Zephyr® Project
Developer Summit

Streamline Testing with Emulator Backend APIs and Generic Tests

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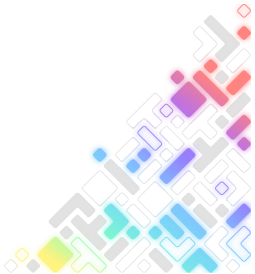
THE LINUX FOUNDATION

#EmbeddedOSSummit

Overview

1. Background on Zephyr Emulators
2. Generic Tests and the Backend API
3. Implementation example



About Me

- Firmware engineer at Google in ChromeOS
- Collaborator in Zephyr Sensors, have also contributed to Twister / testing.

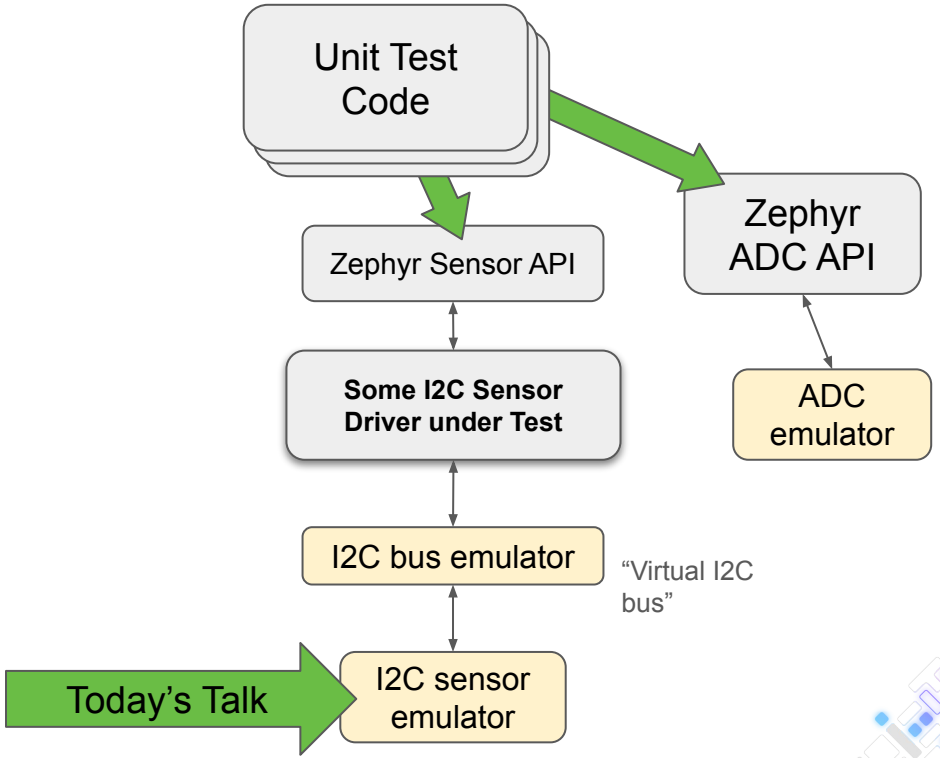
- We use Zephyr in the ChromeOS Embedded Controller
  - System management (USB-PD, charging, thermal, keyboard, etc)
  - Open Source!

chromeOS

Zephyr’s Testing and Emulation Framework

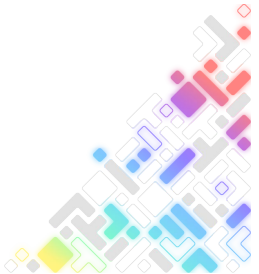
Unit Test Firmware on a PC with Emulators

- Emulators are mock hardware devices
  - Many sensors, but also GPIO, I2C, ADC, etc.
  - Coded in C, compiled in with tests
  - Typically native_posix/native_sim
  - Assembled together via Devicetree
- Validate your driver and even your application code without hardware (great for CI)

