streaming models, there are differences during training and deployment: during training, the offline mode is used for simplicity; during deployment, the streaming mode is employed to better adapt to real-world scenarios where continuous data is received. Due to this difference, the model needs an additional `streaming_forward` function to slightly modify the forward logic to meet the requirements of quantization deployment.

Note:

- In offline mode, the model input is a complete data segment, and the input shape typically has a large size along the time dimension.
- In streaming mode, the model input is continuous data. Since the forward logic is modified, the input shape along the time dimension is smaller, generally equal to the number of split modules mentioned above.

The following code block demonstrates `TestModel_0` with both `forward` and `streaming_forward` functions. `forward` is used for training, while `streaming_forward` is used for quantization deployment. The difference lies in the padding of the input to `self.layer[1]`. This is because the TCN requires padding the input during convolution to maintain consistent time dimension sizes. The modification in `streaming_forward` implements a sliding window approach for padding, which necessitates caching data from previous time steps and concatenating them with the current data to achieve the sliding window effect. Additionally, the cache must be exposed at the model’s input and output to utilize it during quantization deployment.

```
def forward(self, input: Tensor) -> Tensor:
    # input [B, C, T] -> output [B, C, T]
    input = self.prev_conv(input)
    out1 = self.layer[0](input)
    out1 = F.pad(out1, (self.padding, 0), "constant", 0)
    out1 = self.layer[1](out1)
    out2 = self.layer[2](out1)
    output = self.layer[3](out1 * out2) + input
    return output

def streaming_forward(self, input: Tensor, cache: Tensor) -> Tuple[Tensor, Tensor]:
    # input [B, C, T] -> output [B, C, T]
    input = self.prev_conv(input)
    out1 = self.layer[0](input)
    # 1D Depthwise Conv
    assert cache.shape == (out1.size(0), out1.size(1), self.padding), (
        cache.shape,
        (out1.size(0), out1.size(1), self.padding),
    )
    out1 = torch.cat([cache, out1], dim=2)
    # Update cache
    cache = out1[:, :, -self.padding :]

    out1 = self.layer[1](out1)
    out2 = self.layer[2](out1)
    output = self.layer[3](out1 * out2) + input
    return output, cache
```

Finally, since PyTorch defaults to calling the `forward` method, the `streaming_forward` method needs to be wrapped to make it callable during quantization. See quantize_streaming_model.py for the following code block:

```
class ModelStreamingWrapper(nn.Module):
    """A wrapper for model"""

    def __init__(self, model: nn.Module):
        """
        Args:
        model: A pytorch model.
        """
        super().__init__()
```

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```
        self.model = model

    def forward(
        self, input: Tensor, cache: Optional[Tensor] = None
    ) -> Union[Tensor, Tuple[Tensor, Tensor]]:
        """Please see the help information of TestModel_0.streaming_forward"""

        if cache is not None:
            output, new_cache = self.model.streaming_forward(input, cache)
            return output, new_cache
        else:
            output = self.model.streaming_forward(input)
            return output
```

How to Prepare the Calibration Dataset

The calibration dataset must match the input format of your model. The dataset should cover as many possible input scenarios as possible to ensure better model quantization. For streaming mode, the input is a time-dimension slice of the offline mode's input. If there is a cache buffer, you need to call the model's forward method to collect the corresponding cache data for all input slices. See quantize_streaming_model.py for the following code block:

```
def load_calibration_dataset(self) -> Iterable:
    if self.streaming:
        data_total = []
        if self.model_config.get("streaming_cache_shape", []):
            caches = []
            caches.append(
                torch.zeros(size=self.model_config["streaming_cache_shape"][1:])
            )
            if not self.multi_input:
                for data in self.dataset:
                    # Ensure that the size of the W dimension is divisible by self.
↪streaming_window_size.
                    # Split the input and collect cache data.
                    split_tensors = torch.split(
                        data[0] if isinstance(data, tuple) else data,
                        self.streaming_window_size,
                        dim=1,
                    )
                    for index, split_tensor in enumerate(split_tensors):
                        _, cache = self.model(
                            split_tensor.unsqueeze(0), caches[index].unsqueeze(0)
                        )
                        caches.append(cache.squeeze(0))

                    data_total += [
                        list(pair) for pair in zip(list(split_tensors), caches)
                    ]
            else:
                # It depends on which inputs of the model require streaming, so␣
↪multiple inputs have not been added.
                pass

            return data_total
        else:
            if not self.multi_input:
                for data in self.dataset:
                    # Ensure that the size of the W dimension is divisible by self.
↪streaming_window_size.
```

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```
                    # Split the input and collect cache data.
                    split_tensors = torch.split(
                        data[0] if isinstance(data, tuple) else data,
                        self.streaming_window_size,
                        dim=1,
                    )
                    data_total += list(split_tensors)
            else:
                pass

            return data_total
    else:
        return self.dataset
```

3.8.3 Model Deployment

Reference example , this example uses pre-generated data to simulate a real-time data stream.

Note: For basic model loading and inference methods, please refer to other documents:

- *How to Load and Test a Model*
- *How to Perform Model Inference*

In streaming mode, the model receives data frame by frame (or block by block), processes it in real-time, and outputs intermediate results. That is, each frame of data sequentially flows through one module at a time. See app_main.cpp for the following code block:

```
for (int i = 0; i < TIME_SERIES_LENGTH; i++) {
    one_step_input_tensor->set_element_ptr(const_cast<int8_t *>(&test_
↪inputs[i][0]));
    // Because the first layer of model_0 in the example is conv, so the time␣
↪series dimension is 1.
    input_tensor->push(one_step_input_tensor, 1);

    if (i < (input_tensor->get_shape()[1] - 1)) {
        // The data is populated to facilitate accuracy testing, as this step is␣
↪omitted in actual deployment.
        continue;
    } else {
        switch (step_index) {
        case 1:
            output = (*p_model_0)(input_tensor);
            step_index++;
            break;
        case 2:
            output = (*p_model_1)(output);
            step_index++;
            break;
        case 3:
            output = (*p_model_2)(output);
            dl::tool::copy_memory(output_buffer + (i / 3 - 1) * STREAMING_WINDOW_
↪SIZE * TEST_INPUT_CHANNELS,
                                  output->data,
                                  STREAMING_WINDOW_SIZE * TEST_INPUT_CHANNELS);
            step_index = 1;
            break;
        default:
            break;
```

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```
        }
    }
}
```

The following part of the code block is included solely to align the offline accuracy during precision testing. It can be omitted during actual deployment.

