2025 DESIGN AND VERIFICATION™ DVCON CONFERENCE AND EXHIBITION EUROPE

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Next-Gen Verification with Python: Driving Hardware Tests with Pytest and Cocotb

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Qblox B.V

accellera SYSTEMS INITIATIVE

History and change of verif infrastructure (reinier)

Hard selling points (shri) - Done but can add more points to it

Analytic info about verif eng shortage (ronahi)

Slide number for each slide - Done

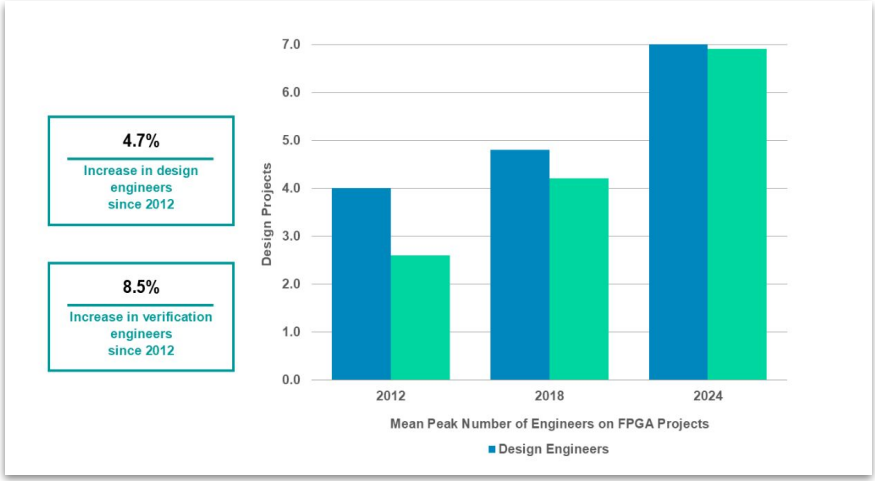
Less text (all)

More support material (images) (abhi)

Time for Slides + Time for demo + time for questions

Verification trends

- Difficulty in getting experienced SV/UVM verification engineers
- Difficulty onboarding to custom verification environment
- Wish to migrate smoothly to something easier?
- Something scalable and open source

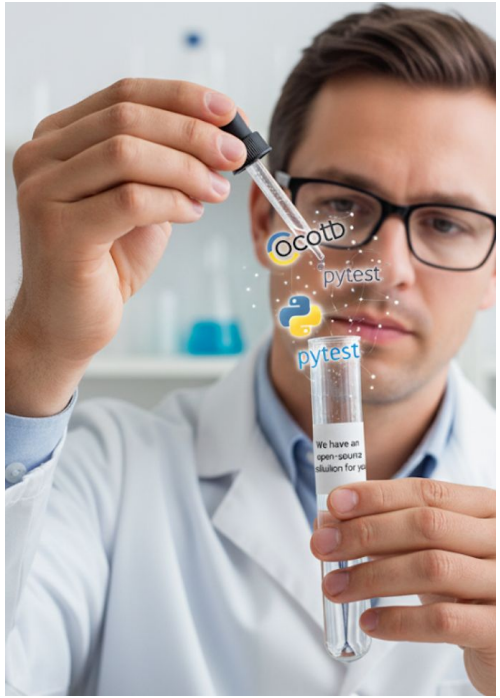


Source : “2024 Siemens EDA and Wilson Research Group FPGA functional verification trend report,” White Paper, Siemens EDA, 2024

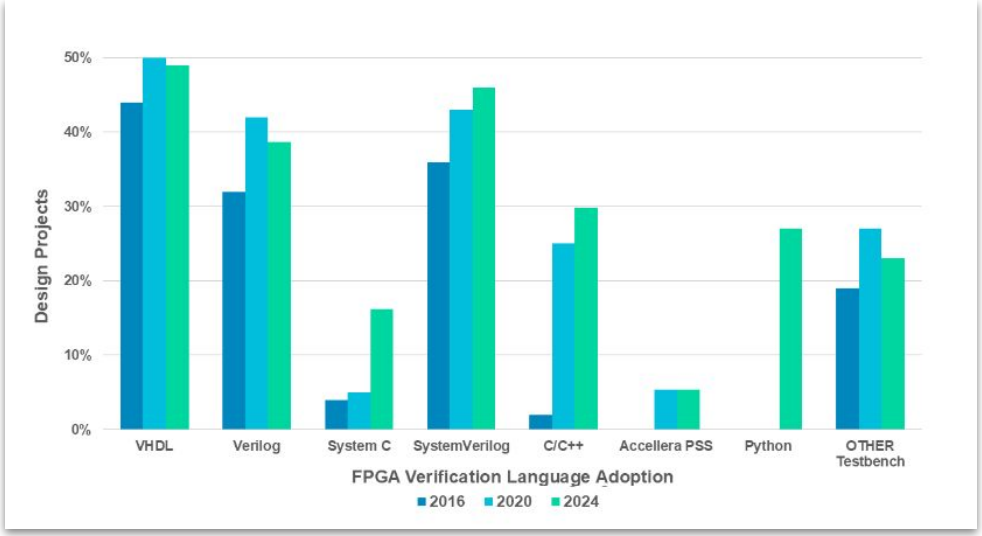
Verification trends

- Difficulty in getting experienced SV/UVM verification engineers
- Difficulty onboarding to custom verification environment
- Wish to migrate smoothly to something easier?
- Something scalable and open source

We have an open-source solution!