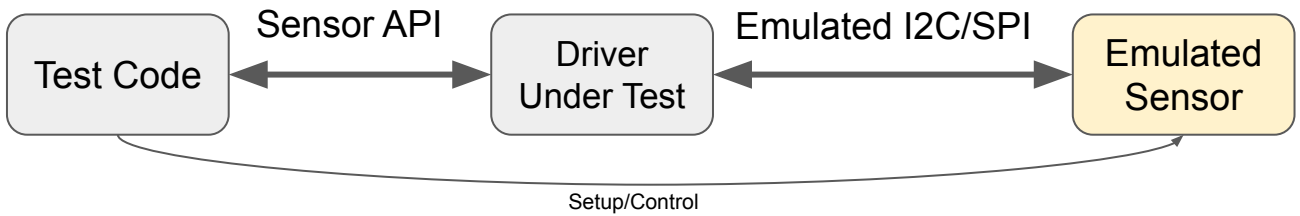


Testing and Emulation is Good

- Zephyr users should have confidence drivers work as intended
- Unfortunately, bugs do occur
  - Common issues: edge cases / range, unutilized features
- Unit testing against emulators is best strategy for call code paths in a driver
  - How can we make this easier?



Basic Test + Emulator Flow



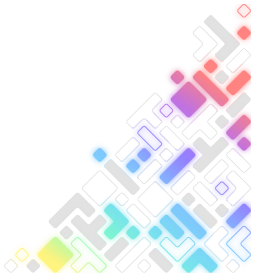
1. Test code uses some mechanism to configure registers on the emulator:
   `emul_mytempsensor_set_reg(0x45, 0x1A87);`
2. Use sensor API to take a sample (fetch/get)
3. Compare against the expected value

This is the only step unique to a device.

Sensor Emul Backend API

Sensor Emulator Backend API

- Standardize the mechanism for setting an expected value on the emulator
  - Use real, SI units
  - Emulator must handle converting SI to register coding
- Discoverability of supported channels and ranges
- Enable a “generic test” that can test a sensor without knowing anything about it
  - Concept can be expanded to other types of peripheral tests



Sensor Emulator Backend API

include/zephyr/drivers/emul_sensor.h

```
__subsystem struct emul_sensor_backend_api {
	/** Sets a given fractional value for a given sensor channel. */
	int (*set_channel)(const struct emul *target, enum sensor_channel ch, const q31_t *value,
			   int8_t shift);
	/** Retrieve a range of sensor values to use with test. */
	int (*get_sample_range)(const struct emul *target, enum sensor_channel ch, q31_t *lower,
				q31_t *upper, q31_t *epsilon, int8_t *shift);









};
```