```
if (i < (input_tensor->get_shape()[1] - 1)) {
    // The data is populated to facilitate accuracy testing, as this step is␣
↪omitted in actual deployment.
    continue;
}
```

As shown above, a frame of data is processed in one module per time step, and the loop repeatedly implements streaming processing.

Note:

- When pushing frame data to the temporary TensorBase, ensure the data types match.
- ESP-DL requires the input/output data layout for Conv, GlobalAveragePool, AveragePool, MaxPool, and Resize to be NHWC or NWC. Therefore, adjust the input data layout according to the first operator of the streaming model when feeding data to the model.

Chapter 4

API Reference

4.1 Tensor API Reference

Tensor is the fundamental data type in esp-dl, used for storing multi-type data such as int8, int16, float, etc., similar to the tensor in PyTorch. We have implemented some common tensor operations. Please refer to the following APIs for details.

4.1.1 Header File

- esp-dl/dl/tensor/include/dl_tensor_base.hpp

4.1.2 Classes

class **`TensorBase`**

This class is designed according to PyTorch Tensor. *TensorBase* is required to ensure that the first address are aligned to 16 bytes and the memory size should be a multiple of 16 bytes.

TODO:: Implement more functions

Public Functions

`TensorBase` (std::vector<int> shape, const void *element, int exponent = 0, dtype_t dtype = DATA_TYPE_FLOAT, bool deep = true, uint32_t caps = MALLOC_CAP_DEFAULT)

Construct a *TensorBase* object.

Parameters

- **`shape`** –Shape of tensor
- **`element`** –Pointer of data
- **`exponent`** –Exponent of tensor, default is 0
- **`dtype`** –Data type of element, default is float
- **`deep`** –True: malloc memory and copy data, false: use the pointer directly
- **`caps`** –Bitwise OR of MALLOC_CAP_* flags indicating the type of memory to be returned

inline virtual **`~TensorBase`** ()

Destroy the *TensorBase* object.

bool **assign** (*TensorBase* *tensor)

Assign tensor to this tensor.

Parameters **tensor** –

Returns ture if assign successfully, otherwise false.

bool **assign** (std::vector<int> shape, const void *element, int exponent, dtype_t dtype)

Assign data to this tensor.

Parameters

- **shape** –
- **element** –
- **exponent** –
- **dtype** –

Returns ture if assign successfully, otherwise false.

inline int **get_size** ()

Get the size of Tensor.

Returns the size of Tensor.

inline int **get_aligned_size** ()

Get the aligned size of Tensor.

Returns the aligned size of Tensor.

inline size_t **get_dtype_bytes** ()

Get the dtype size, in bytes.

Returns the size of dtype.

inline const char ***get_dtype_string** ()

Get the dtype string of Tensor.

Returns the string of Tensor's dtype.

inline int **get_bytes** ()

Get the bytes of Tensor.

Returns the bytes of Tensor.

inline int **get_aligned_bytes** ()

Get the bytes of Tensor.

Returns the bytes of Tensor.

inline virtual void ***get_element_ptr** ()

Get data pointer. If cache(preload data pointer) is not null, return cache pointer, otherwise return data pointer.

Returns the pointer of Tensor's data

template<typename **T**>
inline *T* ***get_element_ptr** ()

Get data pointer by the specified template. If cache(preload data pointer) is not null, return cache pointer, otherwise return data pointer.

Returns the pointer of Tensor's data

TensorBase &**set_element_ptr** (void *data)

Set the data pointer of Tensor.

Parameters **data** –point to data memory

Returns *TensorBase*& self

inline std::vector<int> **get_shape** ()

Get the shape of Tensor.

Returns std::vector<int> the shape of Tensor

TensorBase &**set_shape** (const std::vector<int> shape)

Set the shape of Tensor.

Parameters **shape** –the shape of Tensor.
Returns Tensor.

inline int **get_exponent** ()

Get the exponent of Tensor.

Returns int the exponent of Tensor

inline dtype_t **get_dtype** ()

Get the data type of Tensor.

Returns dtype_t the data type of Tensor

inline uint32_t **get_caps** ()

Get the memory flags of Tensor.

Returns uint32_t the memory flags of Tensor

TensorBase ***reshape** (std::vector<int> shape)

Change a new shape to the Tensor without changing its data.

Parameters **shape** –the target shape
Returns *TensorBase* *self

template<typename **T**>
TensorBase ***flip** (const std::vector<int> &axes)

Flip the input Tensor along the specified axes.

Parameters **axes** –the specified axes
Returns *TensorBase*& self

TensorBase ***transpose** (*TensorBase* *input, std::vector<int> perm = {})

Reverse or permute the axes of the input Tensor.

Parameters
- **input** –the input Tensor
- **perm** –the new arangement of the dims. if perm == {}, the dims arangement will be reversed.

Returns *TensorBase* *self

template<typename **T**>
TensorBase ***transpose** (*T* *input_element, std::vector<int> &input_shape, std::vector<int> &input_axis_offset, std::vector<int> &perm)

Reverse or permute the axes of the input Tensor.

Parameters
- **input_element** –the input data pointer
- **input_shape** –the input data shape
- **input_axis_offset** –the input data axis offset
- **perm** –the new arangement of the dims. if perm == {}, the dims arangement will be reversed.

Returns *TensorBase* *self

bool **is_same_shape** (*TensorBase* *tensor)

Check the shape is the same as the shape of input.

Parameters **tensor** –Input tensor pointer

Returns
- true: same shape
- false: not

bool **equal** (*TensorBase* *tensor, float epsilon = 1e-6, bool verbose = false)

Compare the shape and data of two Tensor.

Parameters
- **tensor** –Input tensor
- **epsilon** –The max error of two element
- **verbose** –If true, print the detail of results

Returns true if two tensor is equal otherwise false

TensorBase ***slice** (const std::vector<int> &start, const std::vector<int> &end, const std::vector<int> &axes = { }, const std::vector<int> &step = { })

Produces a slice of the this tensor along multiple axes.

> **Warning:** The length of start, end and step must be same as the shape of input tensor

Parameters
- **start** –Starting indicesd
- **end** –Ending indices
- **axes** –Axes that starts and ends apply to.
- **step** –Slice step, step = 1 if step is not specified

Returns TensorBase* Output tensor pointer, created by this slice function

template<typename **T**>
TensorBase ***pad** (*T* *input_element, const std::vector<int> &input_shape, const std::vector<int> &pads, const padding_mode_t mode, *TensorBase* *const_value = nullptr)

Pad input tensor.

Parameters
- **input_element** –Data pointer of input tensor
- **input_shape** –Shape of input tensor
- **pads** –The number of padding elements to add, pads format should be: [x1_begin, x2_begin, ⋯, x1_end, x2_end, ⋯]
- **mode** –Supported modes: constant(default), reflect, edge
- **const_value** –(Optional) A scalar value to be used if the mode chosen is constant