Python adoption?



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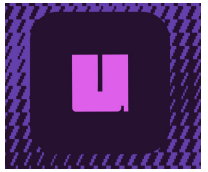
Rapid adoption of python in testbenches in recent years

Why Python?

- Productivity boost
  - Easy to learn
  - Faster reading, writing and debug
- Ecosystem
  - Huge collection of libraries, tools, frameworks
- Development
  - Code auto-completion integrated with editor (Jedi)

Why Python?



- Modern development ecosystem:
  - Dependency management (pip, uv)
  - Documentation generation (Sphinx)
  - Test frameworks (pytest)
  - Code quality: formatters, linters , auto-completion

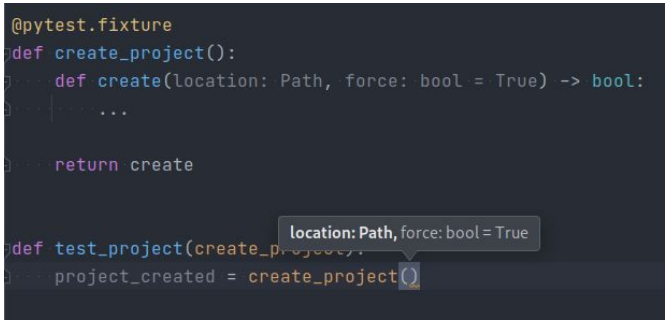
WRITE LESS, VERIFY MORE !

Why Pytest?

```
tests/test_basic_example.py::test_square[1] PASSED
tests/test_basic_example.py::test_square[2] PASSED
tests/test_basic_example.py::test_square[3] PASSED

================================================== 3 passed in 0.01s ======
```

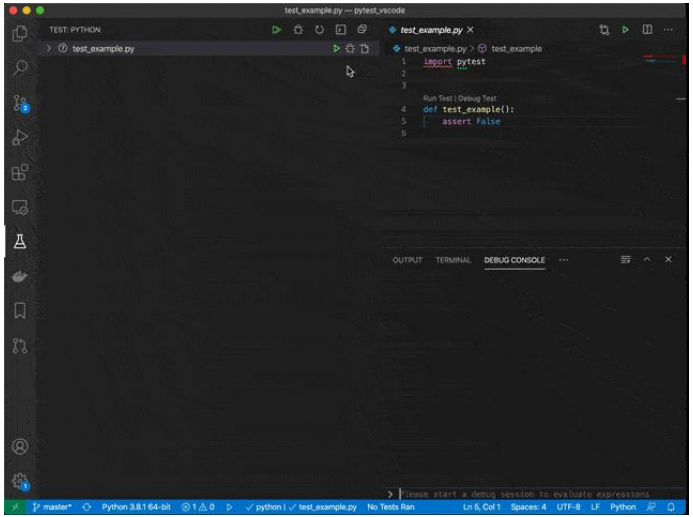
- Test framework
  - **Parametrization**: One test, multiple runs, reduce code redundancy
  - **Fixtures**: set up test prerequisites, reuse, teardown
  - **Parallelization**: distribute test across cores



- Test management (discovery, running, filtering)
  - Easy test discovery with **“`test_`”** functions (no explicit adding of tests)
  - Filter tests using strings, regex

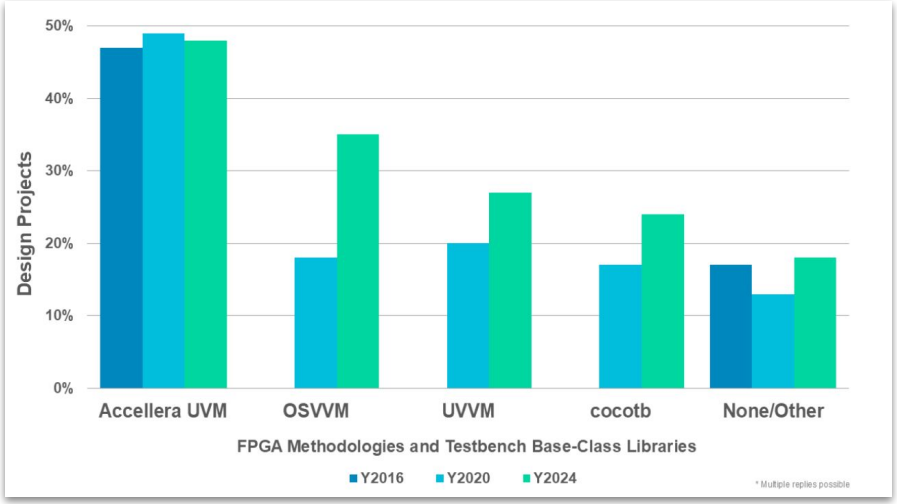
Why Pytest?

- Concise syntax of writing tests, easy to use
- Very well documented with good community support
- Easy to extend with plugin framework:
  - Rich free collection of existing external plugins (~1641)
  - Suit yourself, write own plugin! (integration)
- Integration with IDE and text editors (running tests)



Why Cocotb?