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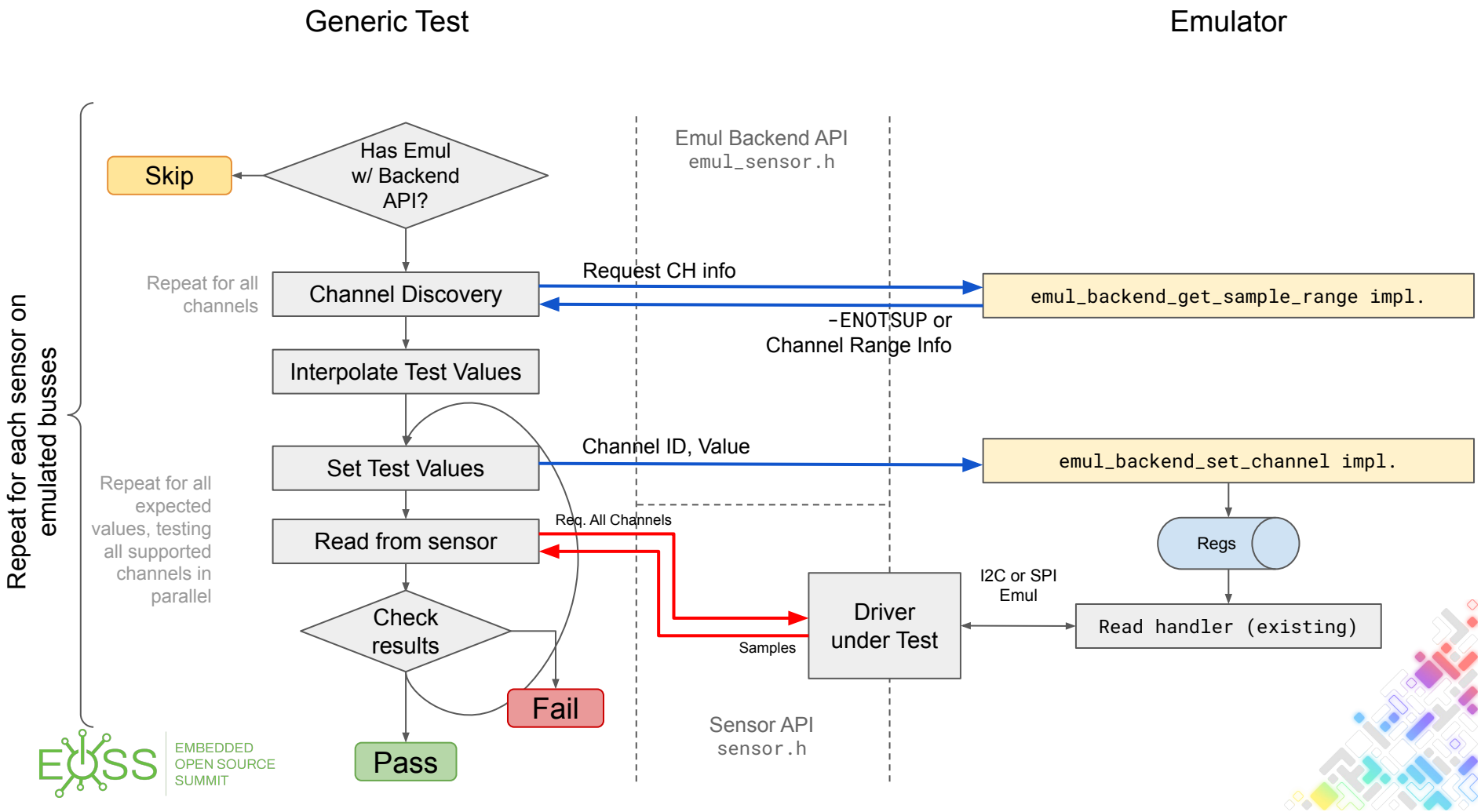
	/** Retrieve a range of sensor values to use with test. */
	int (*get_sample_range)(const struct emul *target, enum sensor_channel ch, q31_t *lower,
				q31_t *upper, q31_t *epsilon, int8_t *shift);