Returns Output tensor pointer

TensorBase ***pad** (*TensorBase* *input, const std::vector<int> &pads, const padding_mode_t mode, *TensorBase* *const_value = nullptr)

Pad input tensor.

Parameters
- **input** –Input tensor pointer
- **pads** –Padding elements to add, pads format should be: [x1_begin, x2_begin, ⋯, x1_end, x2_end, ⋯]
- **mode** –Supported modes: constant(default), reflect, edge
- **const_value** –(Optional) A scalar value to be used if the mode chosen is constant

Returns Output tensor pointer

template<typename **T**>
bool **compare_elements** (const *T* *gt_elements, float epsilon = 1e-6, bool verbose = false)

Compare the elements of two Tensor.

Parameters
- **gt_elements** –The ground truth elements
- **epsilon** –The max error of two element

- **verbose** –If true, print the detail of results

Returns true if all elements are equal otherwise false

int **get_element_index** (const std::vector<int> &axis_index)

Get the index of element.

Parameters **axis_index** –The coordinates of element

Returns int the index of element

std::vector<int> **get_element_coordinates** (int index)

Get the coordinates of element.

Parameters **index** –The index of element

Returns The coordinates of element

template<typename **T**>

T **get_element** (int index)

Get a element of Tensor by index.

Parameters **index** –The index of element

Returns The element of tensor

template<typename **T**>

T **get_element** (const std::vector<int> &axis_index)

Get a element of Tensor.

Parameters **axis_index** –The index of element

Returns The element of tensor

size_t **set_preload_addr** (void *addr, size_t size)

Set preload address of Tensor.

Parameters

- **addr** –The address of preload data
- **size** –Size of preload data

Returns The size of preload data

inline virtual void **preload** ()

Preload the data of Tensor.

void **reset_bias_layout** (quant_type_t op_quant_type, bool is_depthwise)

Reset the layout of Tensor.

> **Warning:** Only available for Convolution. Don't use it unless you know exactly what it does.

Parameters

- **op_quant_type** –The quant type of operation
- **is_depthwise** –Whether is depthwise convolution

void **push** (*TensorBase* *new_tensor, int dim)

Push new_tensor to current tensor. The time series dimension size of new tensor must is lesser or equal than that of the current tensor." .

Parameters

- **new_tensor** –The new tensor will be pushed
- **dim** –Specify the dimension on which to perform streaming stack pushes

virtual void **print** (bool print_data = false)

print the information of *TensorBase*

Parameters **print_data** –Whether print the data

Public Members

int **size**

size of element including padding

std::vector<int> **shape**

shape of Tensor

dtype_t **dtype**

data type of element

int **exponent**

exponent of element

bool **auto_free**

free element when object destroy

std::vector<int> **axis_offset**

element offset of each axis

void *__data__

data pointer

void *__cache__

cache pointer，used for preload and do not need to free

uint32_t **caps**

flags indicating the type of memory

Public Static Functions

static void **slice** (*TensorBase* *input, *TensorBase* *output, const std::vector<int> &start, const std::vector<int> &end, const std::vector<int> &axes = {}, const std::vector<int> &step = {})

Produces a slice along multiple axes.

> **Warning:** The length of start, end and step must be same as the shape of input tensor

Parameters

- **input** –Input Tensor
- **output** –Output Tensor
- **start** –Starting indicesd
- **end** –Ending indices
- **axes** –Axes that starts and ends apply to.
- **step** –Slice step, step = 1 if step is not specified

4.2 Module API Reference

The Module is the base class for operators in esp-dl, and all operators inherit from this base class. This base class defines the basic interfaces for operators, enabling the model layer to automatically execute operators and manage memory planning.

4.2.1 Header File

- esp-dl/dl/module/include/dl_module_base.hpp

4.2.2 Classes

class **Module**

Base class for module.

Public Functions

Module (const char *name = NULL, module_inplace_t inplace = MODULE_NON_INPLACE, quant_type_t quant_type = QUANT_TYPE_NONE)

Construct a new *Module* object.

Parameters
- **name** –Name of module.
- **inplace** –Inplace operation mode
- **quant_type** –Quantization type

virtual **~Module** ()

Destroy the *Module* object. Return resource.

inline virtual std::vector<int> **get_outputs_index** ()

Get the tensor index of this module' s outputs.

Returns Tensor index of model' s tensors

virtual std::vector<std::vector<int>> **get_output_shape** (std::vector<std::vector<int>> &input_shapes) = 0

Calculate output shape by input shape.

Parameters **input_shapes** –Input shapes
Returns outputs shapes

virtual void **forward** (*ModelContext* *context, runtime_mode_t mode = RUNTIME_MODE_AUTO) = 0

Build the module, high-level inferface for *Module* layer.

Parameters
- **context** –*Model* context including all inputs and outputs and other runtime information
- **mode** –Runtime mode, default is RUNTIME_MODE_AUTO

inline virtual void **forward_args** (void *args)

Run the module, Low-level interface for base layer and multi-core processing.

Parameters **args** –ArgsType, arithArgsType, resizeArgsType and so on

inline virtual void **print** ()

print module information

inline virtual void **set_preload_addr** (void *addr, size_t size)

set preload RAM pointer

Parameters

- **addr** –Internal RAM address, should be aligned to 16 bytes
- **size** –The size of RAM address

inline virtual void **preload** ()

Perform a preload operation.

> **Warning:** Not implemented

inline virtual void **reset** ()

reset all state of module, include inputs，outputs and preload cache setting

virtual void **run** (*TensorBase* *input, *TensorBase* *output, runtime_mode_t mode = RUNTIME_MODE_SINGLE_CORE)

Run the module with single input and single output.

Parameters

- **input** –Input tensor
- **output** –Output tensor
- **mode** –Runtime mode

virtual void **run** (std::vector<dl::*TensorBase**> inputs, std::vector<dl::*TensorBase**> outputs, runtime_mode_t mode = RUNTIME_MODE_SINGLE_CORE)

Run the module by inputs and outputs.

Parameters

- **inputs** –Input tensors
- **outputs** –Output tensors
- **mode** –Runtime mode

Public Members

char ***name**

Name of module.

module_inplace_t **inplace**

Inplace type.

quant_type_t **quant_type**

Quantization type.

std::vector<int> **m_inputs_index**

Tensor index of model’s tensors that used for inputs.

std::vector<int> **m_outputs_index**

Tensor index of model’s tensors that used for outputs.

Public Static Functions

static inline *Module* ***deserialize**(fbs::*FbsModel* *fbs_model, std::string node_name)