- Using python and pytest with all benefits in HDL verification targeting FPGA and ASIC
- Portability - running the same tests with different HDL simulators (open-source and proprietary)
- Open-source, maturity, community, well documented



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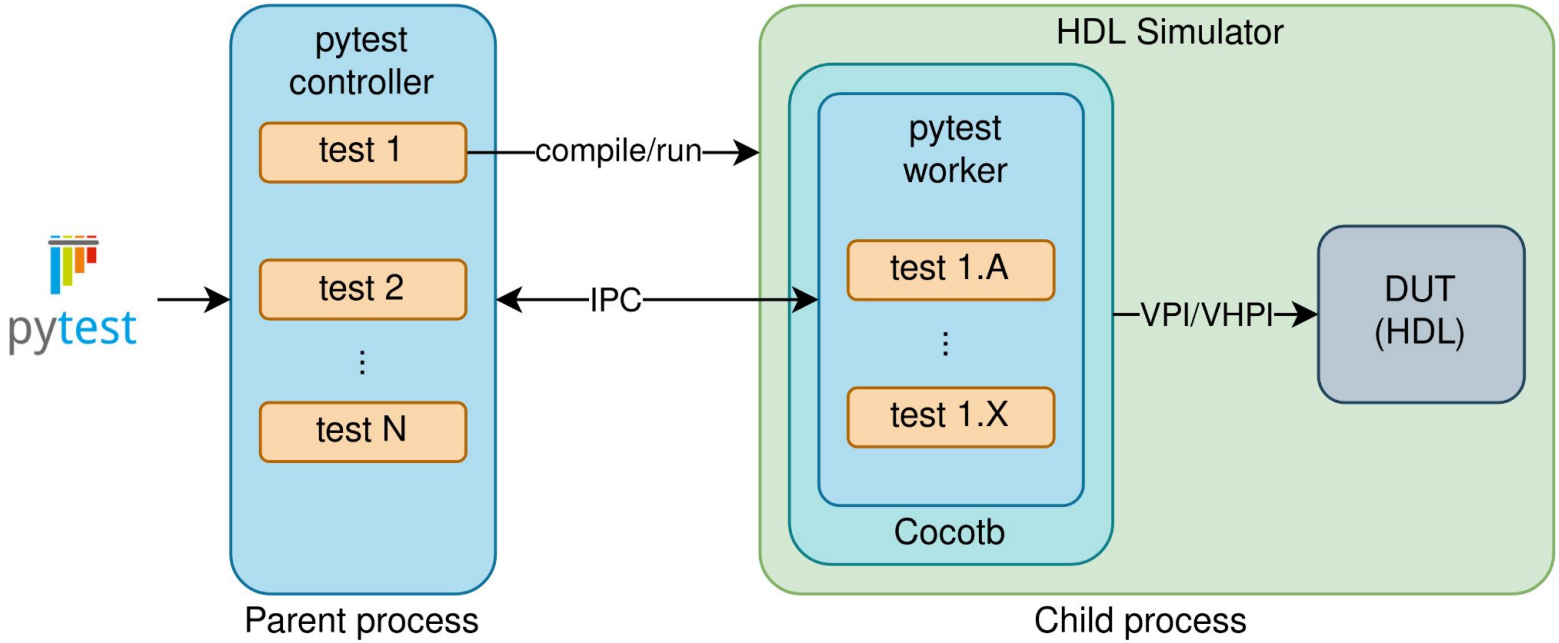
Cons? Any?

- Work in Progress

Cons? Any?

- Runtime performance
  - Slower (without HDL simulator optimization)
  - Example boost - Clock can be generated on HDL side.
- Debugging
  - Two separate debuggers (Python, HDL simulator)
  - Dynamic part of Python may not be aligned with HDL code