	/** Set the attribute value(s) of a given chanel. */
	int (*set_attribute)(const struct emul *target, enum sensor_channel ch,
			     enum sensor_attribute attribute, const void *value);
	/** Get metadata about an attribute. */
	int (*get_attribute_metadata)(const struct emul *target, enum sensor_channel ch,
				      enum sensor_attribute attribute, q31_t *min, q31_t *max,
				      q31_t *increment, int8_t *shift);
};
```

Generic Test


Generic Test
Emulator
Repeat for each sensor on emulated busses
Skip
Has Emul w/ Backend API?
Emul Backend API
emul_sensor.h
Repeat for all channels
Channel Discovery
Request CH info
emul_backend_get_sample_range impl.
-ENOTSUP or Channel Range Info
Interpolate Test Values
Repeat for all expected values, testing all supported channels in parallel
Set Test Values
Channel ID, Value
emul_backend_set_channel impl.
Read from sensor
Req. All Channels
Regs
I2C or SPI Emul
Driver under Test
Samples
Read handler (existing)
Check results
Fail
Pass
Sensor API
sensor.h
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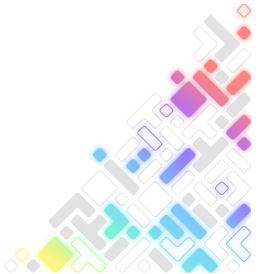
Aside: Fixed point numbers and Sensors V2

- What is `q31_t` and `int8_t shift`?
- The Generic Sensor Test and Sensor Emul Backend API are built around the newer Zephyr Sensors V2 API
  - No longer uses the two-part `struct sensor_value` object
  - Use 32-bit fixed point numbers with SI units
  - Benefits: easier arithmetic and processing, higher throughput using async RTIO tech, compatible with DSP subsystem. See link at end for additional info.



Aside: Fixed point numbers and Sensors V2

$-2^3 = -8$	$2^2 = 4$	$2^1 = 2$	$2^0 = 1$	$2^{-1} = 1/2$	$2^{-2} = 1/4$	$2^{-3} = 1/8$	$2^{-4} = 1/16$
1	0	0	1	0	1	0	0

= -6.75

- Fixed point math is very common in the DSP space
- Bits right of the arbitrary decimal point have fractional weights
- Decimal point location is defined by the `shift`. Set `shift` based on the sample range. (Slightly different from Q*n.m* notation)
- Sensors V2 uses 32-bit signed containers

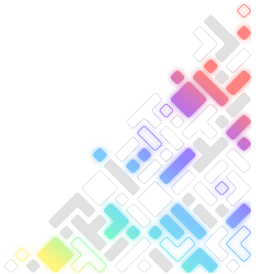
Aside: Fixed point numbers and Sensors V2

Shift value (Sensors V2 API)	Min Value = -2^{shift}	Max Value = (2^{shift} - $2^{-31+shift}$)
-2	-0.25	0.24999999988358468
-1	-0.5	0.49999999976716936
0	-1	0.9999999995343387
1	-2	1.9999999990686774
2	-4	3.999999998137355
31	-2,147,483,648	-2,147,483,647

Examples of shifts and ranges

Aside: Fixed point numbers and Sensors V2

- Suppose you have a temperature sensor with range **`-10℃`** to **`100℃`**
- Which shift to use?
  - Shift of 7 → [-128, 127.99999994039536]
- Temperature of **`50℃`** converts to:
  - $(50 * 2^{31}) >> 7 = 838860800 = 0x32000000$
  - $(838860800 << 7) / 2^{31} = 50.0$
  - We'll check out some C code soon.
- **Watch out for overflow** – order operations carefully and maybe use `int64_t`



Tour of an implementation

(AKM09918C digital compass)

Adding backend API impl. to the AKM09928C (1/4)

- Get sample range returns info about each supported channel, or `-ENOTSUP`
- Epsilon = allowed error (due to sensor accuracy limits)

```
static int akm09918c_emul_backend_get_sample_range(const struct emul *target,
                enum sensor_channel ch, q31_t *lower,
                q31_t *upper, q31_t *epsilon, int8_t *shift)
{
  ARG_UNUSED(target);

  if (!lower || !upper || !epsilon || !shift) {
    return -EINVAL;
  }

  switch (ch) {
  case SENSOR_CHAN_MAGN_X:
  case SENSOR_CHAN_MAGN_Y:
  case SENSOR_CHAN_MAGN_Z:
    /* +/- 49.12 Gs is the measurement range. 0.0015 Gs is the granularity */
    *shift = 6;
    *upper = (int64_t)(49.12 * ((int64_t)INT32_MAX + 1)) >> *shift;
    *lower = -*upper;
    *epsilon = (int64_t)(0.0015 * ((int64_t)INT32_MAX + 1)) >> *shift;
    break;
  default:
    return -ENOTSUP;
  }

  return 0;
}
```

Adding backend API impl. to the AKM09928C (2/4)

- Check inputs
- Determine appropriate internal registers to update
- Individual channels, no XYZ tuples.

```
static int akm09918c_emul_backend_set_channel(const struct emul *target, enum sensor_channel ch,
                const q31_t *value, int8_t shift)
{
  if (!target || !target->data) {
    return -EINVAL;
  }

  struct akm09918c_emul_data *data = target->data;
  uint8_t reg;

  switch (ch) {
  case SENSOR_CHAN_MAGN_X:
    reg = AKM09918C_REG_HXL;
    break;
  case SENSOR_CHAN_MAGN_Y:
    reg = AKM09918C_REG_HYL;
    break;
  case SENSOR_CHAN_MAGN_Z:
    reg = AKM09918C_REG_HZL;
    break;
  /* This function only supports setting single channels, so skip MAGN_XYZ */
  default:
    return -ENOTSUP;
  }
```

Adding backend API impl. to the AKM09928C (3/4)

- Convert SI units to reg. Values
- Remember to update any “data ready” bits
- Clamp to allowed values

```
  /* Set the ST1 register to show we have data */
  data->reg[AKM09918C_REG_ST1] |= AKM09918C_ST1_DRDY;

