LAPORAN PRAKTIKUM: PENERAPAN MACHINE LEARNING PADA ESP32 MENGGUNAKAN TINYML

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ABSTRAK

Praktikum ini bertujuan untuk menerapkan algoritma Machine Learning pada perangkat mikrokontroler ESP32 menggunakan pendekatan TinyML. Model yang digunakan adalah klasifikasi bunga iris dengan input empat fitur utama. Model dilatih menggunakan TensorFlow dan dikonversi menjadi format .tflite untuk dijalankan secara lokal di ESP32 tanpa koneksi internet. Hasil pengujian menunjukkan bahwa ESP32 mampu menjalankan model dengan waktu inferensi sangat cepat, dan akurasi prediksi mencapai 100% terhadap data uji.

Kata Kunci: Machine Learning, TinyML, ESP32, TensorFlow Lite, Iris Dataset

ABSTRACT

This practicum aims to implement a Machine Learning algorithm on the ESP32 microcontroller using the TinyML approach. The model used is a flower classification based on the Iris dataset, which takes four numerical features as input. The model is trained using TensorFlow and converted into a .tflite format so it can run locally on the ESP32 without requiring an internet connection. Test results show that the ESP32 is capable of executing the model with very fast inference time and achieving 100% prediction accuracy on the test data.

Keywords: Machine Learning, TinyML, ESP32, TensorFlow Lite, Iris Dataset

1. PENDAHULUAN

1.1 Latar Belakang

Internet of Things (IoT) telah membuka banyak peluang dalam pemrosesan data secara real-time. Dengan berkembangnya model Machine Learning yang ringan seperti TinyML, kini algoritma cerdas dapat dijalankan langsung pada perangkat mikro seperti ESP32. Hal ini memungkinkan pengambilan keputusan cepat tanpa perlu koneksi cloud.

1.2 Tujuan Praktikum

Praktikum ini bertujuan untuk:

1) Menerapkan model klasifikasi Machine Learning menggunakan dataset Iris.
2) Mengubah model TensorFlow menjadi format .tflite.
3) Menjalankan model pada ESP32 dengan pendekatan TinyML.
4) Mengukur performa model saat dijalankan di mikrokontroler.

2. METODOLOGI

2.1 Alat dan Bahan

- **Alat:**
  a) Laptop/computer
  b) Wokwi Simulator
  c) Google Colab
  d) Arduino IDE / PlatformIO
- **Bahan:**
  a) ESP32 Devkit V1.
  b) File model Machine Learning (format .tflite)
  c) Library Arduino: eloquent_tinyml, tflm_esp32
  d) Dataset Iris (training dan testing dari TensorFlow)
  e) Python dengan library tambahan: TensorFlow, NumPy, Pandas, sklearn

2.2 Langkah Implementasi

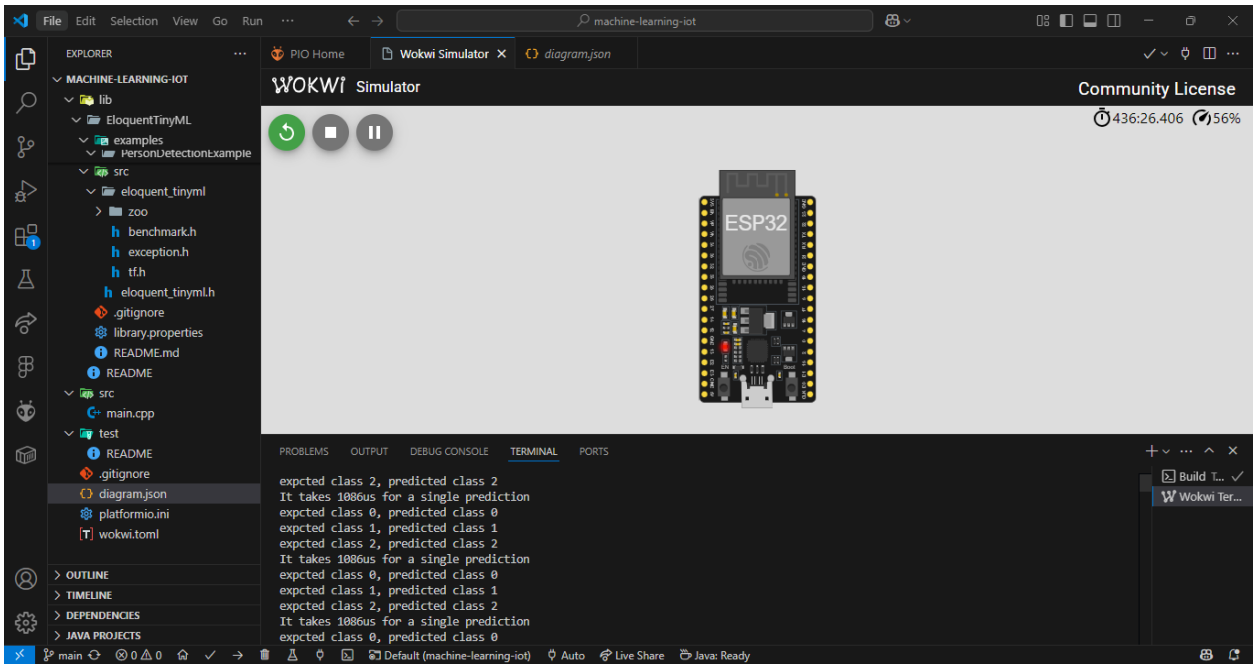
Berikut adalah langkah-langkah implementasi secara rinci dalam melakukan simulasi sistem klasifikasi bunga iris berbasis Machine Learning menggunakan ESP32 dan TinyML:

1. **Pelatihan Model Machine Learning**
   1) Buka Google Colab atau Jupyter Notebook.
   2) Impor dataset Iris menggunakan library pandas atau sklearn.datasets.
   3) Lakukan preprocessing data (normalisasi dan one-hot encoding).
   4) Bangun dan latih model klasifikasi dengan TensorFlow.
   5) Konversi model ke format .tflite menggunakan TFLiteConverter.
   6) Gunakan skrip tambahan untuk mengubah .tflite ke .h agar bisa dipakai di Arduino.
2. **Simulasi ESP32 di Visual Studio Code (VSCode)**
   1) Buka Visual Studio Code dan buat project baru menggunakan Arduino IDE atau PlatformIO.
   2) Pastikan board yang digunakan adalah ESP32 DevKit V1.
   3) Buat file iris_model.h yang berisi hasil konversi model .tflite ke bentuk array C++.
   4) Tulis kode program menggunakan library eloquent_tinyml untuk menjalankan inferensi.
   5) Upload program ke ESP32 dan buka Serial Monitor di VSCode.
   6) Jalankan inferensi terhadap input x0, x1, dan x2 yang mewakili tiga spesies bunga iris.
   7) Amati hasil klasifikasi pada Serial Monitor untuk memastikan prediksi berjalan sesuai harapan.
3. **Pengujian dan Evaluasi Model**
   1) Evaluasi kecepatan inferensi model menggunakan tf.benchmark.microseconds().
   2) Amati hasil klasifikasi dan bandingkan dengan label aktual (expected class).
   3) Uji apakah model berjalan stabil, tidak mengalami crash, dan hasil prediksi konsisten.