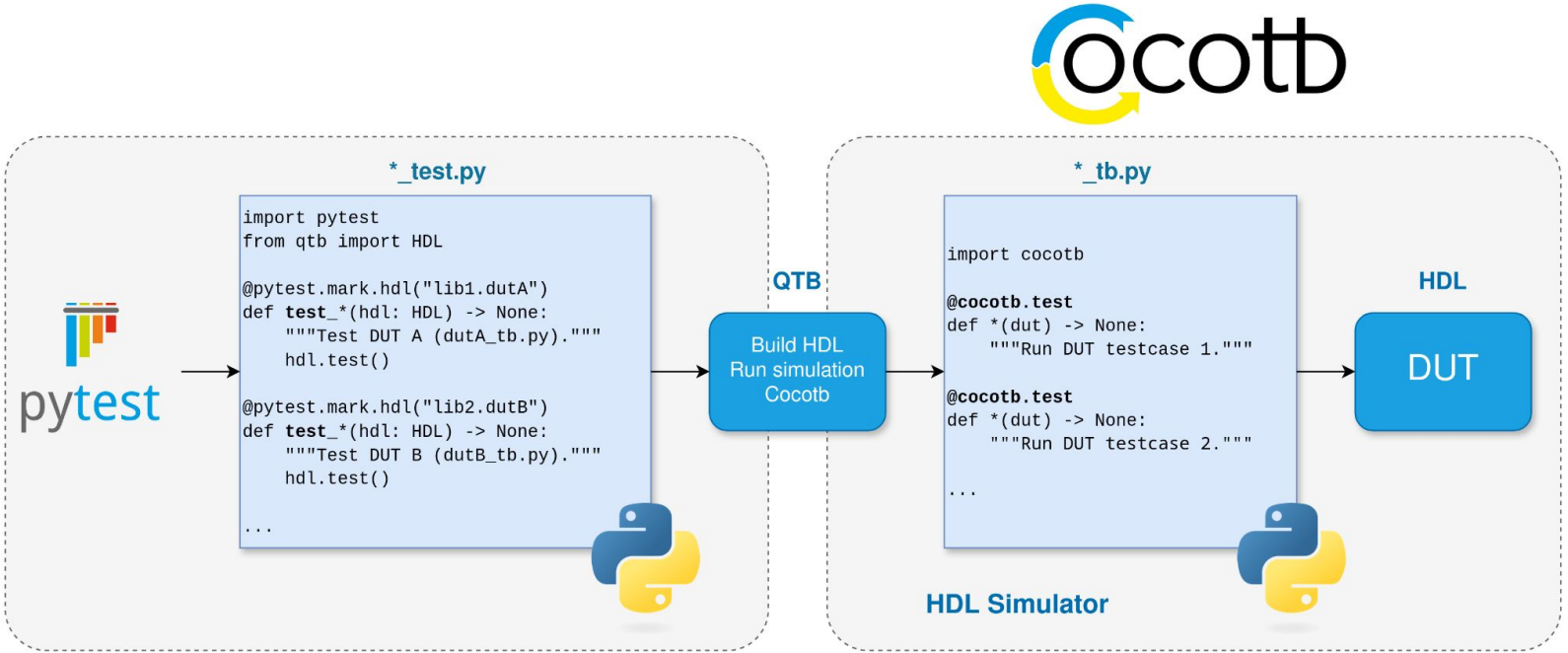
Pytest <-> Cocotb Architecture Overview



Pytest <-> Cocotb Architecture Overview

- Similar architecture to pytest-xdist
- Pytest functions called on pytest **controller** side can compile HDL project and run HDL simulator as separate subprocess
- Pytest functions called on pytest **worker** side will run from HDL simulator to verify DUT using Cocotb
- From user and pytest perspective, controller and worker are **transparent**
- Distinguished using pytest markers (**pytest.mark.***)