  /* Convert fixed-point Gauss values into microgauss and then into its bit representation */
  int32_t microgauss =
    (shift < 0 ? ((int64_t)*value >> -shift) : ((int64_t)*value << shift)) * 1000000 /
    ((int64_t)INT32_MAX + 1);

  int16_t reg_val =
    CLAMP(microgauss, AKM09918C_MAGN_MIN_MICRO_GAUSS, AKM09918C_MAGN_MAX_MICRO_GAUSS) /
    AKM09918C_MICRO_GAUSS_PER_BIT;

  /* Insert reading into registers */
  data->reg[reg] = reg_val & 0xFF;
  data->reg[reg + 1] = (reg_val >> 8) & 0xFF;

  return 0;
}
```

Adding backend API impl. to the AKM09928C (4/4)

```
static const struct emul_sensor_backend_api akm09918c_emul_sensor_backend_api = {
  .set_channel = akm09918c_emul_backend_set_channel,
  .get_sample_range = akm09918c_emul_backend_get_sample_range,
};

#define AKM09918C_EMUL(n)
  const struct akm09918c_emul_cfg akm09918c_emul_cfg_##n;
  struct akm09918c_emul_data akm09918c_emul_data_##n;
  EMUL_DT_INST_DEFINE(n, akm09918c_emul_init, &akm09918c_emul_data_##n,
          &akm09918c_emul_cfg_##n, &akm09918c_emul_api_i2c,                \
          &akm09918c_emul_sensor_backend_api)
```

- Declare struct w/ func popinters
- Register it in `EMUL_DT_INST_DEFINE()`

Generic Test

- Lives under the Sensor “build_all” test
  - tests/drivers/build_all/sensor/src/generic_test.c
- This test has a devicetree with nodes for all sensors (i2c.dtsi, spi.dtsi, etc)

```
#define DECLARE_ZTEST_PER_DEVICE(n)
  ZTEST(generic, test_##n)
  {
    run_generic_test(DEVICE_DT_GET(n));
  }

/* Iterate through each of the emulated buses and create a test for each device. */
DT_FOREACH_CHILD_STATUS_OKAY(DT_NODELABEL(test_i2c), DECLARE_ZTEST_PER_DEVICE)
DT_FOREACH_CHILD_STATUS_OKAY(DT_NODELABEL(test_i3c), DECLARE_ZTEST_PER_DEVICE)
DT_FOREACH_CHILD_STATUS_OKAY(DT_NODELABEL(test_spi), DECLARE_ZTEST_PER_DEVICE)

ZTEST_SUITE(generic, NULL, NULL, before, NULL, NULL);
```

Generic Test - Discover emulator support

- Skip drivers if no emulator or no backend API impl. exists
- All drivers will initialize as Zephyr boots

```c
/**
 * @brief Helper function the carries out the generic sensor test for a given sensor device.
 *        Verifies that the device has a suitable emulator that implements the backend API and
 *        skips the test gracefully if not.
 */
static void run_generic_test(const struct device *dev)
{
  zassert_not_null(dev, "Cannot get device pointer. Is this driver properly instantiated?");

  const struct emul *emul = emul_get_binding(dev->name);

  /* Skip this sensor if there is no emulator loaded. */
  if (!emul) {
    ztest_test_skip();
  }

  /* Also skip if this emulator does not implement the backend API. */
  if (!emul_sensor_backend_is_supported(emul)) {
    ztest_test_skip();
  }
```

Generic Test - Channel discovery

- Table of channel information
- Iterate through all known channels, record info about which are supported
- Generate linearly-interpolated test points throughout range

Note: some lines dropped for brevity

```
/* Discover supported channels on this device and fill out our sensor read request */
for (enum sensor_channel ch = 0; ch < ARRAY_SIZE(channel_table); ch++) {
  if (SENSOR_CHANNEL_3_AXIS(ch)) {
    continue;
  }

  q31_t lower, upper;
  int8_t shift;

  if (emul_sensor_backend_get_sample_range(emul, ch, &lower, &upper,
              &channel_table[ch].epsilon, &shift) == 0) {
    /* This channel is supported */
    channel_table[ch].supported = true;