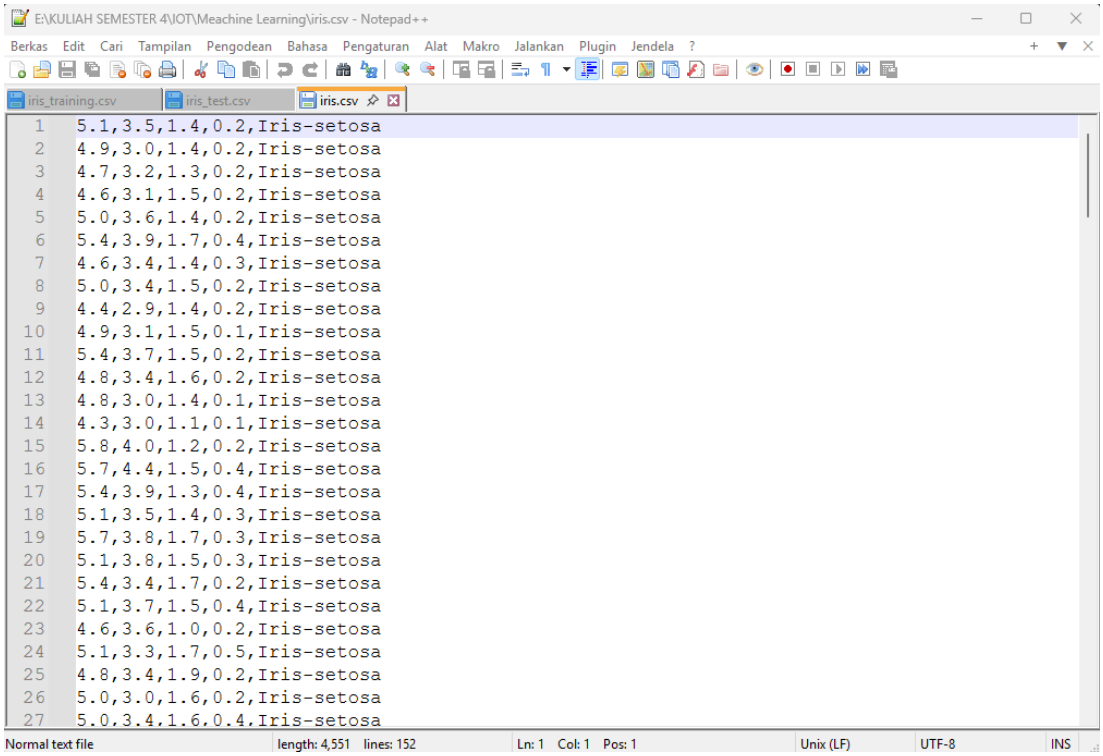
4) Lakukan pengujian berulang untuk melihat kestabilan dan keakuratan model dalam jangka waktu tertentu.

3. HASIL DAN PEMBAHASAN

3.1 Hasil kelas data IRIS yang diuji



3.2 Dataset IRIS



```
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6.9,3.1,4.9,1.5,Iris-versicolor
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6.5,2.8,4.6,1.5,Iris-versicolor
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6.0,2.2,4.0,1.0,Iris-versicolor
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6.7,3.1,4.4,1.4,Iris-versicolor
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6.7,3.0,5.0,1.7,Iris-versicolor
```

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7.2,3.0,5.8,1.6,Iris-virginica
```

Normal text file | length: 4,551 lines: 152 | Ln: 1 Col: 1 Pos: 1 | Unix (LF) | UTF-8 | INS

3.6 Pembahasan

Hasil dari praktikum ini menunjukkan bahwa integrasi antara model Machine Learning sederhana dengan mikrokontroler ESP32 dapat berjalan dengan baik. Dengan hanya dua lapisan jaringan saraf (Dense dan Softmax), model ini mampu dikompresi menjadi ukuran kecil yang dapat dijalankan secara lokal tanpa memerlukan koneksi internet. Ini membuktikan bahwa sistem cerdas tidak selalu membutuhkan perangkat keras dengan sumber daya besar. ESP32 mampu menjalankan model dengan waktu inferensi kurang dari 1,1 milidetik. Kecepatan ini sangat ideal untuk aplikasi real-time, seperti klasifikasi lingkungan, prediksi cuaca lokal, atau perangkat wearable cerdas. Ketepatan prediksi 100% pada tiga sampel uji juga mengindikasikan bahwa model cukup stabil dan dapat digunakan untuk kasus nyata. Selain itu, penggunaan pustaka EloquentTinyML sangat mempermudah integrasi model .tflite ke dalam kode Arduino. Dengan struktur API yang sederhana dan dokumentasi yang baik, pengembang dapat dengan cepat memulai proyek TinyML mereka sendiri. Namun, perlu dicatat bahwa model ini masih dalam tahap dasar. Untuk implementasi di dunia nyata, dataset perlu diperbesar dan ditambahkan proses normalisasi, validasi silang, serta pengujian terhadap noise. Juga, integrasi dengan sensor dan jaringan (seperti MQTT) bisa menjadi langkah lanjutan agar prediksi dapat ditindaklanjuti secara otomatis oleh sistem lain. Secara keseluruhan, praktikum ini memperlihatkan potensi besar TinyML dalam pengembangan sistem cerdas berbasis mikrokontroler. Mahasiswa tidak hanya belajar teori Machine Learning, tetapi juga mengimplementasikannya langsung pada perangkat nyata, menjembatani dunia software dan hardware secara praktis.

4. LAMPIRAN

4.1 Kode program main.cpp