Pytest <-> Cocotb Architecture Overview

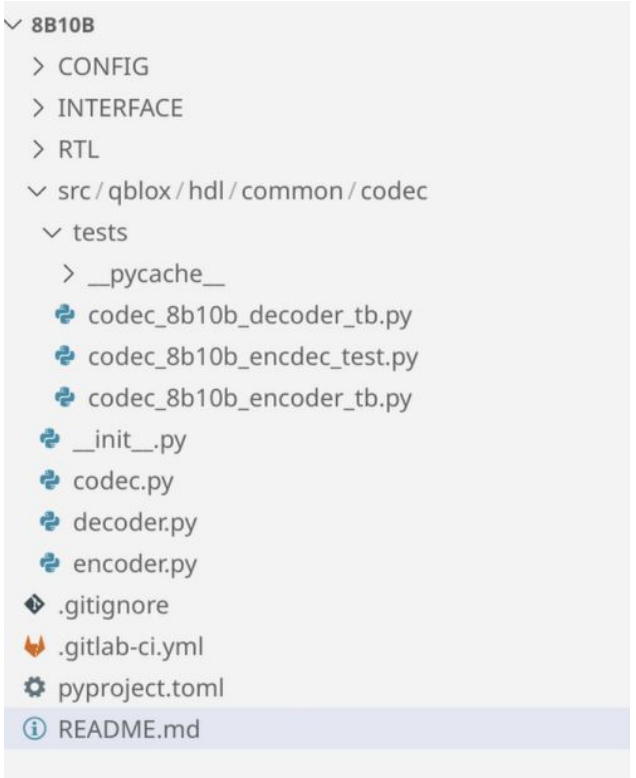


Hands-On: Cocotb and Pytest in Action

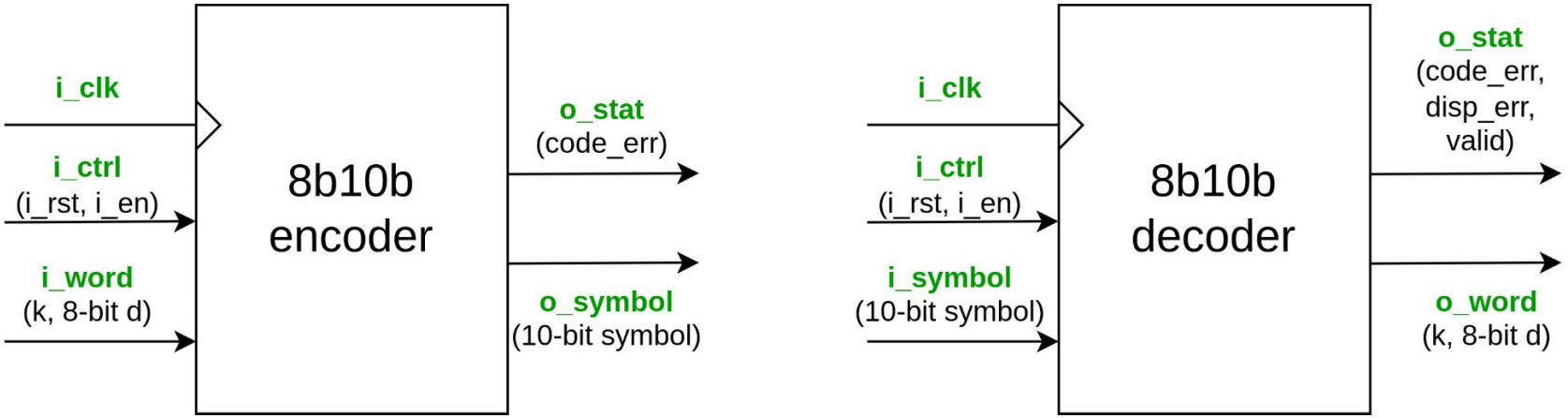
- **Agenda**
  - Will look at simple RTL designs -
    - 8b10b encoder/decoder
    - Pseudo-random binary sequence (PRBS) generator
  - Python project layout and writing a **cocotb** testbench, running with **pytest** framework
  - Test discovery, filtering, parametrization, plug-in capabilities, command line arguments
  - View reports, coverage results
  - Pytest in validation, integration with IDEs (VSCode)
  - Conclusion

Project layout, folder structure

- Working out-of-box with Python project in editable mode (development mode)
- Using python namespace packages (different HDL modules) into single common namespace:
  - `qblox/hdl/`
- Combining and merging distributed HDL modules from different HDL libraries into:
  - `qblox/hdl/<library>/<module>/`

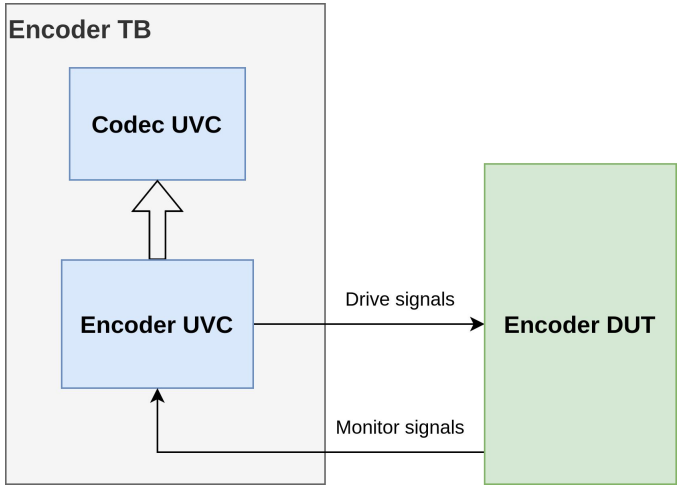


Design under Test (DUT) - 8b10b encoder/decoder



8b10b testbench structure

- First step in writing the testbench -
  - Universal Verification Component (UVCs) to create helper functions to drive and monitor
- `__init__.py` file initializes the top level package (required to make Python treat directories containing this file as packages)
- `codec.py` contains the base UVC (used in encoder and decoder TBs)



8b10b Codec UVCs

```
"""QVC for codec"""

from .encoder import Encoder
from .decoder import Decoder

# https://docs.astral.sh/ruff/rules/unused-import/
# https://docs.python.org/3/tutorial/modules.html#importing-from-a-package
__all__ = ["Encoder", "Decoder"]
```

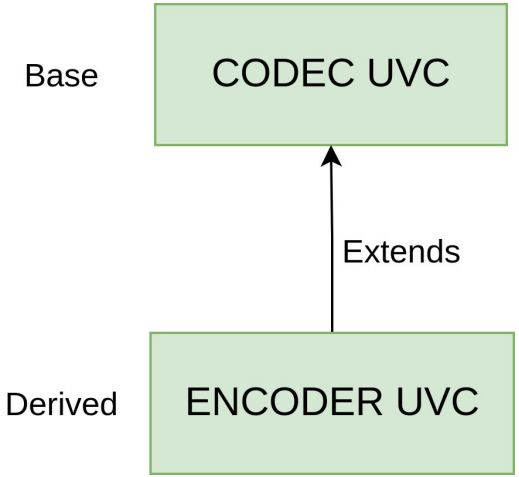
- `__init__.py` code defines a list named `__all__`
  - it is taken to be the list of module names that should be imported when from `package import *`
- In this example, does not contain any other code
  - Could also contain the UVC for the toplevel DUT

8b10b Codec UVCs

- `__init__ (self, dut)`: constructor function to pass DUT instance handle to UVC class
- **`input`** and **`output`** to drive and monitor DUT input/output signals
  - Set to None, can be customized according to Encoder/Decoder UVC.
- Can use standard python libraries like **encdec8b10b**

```python
class Codec:

    async def send(self, data: Union[int, list[int]]) -> None:
        """Send data to codec."""
        if not isinstance(data, Sequence):
            data = [data]

        while data:
            self.input.value = data[0]
            data = data[1:]
            await RisingEdge(self.dut.i_clk)

    async def receive(self, count: int) -> list[int]:
        """Receive data from codec."""
        data = count * [0]
        index = 0

        while index < count:
            await RisingEdge(self.dut.i_clk)
            data[index] = self.output.value.integer
            index += 1

        return data

    def encode(self, data_in, running_disparity=0, ctrl=0):
        """Encode 8b value"""
        # Returns disparity and encoded value
        return EncDec8B10B.enc_8b10b(
            data_in=data_in, running_disparity=running_disparity, ctrl=ctrl
        )

    def decode(self, data_in):
        """Decode 10b value"""
        # Returns control and decoded value
        return EncDec8B10B.dec_8b10b(data_in=data_in)
```