    /* Generate a set of CONFIG_GENERIC_SENSOR_TEST_NUM_EXPECTED_VALS test
     * values.
     */

    channel_table[ch].expected_value_shift = shift;
    for (size_t i = 0; i < CONFIG_GENERIC_SENSOR_TEST_NUM_EXPECTED_VALS; i++) {
      channel_table[ch].expected_values[i] =
        lower +
        (i * ((int64_t)upper - lower) /
         (CONFIG_GENERIC_SENSOR_TEST_NUM_EXPECTED_VALS - 1));
```

Generic Test - Set expected values

- Use backend API to configure emulator
- One set of expected values across supported channels at a time

```
for (size_t iteration = 0; iteration < CONFIG_GENERIC_SENSOR_TEST_NUM_EXPECTED_VALS;
     iteration++) {
  int rv;

  /* Set this iteration's expected values in emul for every supported channel */
  for (size_t i = 0; i < iodev_read_config.count; i++) {
    enum sensor_channel ch = iodev_all_channels[i];

    rv = emul_sensor_backend_set_channel(
      emul, ch, &channel_table[ch].expected_values[iteration],
      channel_table[ch].expected_value_shift);
```

Note: some lines dropped for brevity

Generic Test - Check Results

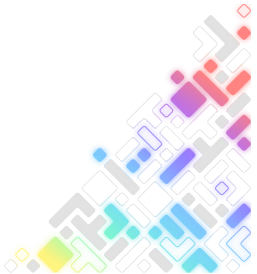
- (not shown: read and retrieve values from Sensor API)
- Normalize all the fixed-point numbers in a big `int64_t` container
- Additional check to ensure all requested channels are received

```
	/* Align everything to be a 64-bit Q32.32 number for comparison */
	int64_t expected_shifted =
	  (int64_t)channel_table[ch].expected_values[iteration]
	  << channel_table[ch].expected_value_shift;
	int64_t actual_shifted = (int64_t)q << shift;
	int64_t epsilon_shifted = (int64_t)channel_table[ch].epsilon
	        << channel_table[ch].expected_value_shift;

	zassert_within(expected_shifted, actual_shifted, epsilon_shifted,
	        "Expected %lld, got %lld (shift %d, ch %d, iteration %d/%d, "
	        "Error %lld, Epsilon %lld)",
	        expected_shifted, actual_shifted, shift, ch, iteration + 1,
	        CONFIG_GENERIC_SENSOR_TEST_NUM_EXPECTED_VALS,
	        expected_shifted - actual_shifted, epsilon_shifted);
}
```

Conclusion

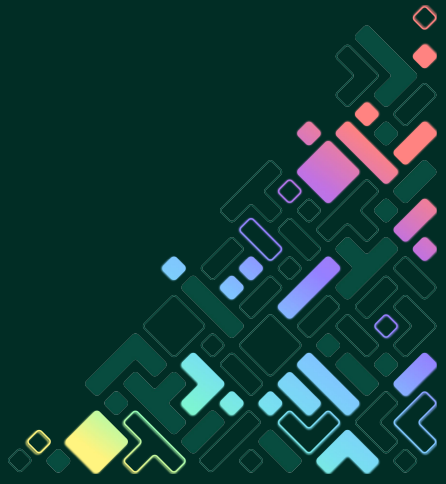
- Tl;dr: Write a backend API implementation for an emulator, get a free test
- Is there a particular sensor important to your project / product?
  - Consider contributing an emulator
  - Time commitment: ~0.5-1 day
  - Prevent regressions!



PRs to explore

- Initial (Generic Test, API, and AKM09918C digital compass impl.)
  - https://github.com/zephyrproject-rtos/zephyr/pull/60394
- ICM42688 motion sensor emul backend API implementation
  - https://github.com/zephyrproject-rtos/zephyr/pull/61051
- SB-TSI (Sideband temperature sensor interface) emul w/ backend API
  - https://github.com/zephyrproject-rtos/zephyr/pull/60818
- Add attribute support to backend API, add BMI160 accel backend API impl.
  - https://github.com/zephyrproject-rtos/zephyr/pull/65278
- Yuval Peress's ZDS 2023 talk on Sensors V2
  - https://eoss2023.sched.com/event/1Leca

Q&A



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