create module instance by node serialization information

Parameters
- **fbs_model** –Flatbuffer's model
- **node_name** –The node name in model's graph

Returns The pointer of module instance

4.2.3 Header File

- esp-dl/dl/module/include/dl_module_creator.hpp

4.2.4 Classes

class **ModuleCreator**

Singleton class for registering modules.

Public Types

using **Creator** = std::function<*Module**(fbs::*FbsModel**, std::string)>

Module creator function type.

Public Functions

inline void **register_module**(const std::string &op_type, *Creator* creator)

Register a module creator to the module creator map This function allows for the dynamic registration of new module types and their corresponding creator functions at runtime. By associating the module type name with the creator function, the system can flexibly create instances of various modules.

Parameters
- **op_type** –The module type name, used as the key in the map
- **creator** –The module creator function, used to create modules of a specific type

inline *Module* ***create**(fbs::*FbsModel* *fbs_model, const std::string &op_type, const std::string name)

Create module instance pointer.

Parameters
- **fbs_model** –Flatbuffer model pointer
- **op_type** –Module/Operator type
- **name** –*Module* name

Returns *Module* instance pointer

inline void **register_dl_modules**()

Pre-register the already implemented modules.

inline void **print**()

Print all modules has been registered.

inline void **clear**()

Clear all modules has been registered.

Public Static Functions

static inline *ModuleCreator* ***get_instance**()

Get instance of *ModuleCreator* by this function. It is only safe method to get instance of *ModuleCreator* becase *ModuleCreator* is a singleton class.

Returns *ModuleCreator* instance pointer

4.3 Model API Reference

This section covers model loading and static memory planning, making it convenient for users to directly load and run ESPDL models.

4.3.1 Header File

- esp-dl/dl/model/include/dl_model_base.hpp

4.3.2 Macros

DL_LOG_INFER_LATENCY_INIT_WITH_SIZE(size)

DL_LOG_INFER_LATENCY_INIT()

DL_LOG_INFER_LATENCY_START()

DL_LOG_INFER_LATENCY_END()

DL_LOG_INFER_LATENCY_PRINT(prefix, key)

DL_LOG_INFER_LATENCY_END_PRINT(prefix, key)

DL_LOG_INFER_LATENCY_ARRAY_INIT_WITH_SIZE(n, size)

DL_LOG_INFER_LATENCY_ARRAY_INIT(n)

DL_LOG_INFER_LATENCY_ARRAY_START(i)

DL_LOG_INFER_LATENCY_ARRAY_END(i)

DL_LOG_INFER_LATENCY_ARRAY_PRINT(i, prefix, key)

DL_LOG_INFER_LATENCY_ARRAY_END_PRINT(i, prefix, key)

4.3.3 Classes

class **Model**

Neural Network *Model*.

Public Functions

Model (const char *rodata_address_or_partition_label_or_path, fbs::model_location_type_t location = fbs::MODEL_LOCATION_IN_FLASH_RODATA, int max_internal_size = 0, memory_manager_t mm_type = MEMORY_MANAGER_GREEDY, const uint8_t *key = nullptr, bool param_copy = true)

Create the *Model* object by rodata address or partition label.

Parameters

- **rodata_address_or_partition_label_or_path** –The address of model data while location is MODEL_LOCATION_IN_FLASH_RODATA. The label of partition while location is MODEL_LOCATION_IN_FLASH_PARTITION. The path of model while location is MODEL_LOCATION_IN_SDCARD.
- **location** –The model location.
- **max_internal_size** –In bytes. Limit the max internal size usage. Only take effect when there's a PSRAM, and you want to alloc memory on internal RAM first.
- **mm_type** –Type of memory manager
- **key** –The key of encrypted model.
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Model (const char *rodata_address_or_partition_label_or_path, int model_index, fbs::model_location_type_t location = fbs::MODEL_LOCATION_IN_FLASH_RODATA, int max_internal_size = 0, memory_manager_t mm_type = MEMORY_MANAGER_GREEDY, const uint8_t *key = nullptr, bool param_copy = true)

Create the *Model* object by rodata address or partition label.

Parameters

- **rodata_address_or_partition_label_or_path** –The address of model data while location is MODEL_LOCATION_IN_FLASH_RODATA. The label of partition while location is MODEL_LOCATION_IN_FLASH_PARTITION. The path of model while location is MODEL_LOCATION_IN_SDCARD.
- **model_index** –The model index of packed models.
- **location** –The model location.
- **max_internal_size** –In bytes. Limit the max internal size usage. Only take effect when there's a PSRAM, and you want to alloc memory on internal RAM first.
- **mm_type** –Type of memory manager
- **key** –The key of encrypted model.
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Model (const char *rodata_address_or_partition_label_or_path, const char *model_name, fbs::model_location_type_t location = fbs::MODEL_LOCATION_IN_FLASH_RODATA, int max_internal_size = 0, memory_manager_t mm_type = MEMORY_MANAGER_GREEDY, const uint8_t *key = nullptr, bool param_copy = true)

Create the *Model* object by rodata address or partition label.

Parameters

- **rodata_address_or_partition_label_or_path** –The address of model data while location is MODEL_LOCATION_IN_FLASH_RODATA. The label of partition while location is MODEL_LOCATION_IN_FLASH_PARTITION. The path of model while location is MODEL_LOCATION_IN_SDCARD.
- **model_name** –The model name of packed models.
- **location** –The model location.

- **max_internal_size** –In bytes. Limit the max internal size usage. Only take effect when there's a PSRAM, and you want to alloc memory on internal RAM first.
- **mm_type** –Type of memory manager
- **key** –The key of encrypted model.
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Model (fbs::*FbsModel* *fbs_model, int internal_size = 0, memory_manager_t mm_type = MEMORY_MANAGER_GREEDY)

Create the *Model* object by fbs_model.

Parameters
- **fbs_model** –The fbs model.
- **internal_size** –Internal ram size, in bytes
- **mm_type** –Type of memory manager

virtual **~Model** ()

Destroy the *Model* object.

virtual esp_err_t **load** (const char *rodata_address_or_partition_label_or_path, fbs::model_location_type_t location = fbs::MODEL_LOCATION_IN_FLASH_RODATA, const uint8_t *key = nullptr, bool param_copy = true)

Load model graph and parameters from FLASH or sdcard.

Parameters
- **rodata_address_or_partition_label_or_path** –The address of model data while location is MODEL_LOCATION_IN_FLASH_RODATA. The label of partition while location is MODEL_LOCATION_IN_FLASH_PARTITION. The path of model while location is MODEL_LOCATION_IN_SDCARD.
- **location** –The model location.
- **key** –The key of encrypted model.
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Returns
- ESP_OK Success
- ESP_FAIL Failed

virtual esp_err_t **load** (const char *rodata_address_or_partition_label_or_path, fbs::model_location_type_t location = fbs::MODEL_LOCATION_IN_FLASH_RODATA, int model_index = 0, const uint8_t *key = nullptr, bool param_copy = true)