8b10b Encoder UVC




```python
class Encoder(Codec):
    """Codec 8b/10b encoder."""

    def __init__(self, dut, active: bool = False):
        """Create new instance of 8b/10b encoder.

        Args:
            initialize: If True, initialize all inputs of encoder. By default is False.
        """
        super().__init__(dut)

        self.input = dut.i_word.d
        self.output = dut.o_symbol

        if active:
            self.initialize()

    def initialize(self):
        """Initialize all inputs of encoder."""
        super().initialize()
        self.dut.i_word.k.value = 0
        self.dut.i_word.d.value = 0
```

8b10b testbench

- Test defined using `@cocotb.test` decorator
- Instantiate UVC, generate clock, drive reset sequence
- Use UVC functions or directly drive DUT signals in TB

```python
@cocotb.test()
async def simple_transfer_encoder(dut, count: int = 1024):
    """Test 8b/10b encoder using stream of bytes"""

    # Generate clock in the background
    generate_clock(clock=dut.i_clk)

    # Encoder QVC initialization
    encoder = Encoder(dut, active=True)

    # Reset encoder DUT
    await encoder.reset()

    # Enable encoder DUT
    encoder.enable = True

    # Running disparity
    disp = 0

    # Generate data of 0..255 + random bytes. This will allow to increase code coverage hits
    expected = list(range(256)) + [random.randint(0, 255) for _ in range(count)]
    expected = expected[:count]
    random.shuffle(expected)

    # Generate reference data for encoder output
    encoded_expected = len(expected) * [0]

    for index, value in enumerate(expected):
        disp, encoded_expected[index] = encoder.encode(value, disp)
```

8b10b testbench

- Test defined using `@cocotb.test` decorator
- Instantiate UVC, generate clock, drive reset sequence
- Use UVC functions or directly drive DUT signals in TB
- Finish test with checkers/assertions

```python
async def simple_transfer_encoder(dut, count: int = 1024):

    # One clock cycle delay between input and output of encoder, hence one extra receive
    tasks = (
        cocotb.start_soon(encoder.send(expected)),
        cocotb.start_soon(encoder.receive(len(expected) + 1)),
    )

    # Wait for tasks to finish
    await Combine(*tasks)
    encoded_captured = tasks[1].result()[1:]

    # Assert captured encoder output with expected encoded data
    assert (
        encoded_expected == encoded_captured
    ), "Captured encoded data is not equal to expected encoded data"
```

Checkers/assertions

```python
async def checker(self):
    """Checkers for module"""

    while True:
        await FallingEdge(self.dut.i_clk)

        # Write model for calculating expected outputs
        exp_output = 0x145

        # Compare against DUT values
        assert self.dut.o_status.value == exp_output, "Status not matching"
```

- Can define checkers inside the UVC
  - Async function running till test end
  - Can write cycle accurate models and check signals at every clock cycle using assertions
- Can also define assertions/checkers directly in the TB

Writing pytest for testbench (fixtures, markers)

- Usage of **HDL** fixture in our pytest plugin (**QTB**)
- Contains information about HDL environment
  - HDL source files, libraries, HDL define macros, information about HDL simulator
- Usage of markers to provide metadata information to tests

```python
"""Pytest for 8b10b encoder decoder"""

import pytest
from qtb import HDL


@pytest.mark.hdl("common_lib.codec_8b10b_encoder")
def test_encoder(hdl: HDL):
    """Test 8b10b encoder DUT"""
    hdl.test()


@pytest.mark.hdl("common_lib.codec_8b10b_decoder")
def test_decoder(hdl: HDL):
    """Test 8b10b decoder DUT"""
    hdl.test()
```

Writing pytest for testbench

- Our pytest plugin (**QTB**) provides own predefined list of markers
  - `@pytest.mark.hdl()` allows to pass additional metadata to the QTB fixture **hdl**
- `@pytest.mark.parametrize(argnames, argvalues)`
  - Defined args used to parameterize test function.

```python
"""Pytest for 8b10b encoder decoder"""

import pytest
from qtb import HDL


@pytest.mark.hdl("common_lib.codec_8b10b_encoder")
def test_encoder(hdl: HDL):
    """Test 8b10b encoder DUT"""
    hdl.test()


@pytest.mark.hdl("common_lib.codec_8b10b_decoder")
def test_decoder(hdl: HDL):
    """Test 8b10b decoder DUT"""
    hdl.test()
```

Tests discovery

- The pytest framework will automatically discover all tests based on Python file names and Python function names.
- Python **file** name, by default, **MUST** start from the `test_*` prefix or end with the `*_test.py` suffix
  - `codec_8b10b_encdec_test.py` - Pytest that will build HDL and run Cocotb testbench
  - `codec_8b10b_encoder_tb.py` - Cocotb testbench executed from HDL simulator
- Python **function** must start with `test_*` prefix