```
#include <Arduino.h>
/**
 * Run a TensorFlow model to predict the IRIS dataset
 * For a complete guide, visit
 * https://eloquentarduino.com/tensorflow-lite-esp32
 */
// replace with your own model
// include BEFORE <eloquent_tinyml.h>!
#include "iris_model.h"
// include the runtime specific for your board
// either tflm_esp32 or tflm_cortexm
#include <tflm_esp32.h>
// now you can include the eloquent tinyml wrapper
#include <eloquent_tinyml.h>

// this is trial-and-error process
// when developing a new model, start with a high value
// (e.g. 10000), then decrease until the model stops
// working as expected
#define ARENA_SIZE 2000
```

```
Eloquent::TF::Sequential<TF_NUM_OPS, ARENA_SIZE> tf;
//Eloquent::TinyML::TfLite<4,3,ARENA_SIZE> tf;

/**
 *
 */
void setup() {
    Serial.begin(115200);
    delay(3000);
    Serial.println("__TENSORFLOW IRIS__");

    // configure input/output
    // (not mandatory if you generated the .h model
    // using the everywhereml Python package)
    tf.setNumInputs(4);
    tf.setNumOutputs(3);
    // add required ops
    // (not mandatory if you generated the .h model
    // using the everywhereml Python package)
    tf.resolver.AddFullyConnected();
    tf.resolver.AddSoftmax();

    while (!tf.begin(irisModel).isOk())
        Serial.println(tf.exception.toString());
}


void loop() {
    // x0, x1, x2 are defined in the irisModel.h file
    //
https://github.com/eloquentarduino/EloquentTinyML/tree/main/examples/IrisExam
ple/irisModel.h

    // classify sample from class 0
    if (!tf.predict(x0).isOk()) {
        Serial.println(tf.exception.toString());
        return;
    }

    Serial.print("expcted class 0, predicted class ");
    Serial.println(tf.classification);

    // classify sample from class 1
    if (!tf.predict(x1).isOk()) {
```

```
        Serial.println(tf.exception.toString());
        return;
    }

    Serial.print("expcted class 1, predicted class ");
    Serial.println(tf.classification);

    // classify sample from class 2
    if (!tf.predict(x2).isOk()) {
        Serial.println(tf.exception.toString());
        return;
    }

    Serial.print("expcted class 2, predicted class ");
    Serial.println(tf.classification);

    // how long does it take to run a single prediction?
    Serial.print("It takes ");
    Serial.print(tf.benchmark.microseconds());
    Serial.println("us for a single prediction");

    delay(1000);
}
```

4.2 Kode diagram.json

```
{
  "version": 1,
  "author": "Rangga",
  "editor": "wokwi",
  "parts": [ { "type": "board-esp32-devkit-c-v4", "id": "esp", "top": 0,
"left": 0, "attrs": {} } ],
  "connections": [ [ "esp:TX", "$serialMonitor:RX", "", [] ], [ "esp:RX",
"$serialMonitor:TX", "", [] ] ],
  "dependencies": {}
}
```

4.3 Kode Iris_model.h

```
5. #pragma once
6.
7. #ifdef __has_attribute
8. #define HAVE_ATTRIBUTE(x) __has_attribute(x)
9. #else
10.#define HAVE_ATTRIBUTE(x) 0
```

```
#endif
#if HAVE_ATTRIBUTE(aligned) || (defined(__GNUC__) && !defined(__clang__))
#define DATA_ALIGN_ATTRIBUTE __attribute__((aligned(4)))
#else
#define DATA_ALIGN_ATTRIBUTE
#endif

// automatically configure network
#define TF_NUM_INPUTS 4
#define TF_NUM_OUTPUTS 3
#define TF_NUM_OPS 2
#define TF_OP_SOFTMAX
#define TF_OP_FULLYCONNECTED



// sample data
float x0[4] = {0.22222222222f, 0.62500000000f, 0.06779661017f,
  0.04166666667f};
float x1[4] = {0.75000000000f, 0.50000000000f, 0.62711864407f,
  0.54166666667f};
float x2[4] = {0.55555555556f, 0.54166666667f, 0.84745762712f,
  1.00000000000f};