Load model graph and parameters from FLASH or sdcard.

Parameters
- **rodata_address_or_partition_label_or_path** –The address of model data while location is MODEL_LOCATION_IN_FLASH_RODATA. The label of partition while location is MODEL_LOCATION_IN_FLASH_PARTITION. The path of model while location is MODEL_LOCATION_IN_SDCARD.
- **location** –The model location.
- **model_index** –The model index of packed models.
- **key** –The key of encrypted model.
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very

tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Returns

- ESP_OK Success
- ESP_FAIL Failed

virtual esp_err_t **load** (const char *rodata_address_or_partition_label_or_path, fbs::model_location_type_t location = fbs::MODEL_LOCATION_IN_FLASH_RODATA, const char *model_name = nullptr, const uint8_t *key = nullptr, bool param_copy = true)

Load model graph and parameters from FLASH or sdcard.

Parameters

- **`rodata_address_or_partition_label_or_path`** –The address of model data while location is MODEL_LOCATION_IN_FLASH_RODATA. The label of partition while location is MODEL_LOCATION_IN_FLASH_PARTITION. The path of model while location is MODEL_LOCATION_IN_SDCARD.
- **`location`** –The model location.
- **`model_name`** –The model name of packed models.
- **`key`** –The key of encrypted model.
- **`param_copy`** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Returns

- ESP_OK Success
- ESP_FAIL Failed

virtual esp_err_t **load** (fbs::*FbsModel* *fbs_model)

Load model graph and parameters from Flatbuffers model.

Parameters **`fbs_model`** –The FlatBuffers model

Returns

- ESP_OK Success
- ESP_FAIL Failed

virtual void **build** (size_t max_internal_size, memory_manager_t mm_type = MEMORY_MANAGER_GREEDY, bool preload = false)

Allocate memory for the model.

Parameters

- **`max_internal_size`** –In bytes. Limit the max internal size usage. Only take effect when there’s a PSRAM, and you want to alloc memory on internal RAM first.
- **`mm_type`** –Type of memory manager
- **`preload`** –Whether to preload the model’s parameters to internal ram (not implemented yet)

virtual void **run** (runtime_mode_t mode = RUNTIME_MODE_SINGLE_CORE)

Run the model module by module.

Parameters **`mode`** –Runtime mode.

virtual void **run** (*TensorBase* *input, runtime_mode_t mode = RUNTIME_MODE_SINGLE_CORE)

Run the model module by module.

Parameters

- **`input`** –The model input.
- **`mode`** –Runtime mode.

virtual void **run** (std::map<std::string, *TensorBase**> &user_inputs, runtime_mode_t mode = RUNTIME_MODE_SINGLE_CORE, std::map<std::string, *TensorBase**> user_outputs = {})

Run the model module by module.

Parameters
- **user_inputs** –The model inputs.
- **mode** –Runtime mode.
- **user_outputs** –It's for debug to pecify the output of the intermediate layer; Under normal use, there is no need to pass a value to this parameter. If no parameter is passed, the default is the graphical output, which can be obtained through *Model::get_outputs()*.

void **minimize** ()

Minimize the model.

esp_err_t **test** ()

Test whether the model inference result is correct. The model should contain test_inputs and test_outputs. Enable export_test_values option in esp-ppq to use this api.

Returns esp_err_t

std::map<std::string, mem_info_t> **get_memory_info** ()

Get memory info.

Returns Memory usage statistics on internal and PSRAM.

std::map<std::string, module_info> **get_module_info** ()

Get module info.

Returns return Type and latency of each module.

void **print_module_info** (const std::map<std::string, module_info> &info, bool sort_module_by_latency = false)

Print the module info obtained by get_module_info function.

Parameters
- **info** –
- **sort_module_by_latency** –

void **profile_memory** ()

Print model memory summary.

void **profile_module** (bool sort_module_by_latency = false)

Print module info summary. (Name, Type, Latency)

Parameters **sort_module_by_latency** –True The module is printed in latency decreasing sort. False The module is printed in ONNX topological sort.

void **profile** (bool sort_module_by_latency = false)

Combination of profile_memory & profile_module.

Parameters **sort_module_by_latency** –True The module is printed in latency decreasing sort. False The module is printed in ONNX topological sort.

virtual std::map<std::string, *TensorBase**> &**get_inputs** ()

Get inputs of model.

Returns The map of model input's name and TensorBase*

virtual *TensorBase* ***get_input** ()

Get the only input of model.

Returns TensorBase*

virtual *TensorBase* ***get_input*** (const std::string &name)

Get input of model by name.

Parameters **name** –input name

Returns TensorBase*

virtual *TensorBase* ***get_intermediate*** (const std::string &name)

Get intermediate *TensorBase* of model.

Note: When using memory manager, the content of *TensorBase*' s data may be overwritten by the outputs of other

---

Parameters **name** –The name of intermediate Tensor. operators.

Returns The intermediate TensorBase*.

virtual std::map<std::string, *TensorBase**> &**get_outputs** ()

Get outputs of model.

Returns The map of model output' s name and TensorBase*

virtual *TensorBase* ***get_output*** ()

Get the only output of model.

Returns TensorBase*

virtual *TensorBase* ***get_output*** (const std::string &name)

Get output of model by name.

Parameters **name** –output name

Returns TensorBase*

std::string **get_metadata_prop** (const std::string &key)

Get the model' s metadata prop.

Parameters **key** –The key of metadata prop

Returns The value of metadata prop

virtual void **print** ()

Print the model.

inline virtual fbs::*FbsModel* ***get_fbs_model*** ()

Get the fbs model instance.

Returns *fbs::FbsModel* *

4.3.4 Header File

- esp-dl/dl/model/include/dl_model_context.hpp

4.3.5 Macros

CONTEXT_PARAMETER_OFFSET

Offset for parameter tensors

4.3.6 Classes

class **ModelContext**

Model Context class including variable tensors and parameters.

Public Functions

inline **ModelContext**()

Constructor for *ModelContext*. Initializes the PSRAM and internal root pointers to nullptr.

inline **~ModelContext**()

Destructor for *ModelContext*. Clears all resources and tensors.

int **add_tensor**(const std::string name, bool is_paramter = false, *TensorBase* *tensor = nullptr)

Adds a tensor to the parameter or variable list.

Parameters
- **name** –The name of the tensor.
- **is_paramter** –Whether the tensor is a parameter (default: false).
- **tensor** –Pointer to the *TensorBase* object (default: nullptr).

Returns int Returns the index of the added tensor.

int **push_back_tensor**(*TensorBase* *tensor, bool is_paramter = false)

Push back a tensor.

Parameters
- **tensor** –Pointer to the *TensorBase* object.