Tests discovery

- To collect all tests
  - **`pytest --collect-only`**
  - **`pytest --co`** (shorthand)
- **`pytest`** searches for tests everywhere in current working directory
  - Unless defined in **`pyproject.toml`** or using cmdline args

```
$ pytest --collect-only

Setup Python virtual environment

Load HDL design from dflow
============================================================================================
platform linux -- Python 3.12.5, pytest-8.4.1, pluggy-1.6.0
rootdir: /home/abhiroop/qblox/projects/standalone/fpga/HDL_Design/common_lib/8b10b
configfile: pyproject.toml
testpaths: src/qblox/hdl/common/codec/tests
plugins: qtb-0.2.3
collected 12 items

<Dir 8b10b>
  <Dir src>
    <Dir qblox>
      <Dir hdl>
        <Dir common>
          <Package codec>
            <Dir tests>
              <Module codec_8b10b_encdec_test.py>
                <Runner test_encoder>
                  <Testbench codec_8b10b_encoder_tb.py>
                    <Test simple_transfer_encoder>
                    <Test simple_transfer_encoder[count:1]>
                    <Test simple_transfer_encoder[count:16]>
                    <Test simple_transfer_encoder[count:1024]>
                    <Test simple_transfer_encoder[count:2048]>
                    <Test simple_transfer_encoder[count:4096]>
                <Runner test_decoder>
                  <Testbench codec_8b10b_decoder_tb.py>
                    <Test simple_transfer_decoder>
                    <Test simple_transfer_decoder[count:1]>
                    <Test simple_transfer_decoder[count:16]>
                    <Test simple_transfer_decoder[count:1024]>
                    <Test simple_transfer_decoder[count:2048]>
                    <Test simple_transfer_decoder[count:4096]>
```

Test filtering and selection

- Include or exclude tests based on their names and markers
  - Using `-k EXPRESSION` cmdline option. By default, pytest utility will run all tests.
- To run specific test(s) that will match provided expression:
  - `pytest -k <test-name>`
- With `or` statement:
  - `pytest -k '<test-name-1> or <test-name-2>'`
- With `and` and `not` statements:
  - `pytest -k '<test-name-1> and not <test-name-2>'`
- Use the `--collect-only` command line option to list all available names to be used later with `-k`:
  - `pytest --collect-only --quiet`

Test filtering and selection

- `pytest -s -k 'test_encoder and simple_transfer_encoder[count:1]'`

```
Test: src/qblox/hdl/common/codec/tests/codec_8b10b_encoder_tb.py::simple_transfer_encoder[count:1]
     0.00ns INFO     cocotb.regression                  running simple_transfer_encoder_001 (1/1)
                                                          Automatically generated test

                                                          count: 1
    20.00ns INFO     cocotb.regression                  simple_transfer_encoder_001 passed
.
Summary
    20.00ns INFO     cocotb.regression                  ********************************************************************************************************
                                                        ** TEST                                          STATUS  SIM TIME (ns)  REAL TIME (s)  RATIO (ns/s) **
                                                        ********************************************************************************************************
                                                        ** codec_8b10b_encoder_tb.simple_transfer_encoder_001   PASS          20.00           0.00      13148.95  **
                                                        ********************************************************************************************************
                                                        ** TESTS=1 PASS=1 FAIL=0 SKIP=0                                20.00           0.16        122.06  **
                                                        ********************************************************************************************************
```

Test logging

- pytest framework can colorize logs
  - add various colorful sections to increase readability
  - lot of options to configure Python logging from configuration file or command line.
- By default, pytest hides standard output from tests
  - It will show it only for failed tests. To disable it:

```
pytest --capture=no
pytest -s (shorthand)
```

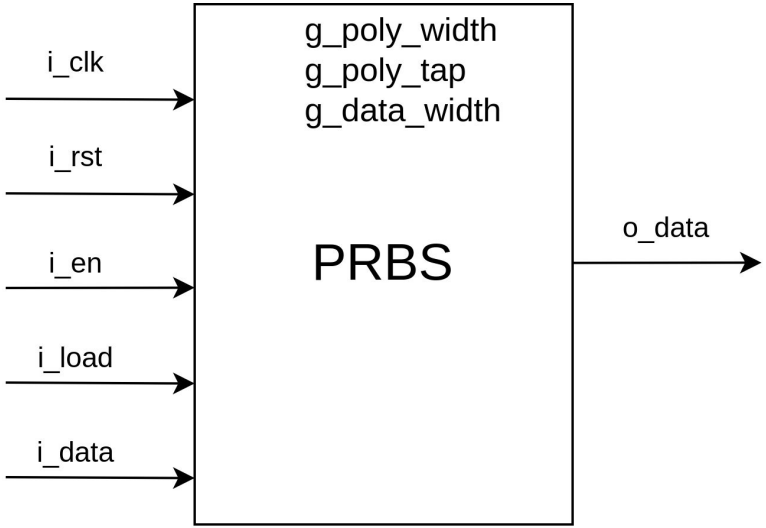
Test logging

```
**************************************************************************************************************
** TEST                                                STATUS  SIM TIME (ns)  REAL TIME (s)  RATIO (ns/s) **
**************************************************************************************************************
** codec_8b10b_decoder_tb.simple_transfer_decoder       PASS        4112.00           0.17      24299.91  **
** codec_8b10b_decoder_tb.simple_transfer_decoder_001   PASS          24.00           0.00      16845.30  **
** codec_8b10b_decoder_tb.simple_transfer_decoder_002   PASS          84.00           0.00      23980.79  **
** codec_8b10b_decoder_tb.simple_transfer_decoder_003   PASS        4116.00           0.17      24858.22  **
** codec_8b10b_decoder_tb.simple_transfer_decoder_004   PASS        8212.00           0.33      24733.75  **
** codec_8b10b_decoder_tb.simple_transfer_decoder_005   PASS       16404.00           0.68      24156.70  **
**************************************************************************************************************
** TESTS=6 PASS=6 FAIL=0 SKIP=0                                   32952.01           1.59      20765.16  **
**************************************************************************************************************
```