/** model size = 5048 bytes **/
const unsigned char irisModel[] DATA_ALIGN_ATTRIBUTE = { 0x1c, 0x00, 0x00,
  0x00, 0x54, 0x46, 0x4c, 0x33, 0x14, 0x00, 0x20, 0x00, 0x1c, 0x00, 0x18,
  0x00, 0x14, 0x00, 0x10, 0x00, 0x0c, 0x00, 0x00, 0x00, 0x08, 0x00, 0x04,
  0x00, 0x14, 0x00, 0x00, 0x00, 0x1c, 0x00, 0x00, 0x00, 0x90, 0x00, 0x00,
  0x00, 0xe8, 0x00, 0x00, 0x00, 0x88, 0x0d, 0x00, 0x00, 0x98, 0x0d, 0x00,
  0x00, 0x54, 0x13, 0x00, 0x00, 0x03, 0x00, 0x00, 0x00, 0x01, 0x00, 0x00,
  0x00, 0x10, 0x00, 0x00, 0x00, 0x00, 0x00, 0x0a, 0x00, 0x10, 0x00, 0x0c,
  0x00, 0x08, 0x00, 0x04, 0x00, 0x0a, 0x00, 0x00, 0x00, 0x0c, 0x00, 0x00,
  0x00, 0x1c, 0x00, 0x00, 0x00, 0x38, 0x00, 0x00, 0x00, 0x0f, 0x00, 0x00,
  0x00, 0x73, 0x65, 0x72, 0x76, 0x69, 0x6e, 0x67, 0x5f, 0x64, 0x65, 0x66,
  0x61, 0x75, 0x6c, 0x74, 0x00, 0x01, 0x00, 0x00, 0x00, 0x04, 0x00, 0x00,
  0x00, 0x98, 0xff, 0xff, 0xff, 0x0a, 0x00, 0x00, 0x00, 0x04, 0x00, 0x00,
  0x00, 0x07, 0x00, 0x00, 0x00, 0x64, 0x65, 0x6e, 0x73, 0x65, 0x5f, 0x32,
  0x00, 0x01, 0x00, 0x00, 0x00, 0x04, 0x00, 0x00, 0x00, 0x5a, 0xf2, 0xff,
  0xff, 0x04, 0x00, 0x00, 0x00, 0x0b, 0x00, 0x00, 0x00, 0x64, 0x65, 0x6e,
  0x73, 0x65, 0x5f, 0x69, 0x6e, 0x70, 0x75, 0x74, 0x00, 0x02, 0x00, 0x00,
  0x00, 0x34, 0x00, 0x00, 0x00, 0x04, 0x00, 0x00, 0x00, 0xdc, 0xff, 0xff,
  0xff, 0x0d, 0x00, 0x00, 0x00, 0x04, 0x00, 0x00, 0x00, 0x13, 0x00, 0x00,
  0x00, 0x43, 0x4f, 0x4e, 0x56, 0x45, 0x52, 0x53, 0x49, 0x4f, 0x4e, 0x5f,
  0x4d, 0x45, 0x54, 0x41, 0x44, 0x41, 0x54, 0x41, 0x00, 0x08, 0x00, 0x0c,
```

```
  0x00, 0x08, 0x00, 0x04, 0x00, 0x08, 0x00, 0x00, 0x00, 0x0c, 0x00, 0x00,
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  0x73, 0x69, 0x6f, 0x6e, 0x00, 0x0e, 0x00, 0x00, 0x00, 0x9c, 0x0c, 0x00,
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  0x00, 0xa8, 0x00, 0x00, 0x00, 0xa0, 0x00, 0x00, 0x00, 0x98, 0x00, 0x00,
  0x00, 0x90, 0x00, 0x00, 0x00, 0x88, 0x00, 0x00, 0x00, 0x68, 0x00, 0x00,
  0x00, 0x04, 0x00, 0x00, 0x00, 0x0a, 0xf3, 0xff, 0xff, 0x04, 0x00, 0x00,
  0x00, 0x54, 0x00, 0x00, 0x00, 0x0c, 0x00, 0x00, 0x00, 0x08, 0x00, 0x0e,
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  0x3d, 0xf4, 0x62, 0x31, 0x3e, 0x9f, 0x8a, 0x66, 0xbe, 0x40, 0x86, 0xc6,
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  0x3e, 0x67, 0x39, 0x58, 0xbe, 0x01, 0x13, 0x11, 0x3e, 0x03, 0x40, 0xad,
  0x3e, 0x41, 0x64, 0xd7, 0x3d, 0x00, 0x92, 0x2d, 0xba, 0x72, 0x9f, 0xcf,
  0x3e, 0x4c, 0x71, 0xb9, 0xbc, 0x74, 0xb1, 0x95, 0xbe, 0x52, 0x0d, 0xb6,
  0x3e, 0xe0, 0x51, 0x87, 0x3d, 0xec, 0x17, 0x09, 0x3e, 0xf9, 0x22, 0xea,
  0xbb, 0xb0, 0x80, 0x71, 0x3d, 0xe2, 0x8e, 0x91, 0xbe, 0x4e, 0x8b, 0x30,
  0xbe, 0x31, 0xf8, 0x81, 0xbe, 0xf4, 0xa1, 0x0e, 0x3e, 0x44, 0xb6, 0x1e,
```