- **is_paramter** –Whether the tensor is a parameter (default: false).

Returns int Returns the index of the added tensor.

void **update_tensor**(int index, *TensorBase* *tensor)

Updates the tensor at the specified index.

Parameters
- **index** –The index of the tensor to update.
- **tensor** –Pointer to the new *TensorBase* object.

TensorBase ***get_tensor**(int index)

Gets the tensor by its index.

Parameters **index** –The index of the tensor.

Returns TensorBase* Returns the pointer to the *TensorBase* object, or nullptr if the index is invalid.

TensorBase ***get_tensor**(const std::string &name)

Gets the tensor by its name.

Parameters **name** –The name of the tensor.

Returns TensorBase* Returns the pointer to the *TensorBase* object, or nullptr if the name is not found.

int **get_tensor_index**(const std::string &name)

Gets the tensor index by its name.

Parameters **name** –The name of the tensor.

Returns int Returns index if the name is found, else -1

int **get_variable_index**(const std::string &name)

Gets the variable tensor index by its name.

Parameters **name** –The name of the tensor.

Returns int Returns index if the name is found and is variable tensor, else -1 inline int **get_variable_count** ()

Gets the count of variable tensors.

Returns int Returns the number of variable tensors.

inline int **get_parameter_count** ()

Gets the count of parameter tensors.

Returns int Returns the number of parameter tensors.

bool **root_alloc** (size_t internal_size, size_t psram_size, int alignment = 16)

Allocates memory for PSRAM and internal roots.

Parameters
- **internal_size** –The size of the internal memory in bytes.
- **psram_size** –The size of the PSRAM memory in bytes.
- **alignment** –The alignment of the memory in bytes.

Returns Bool Return true if the allocation is successful, false otherwise.

inline void ***get_psram_root** ()

Gets the pointer to the PSRAM root.

Returns Void* Returns the pointer to the PSRAM root.

inline void ***get_internal_root** ()

Gets the pointer to the internal root.

Returns Void* Returns the pointer to the internal root.

size_t **get_parameter_memory_size** (mem_info_t &mem_info, bool copy)

Gets the size of the parameters in bytes.

Parameters
- **mem_info** –The size of the memory used by the parameters in bytes, filtered by copy option.
- **copy** –Filter the parameters by auto_free.

Returns size_t Returns the total size of the parameters memory in bytes.

size_t **get_variable_memory_size** (mem_info_t &mem_info)

Get the variable memory size object.

Parameters **mem_info** –The size of the memory used by the variables in bytes.

Returns size_t Returns the total size of the variables memory in bytes.

inline void **root_free** ()

Frees the memory allocated for PSRAM and internal roots. This function ensures proper cleanup of allocated memory.

inline void **minimize** ()

Minimizes the context by clearing the name-to-index map. This is used to free unnecessary intermediate variables during the inference.

inline void **clear** ()

Clears all resources and tensors in the context. This includes clearing variables, parameters, name-to-index map, and freeing memory.

Public Members

std::vector<*TensorBase**> **m_variables**

Variable tensors of model, the first one is nullptr std::vector<*TensorBase**> **m_parameters**

Parameters of model, the first one is nullptr

4.3.7 Header File

- esp-dl/dl/model/include/dl_memory_manager.hpp

4.3.8 Classes

class **MemoryManagerBase**

Memory manager base class, each model has its own memory manager TODO: share memory manager with different models.

Subclassed by *dl::MemoryManagerGreedy*

Public Functions

inline **MemoryManagerBase** (int alignment = 16)

Construct a new Memory Manager Base object.

Parameters **alignment** –Memory address alignment

inline virtual **~MemoryManagerBase** ()

Destroy the MemoryManager object. Return resource.

virtual bool **alloc** (fbs::*FbsModel* *fbs_model, std::vector<dl::module::*Module**> &execution_plan, *ModelContext* *context) = 0

Allocate memory for each tensor, include all input and output tensors.

Parameters
- **fbs_model** –FlatBuffer' s *Model*
- **execution_plan** –Topological sorted module list
- **context** –*Model* context

Returns Bool Return true if the allocation is successful, false otherwise.

Public Members

int **alignment**

The root pointer needs to be aligned must be a power of two

class **TensorInfo**

Tensor info, include tensor name, shape, dtype, size, time range and call times, which is used to plan model memory.

Public Functions

TensorInfo (std::string &name, int time_begin, int time_end, std::vector<int> shape, dtype_t dtype, int exponent, bool is_internal = false)

Construct a new Tensor Info object.

Parameters
- **name** –Tensor name

- **time_begin** –Tensor lifetime begin
- **time_end** –Tensor lifetime end
- **shape** –Tensor shape
- **dtype** –Tensor dtype
- **exponent** –Tensor exponent
- **is_internal** –Is tensor in internal RAM or not

inline **~TensorInfo**()

Destroy the Tensor Info object.

void **set_inplace_leader_tensor**(*TensorInfo* *tensor)

Set the inplace leader tensor object.

Parameters **tensor** –Inplace leader tensor

inline void **set_inplace_follower_tensor**(*TensorInfo* *tensor)

Set the inplace follower tensor object.

Parameters **tensor** –Inplace follower tensor

inline *TensorInfo* ***get_inplace_follower_tensor**()

Get the inplace follower tensor object.

Returns TensorInfo* Inplace follower tensor

void **update_time**(int new_time)

Update Tensor lifetime.

Parameters **new_time** –new tensor lifetime

TensorBase ***create_tensor**(void *internal_root, void *psram_root)

Create a *TensorBase* object according to *TensorInfo*.

Parameters

- **internal_root** –Internal RAM root pointer
- **psram_root** –PSRAM root pointer

Returns TensorBase*

inline bool **is_inplaced**()

Is inplaced or not.

Returns true if inplaced else false

inline uint32_t **get_offset**()

Get the tensor offset.

Returns uint32_t

inline void **set_offset**(uint32_t offset)

Set the tensor offset.

Parameters **offset** –

inline uint32_t **get_internal_offset**()

Get the internal offset.

Returns uint32_t

inline bool **get_internal_state**()

Get the internal state.

Returns true if is internal else false

inline void **set_internal_state**(bool is_internal)

Set the internal state.

Parameters **is_internal** –

inline void **set_internal_offset** (uint32_t offset)

Set the internal offset.

Parameters **offset** –

inline int **get_time_end** ()

Get the liftetime end.

Returns int

inline int **get_time_begin** ()

Get the liftetime begin.

Returns int

inline size_t **get_size** ()

Get the tensor size.

Returns size_t

inline std::string **get_name** ()

Get the tensor name.

Returns std::string

inline std::vector<int> **get_shape** ()