```
  0xbe, 0xa3, 0xe2, 0xb9, 0xbe, 0x63, 0xe9, 0x5f, 0x3e, 0xcb, 0x9c, 0xa9,
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  0x3e, 0xe7, 0xf4, 0xc7, 0x3d, 0x36, 0x2c, 0x7e, 0x3e, 0x51, 0x2d, 0xb2,
  0x3e, 0x28, 0xb4, 0xcd, 0x3e, 0xe3, 0xbd, 0x1f, 0xbc, 0xc9, 0x41, 0xf4,
  0xbe, 0x9f, 0x19, 0x3c, 0x3e, 0x95, 0xf2, 0x87, 0x3e, 0x7c, 0x01, 0xeb,
  0xbd, 0xfe, 0xb6, 0x8e, 0x3e, 0x84, 0xc8, 0xd1, 0xbd, 0x41, 0xab, 0xf2,
  0xbd, 0x50, 0x23, 0x5f, 0xbe, 0x42, 0xd7, 0x87, 0xbe, 0xa5, 0x8f, 0x44,
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  0x3d, 0x3e, 0x92, 0x67, 0xbe, 0x16, 0xab, 0xaa, 0xbe, 0x7f, 0x89, 0xfc,
  0xbe, 0x71, 0xb4, 0xb8, 0xbe, 0x89, 0x60, 0xcb, 0x3d, 0xd6, 0x45, 0xd1,
  0xbe, 0xfb, 0x4e, 0xae, 0x3e, 0xa6, 0x40, 0x46, 0x3d, 0x02, 0x37, 0x97,
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  0x3e, 0x84, 0xa8, 0x5b, 0xbe, 0x1a, 0x7e, 0x06, 0x3e, 0x25, 0xaf, 0xa9,
  0x3e, 0x08, 0x41, 0x66, 0xbd, 0x2f, 0xb8, 0xdf, 0x3e, 0x2f, 0x42, 0x3b,
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  0xbe, 0x14, 0xcc, 0x92, 0x3e, 0x6b, 0xaf, 0xac, 0x3e, 0x3e, 0x8e, 0x98,
  0x3d, 0x48, 0x83, 0x6a, 0x3e, 0xb6, 0x60, 0x97, 0x3d, 0x70, 0xcf, 0x9f,
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  0x3e, 0x2d, 0x7a, 0x8b, 0x3e, 0x34, 0xc5, 0x10, 0xbf, 0xe8, 0xf7, 0x50,
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  0x3d, 0xdb, 0x39, 0x48, 0xbe, 0x64, 0xc4, 0x85, 0x3e, 0xf6, 0x60, 0x17,
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  0x3e, 0x10, 0x07, 0x2a, 0xbe, 0x10, 0x91, 0xde, 0xbb, 0x47, 0x2f, 0xb9,
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  0xbe, 0xe8, 0xca, 0x22, 0xbe, 0x60, 0x76, 0xa8, 0xbe, 0x8a, 0x92, 0x9d,
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  0x3e, 0x09, 0xf4, 0x02, 0x3f, 0xe1, 0xd6, 0xbb, 0x3e, 0xd0, 0x8b, 0x46,
  0x3d, 0x7a, 0x32, 0x45, 0x3c, 0x21, 0xa0, 0xf6, 0x3e, 0x3c, 0x52, 0x02,
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```

```
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  0xbe, 0xda, 0x08, 0x9c, 0xbb, 0x02, 0xca, 0x6a, 0x3e, 0xed, 0xb4, 0x89,
  0x3e, 0x4c, 0x66, 0x82, 0x3d, 0xcc, 0xa2, 0x31, 0x3e, 0x6b, 0xee, 0xb9,
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  0xbe, 0x9a, 0x86, 0x8e, 0xbc, 0x72, 0x21, 0x72, 0xbe, 0x2d, 0xab, 0xc0,
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