Get the tensor shape.

Returns std::vector<int>

inline void **print** ()

print tensor info

class **MemoryChunk**

Memory chunk, include size, is free, offset, alignment and tensor, which is used to simulate memory allocation.

Public Functions

MemoryChunk (size_t size, int is_free, int alignment = 16)

Construct a new Memory Chunk object.

Parameters

- **size** –Memory chunk size
- **is_free** –Whether free or not
- **alignment** –Memory chunk alignment

MemoryChunk (*TensorInfo* *tensor, int alignment = 16)

Construct a new Memory Chunk object.

Parameters

- **tensor** –*TensorInfo*
- **alignment** –Memory chunk alignment

inline **~MemoryChunk** ()

Destroy the Memory Chunk object.

MemoryChunk ***merge_free_chunk*** (*MemoryChunk* *chunk)

Merge continuous free chunk.

Parameters **chunk** –

Returns MemoryChunk*

MemoryChunk ***insert** (*TensorInfo* *tensor)

Insert tensor into free chunk.

Parameters **tensor** –

Returns MemoryChunk*

MemoryChunk ***extend** (*TensorInfo* *tensor)

Extend free chunk and insert tensor.

Parameters **tensor** –

Returns MemoryChunk*

inline void **free** ()

Free memory chunk, set is_free to true and set tensor to nullptr.

size_t **get_aligned_size** (size_t size)

get aligned size, which is 16/alignemt bytes aligned

Parameters **size** –

Returns size_t

Public Members

size_t **size**

Memeory chunk size

bool **is_free**

Whether memory chunk is free or not

int **offset**

Offset relative to root pointer

int **alignment**

Memory address alignment

TensorInfo ***tensor**

Info of the tensor which occupies the memory

4.3.9 Header File

- esp-dl/dl/model/include/dl_memory_manager_greedy.hpp

4.3.10 Classes

class **MemoryManagerGreedy** : public dl::*MemoryManagerBase*

Greedy memory manager that allocates memory for tensors in execution order, prioritizing internal RAM allocation first.

Public Functions

inline **MemoryManagerGreedy** (int max_internal_size, int alignment = 16)

Constructs a greedy memory manager with specified constraints.

Parameters
- **max_internal_size** –Maximum allowed internal RAM usage in bytes
- **alignment** –Memory address alignment requirement (default: 16 bytes)

inline **~MemoryManagerGreedy** ()

Destructor that releases all managed memory resources.

virtual bool **alloc** (fbs::*FbsModel* *fbs_model, std::vector<dl::module::*Module**> &execution_plan, *ModelContext* *context)

Allocates memory for all network tensors following greedy strategy.

Parameters
- **fbs_model** –FlatBuffer model containing network architecture
- **execution_plan** –Execution graph ordered by computation dependencies
- **context** –Device-specific runtime configuration

Returns bool True if successful allocation, false if memory insufficient

void **free** ()

Releases all allocated memory including tensor buffers and memory pools.

4.4 Fbs API Reference

The esp-dl model utilizes FlatBuffers to store information about parameters and the computation graph. Taking into account the encryption requirements of some models, this part has not been open-sourced. However, we provide a set of APIs to facilitate users in loading and parsing esp-dl models.

4.4.1 Header File

- esp-dl/fbs_loader/include/fbs_loader.hpp

4.4.2 Classes

class **FbsLoader**

Class for parser the flatbuffers.

Public Functions

FbsLoader (const char *rodata_address_or_partition_label_or_path = nullptr, model_location_type_t location = MODEL_LOCATION_IN_FLASH_RODATA)

Construct a new *FbsLoader* object.

Parameters
- **rodata_address_or_partition_label_or_path** –The address of model data while location is MODEL_LOCATION_IN_FLASH_RODATA. The label of partition while location is MODEL_LOCATION_IN_FLASH_PARTITION. The path of model while location is MODEL_LOCATION_IN_SDCARD.
- **location** –The model location.

~FbsLoader ()

Destroy the *FbsLoader* object.

FbsModel ***load**(const uint8_t *key = nullptr, bool param_copy = true)

Load the model. If there are multiple sub-models, the first sub-model will be loaded.

Parameters

- **key** –NULL or a 128-bit AES key, like {0x00, 0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07, 0x08, 0x09, 0x0a, 0x0b, 0x0c, 0x0d, 0x0e, 0x0f}
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Returns Return nullptr if loading fails. Otherwise return the pointer of *FbsModel*.

FbsModel ***load**(const int model_index, const uint8_t *key = nullptr, bool param_copy = true)

Load the model by model index.

Parameters

- **model_index** –The index of model.
- **key** –NULL or a 128-bit AES key, like {0x00, 0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07, 0x08, 0x09, 0x0a, 0x0b, 0x0c, 0x0d, 0x0e, 0x0f}.
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Returns Return nullptr if loading fails. Otherwise return the pointer of *FbsModel*.

FbsModel ***load**(const char *model_name, const uint8_t *key = nullptr, bool param_copy = true)

Load the model by model name.

Parameters

- **model_name** –The name of model.
- **key** –NULL or a 128-bit AES key, like {0x00, 0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07, 0x08, 0x09, 0x0a, 0x0b, 0x0c, 0x0d, 0x0e, 0x0f}
- **param_copy** –Set to false to avoid copy model parameters from FLASH to PSRAM. Only set this param to false when your PSRAM resource is very tight. This saves PSRAM and sacrifices the performance of model inference because the frequency of PSRAM is higher than FLASH. Only takes effect when MODEL_LOCATION_IN_FLASH_RODATA(CONFIG_SPIRAM_RODATA not set) or MODEL_LOCATION_IN_FLASH_PARTITION.

Returns Return nullptr if loading fails. Otherwise return the pointer of *FbsModel*.

int **get_model_num**()

Get the number of models.

Returns The number of models

void **list_models**()

List all model' s name.

const char ***get_model_location_string**()

Get the model location string.

Returns The model location string.

4.4.3 Header File

- esp-dl/fbs_loader/include/fbs_model.hpp

4.4.4 Classes

class **FbsModel**

Flatbuffer model object.

Public Functions

FbsModel (const void *data, size_t size, model_location_type_t location, bool encrypt, bool rodata_move, bool auto_free, bool param_copy)

Construct a new *FbsModel* object.

Parameters
- **data** –The data of model flatbuffers.
- **size** –The size of model flatbuffers in bytes.
- **location** –The location of model flatbuffers.
- **encrypt** –Whether the model flatbuffers is encrypted or not.
- **rodata_move** –Whether the model flatbuffers is moved from FLASH rodata to PSRAM.
- **auto_free** –Whether to free the model flatbuffers data when destroy this class instance.
- **param_copy** –Whether to copy the parameter in flatbuffers.

~FbsModel ()

Destroy the *FbsModel* object.

void **print** ()

Print the model information.

std::vector<std::string> **topological_sort** ()

Return vector of node name in the order of execution.

Returns topological sort of node name.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, int &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, float &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, std::string &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.

- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, std::vector<int> &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, std::vector<float> &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, dl::quant_type_t &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, dl::activation_type_t &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, dl::resize_mode_t &ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_attribute** (std::string node_name, std::string attribute_name, dl::*TensorBase* *&ret_value)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **attribute_name** –The name of attribute.
- **ret_value** –The attribute value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_input_shape** (std::string node_name, int index, std::vector<int> &ret_value)

Get operation input shape.

Parameters
- **node_name** –The name of operation.
- **index** –The index of inputs
- **ret_value** –Return shape value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_output_shape** (std::string node_name, int index, std::vector<int> &ret_value)

Get operation output shape.

Parameters
- **node_name** –The name of operation.
- **index** –The index of outputs
- **ret_value** –Return shape value.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

esp_err_t **get_operation_inputs_and_outputs** (std::string node_name, std::vector<std::string> &inputs, std::vector<std::string> &outputs)

Get the attribute of node.

Parameters
- **node_name** –The name of operation.
- **inputs** –The vector of operation inputs.
- **outputs** –The vector of operation outputs.

Returns esp_err_t Return ESP_OK if get successfully. Otherwise return ESP_FAIL.

std::string **get_operation_type** (std::string node_name)

Get operation type, "Conv", "Linear" etc.

Parameters **node_name** –The name of operation

Returns The type of operation.

dl::*TensorBase* ***get_operation_parameter** (std::string node_name, int index = 1, uint32_t caps = MALLOC_CAP_DEFAULT)

Return if the variable is a parameter.

Parameters
- **node_name** –The name of operation
- **index** –The index of the variable
- **caps** –Bitwise OR of MALLOC_CAP_* flags indicating the type of memory to be returned

Returns *dl::TensorBase**

dl::*TensorBase* ***get_operation_lut** (std::string node_name, uint32_t caps = MALLOC_CAP_DEFAULT, std::string attribute_name = "lut")

Get LUT(Look Up Table) if the operation has LUT.

Parameters
- **node_name** –The name of operation
- **caps** –Bitwise OR of MALLOC_CAP_* flags indicating the type of memory to be returned
- **attribute_name** –The name of LUT attribute

Returns *dl::TensorBase**

bool **is_parameter** (std::string name)

return true if the variable is a parameter

Parameters **name** –Variable name

Returns true if the variable is a parameter else false

const void ***get_tensor_raw_data** (std::string tensor_name)

Get the raw data of FlatBuffers::Dl::Tensor.

Parameters **tensor_name** –The name of Tensor.
Returns uint8_t * The pointer of raw data.

dl::dtype_t **get_tensor_dtype** (std::string tensor_name)

Get the element type of tensor tensor.

Parameters **tensor_name** –The tensor name.
Returns FlatBuffers::Dl::TensorDataType

std::vector<int> **get_tensor_shape** (std::string tensor_name)

Get the shape of tensor.

Parameters **tensor_name** –The name of tensor.
Returns std::vector<int> The shape of tensor.

std::vector<int> **get_tensor_exponents** (std::string tensor_name)

Get the exponents of tensor.

> **Warning:** When quantization is PER_CHANNEL, the size of exponents is same as out_channels. When quantization is PER_TENSOR, the size of exponents is 1.

Parameters **tensor_name** –The name of tensor.
Returns The exponents of tensor.

dl::dtype_t **get_value_info_dtype** (std::string var_name)

Get the element type of value_info.

Parameters **var_name** –The value_info name.
Returns dl::dtype_t

std::vector<int> **get_value_info_shape** (std::string var_name)

Get the shape of value_info.

Parameters **var_name** –The value_info name.
Returns the shape of value_info.

int **get_value_info_exponent** (std::string var_name)

Get the exponent of value_info. Only support PER_TENSOR quantization.

Parameters **var_name** –The value_info name.
Returns the exponent of value_info

const void ***get_test_input_tensor_raw_data** (std::string tensor_name)

Get the raw data of test input tensor.

Parameters **tensor_name** –The name of test input tensor.
Returns uint8_t * The pointer of raw data.

const void ***get_test_output_tensor_raw_data** (std::string tensor_name)

Get the raw data of test output tensor.

Parameters **tensor_name** –The name of test output tensor.
Returns uint8_t * The pointer of raw data.

dl::*TensorBase* ***get_test_input_tensor** (std::string tensor_name)

Get the test input tensor.

Parameters **tensor_name** –The name of test input tensor.

Returns The pointer of tensor.

dl::*TensorBase* ***get_test_output_tensor*** (std::string tensor_name)

Get the test output tensor.

Parameters **tensor_name** –The name of test output tensor.
Returns The pointer of tensor.

std::vector<std::string> **get_test_outputs_name** ()

Get the name of test outputs.

Returns the name of test outputs

std::vector<std::string> **get_graph_inputs** ()

Get the graph inputs.

Returns the name of inputs

std::vector<std::string> **get_graph_outputs** ()

Get the graph outputs.

Returns the name of ounputs

void **clear_map** ()

Clear all map.

void **load_map** ()

Load all map.

std::string **get_model_name** ()

Get the model name.

Returns the name of model

int64_t **get_model_version** ()

Get the model version.

Returns The version of model

std::string **get_model_doc_string** ()

Get the model doc string.

Returns The doc string of model

std::string **get_model_metadata_prop** (const std::string &key)

Get the model's metadata prop.

Parameters **key** –The key of metadata prop
Returns The value of metadata prop

void **get_model_size** (size_t *internal_size, size_t *psram_size, size_t *psram_rodata_size, size_t *flash_size)

Get the model size.

Parameters
- **internal_size** –Flatbuffers model internal RAM usage
- **psram_size** –Flatbuffers model PSRAM usage
- **psram_rodata_size** –Flatbuffers model PSRAM rodate usage. If CONFIG_SPIRAM_RODATA option is on, \ Flatbuffers model in FLASH rodata will be copied to PSRAM
- **flash_size** –Flatbuffers model FLASH usage

Public Members

bool **m_param_copy**

copy flatbuffers param or not.

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