- Pytest log with standard output enabled
- Log files stored in **`sim`** directory, using standard python logging
- Each test result generated under name of TB combined with test name

Test parameterization

- Let’s take another example design - Pseudo Random Binary Sequence(**PRBS**) generator
- Usage of LFSR, based on standard polynomial (defined by generics **`g_poly_width`**, **`g_poly_tap`**), with parallel output (based on **`g_data_width`**)



Test parameterization

- Running different generics with the same test using pytest parametrize marker

```python
# Parametrizing different core widths and taps
@pytest.mark.hdl("common_lib.prbs")
@pytest.mark.parametrize(
    "g_poly_width,g_poly_tap", [(9, 5), (15, 14), (23, 18), (31, 28)]
)
def test_prbs_parametrized(hdl: HDL, g_poly_width, g_poly_tap):
    """Test PRBS with different cores"""
    hdl["g_poly_width"] = g_poly_width
    hdl["g_poly_tap"] = g_poly_tap
    hdl.test()
```

Pytest command line arguments

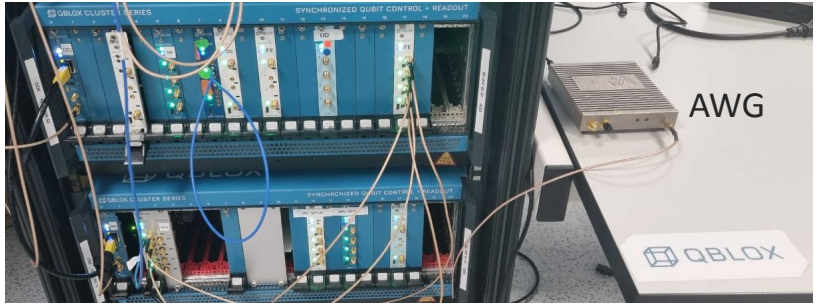
- Additional CLI arguments can be added using pytest_addoption
- Pytest is using standard Python built-in argparse module
- Only long names with double dashes -- are supported
- They will be part of pytest --help output
- They can be used in fixtures and tests
- Examples:
  - **`--gui`** to start HDL simulator with GUI
  - **`--hdl-coverage`** to enable HDL code coverage

Pytest plugin capabilities - pyloops

- Pytest plugin example for loops: https://pypi.org/project/pytest-loop
- Use the `--loop` command line option: `pytest --loop=10 test_file.py`
- Decorator:

```
import pytest
@pytest.mark.test_creation
@pytest.mark.loop(25 if PYLOOPS_ENABLED else 0)
def test_scope_acq_inp_cal(my_dut, awg):
    Pass
```

Pytest for validation



Validation v/s verification tests:

- Validation relies on availability of test equipment. Simulation resources are always present
- Functional checks performed in validation regression, similar to verification
- Stress-test a design until its limits. (temperature cycling, corner cases)
- Real-time tests

The Need for Dynamic Test Control in validation:

- Dynamic control over test variables and parameters
- "Knobs" for specific thresholds, edge cases, or critical events - pinpoint bugs

Pytest empowering validation

Parameterized Fixtures (`pytest.fixture(params=...)`): Running test with diverse input data or configurations

```python
@pytest.fixture (scope="session")
def my_dut():
    return My_qblox_module(IP = "101.101.101.101", slot = "2")

@pytest.fixture(scope="session")
def signal_generator():
    """Setup signal generator, then close."""

    print("\n--- Setting up signal generator connection---")
    signal_gen = set_sig_gen.SignalGeneratorDriver('101.101.101.101', 2020)
    signal_gen.set_power_state(0)

    yield signal_gen  # The object is given to the test.

    print("--- Tearing down signal generator connection ---")
    signal_gen.set_power_state(0)
    signal_gen.close()  # Cleanup, close connection, etc.
```

SETUP

YIELD

TEARDOWN

Pytest empowering validation

- **Pytest Hooks:** Allows reading external setup files (JSON/TOML).
- **Indirect Parametrization:** Similar to verification
- **Interactive Mode (via Custom Hooks):** Facilitates real-time debugging and immediate feedback.
  - Example: A custom hook can automatically drop the tester into a Python Debugger.

VS code integration with pytest

Benefits of Integration:

- Run tests in the editor.
- Breakpoints, step through code, inspect variables.
- Visual summary of test results.
- Test-driven development workflow.

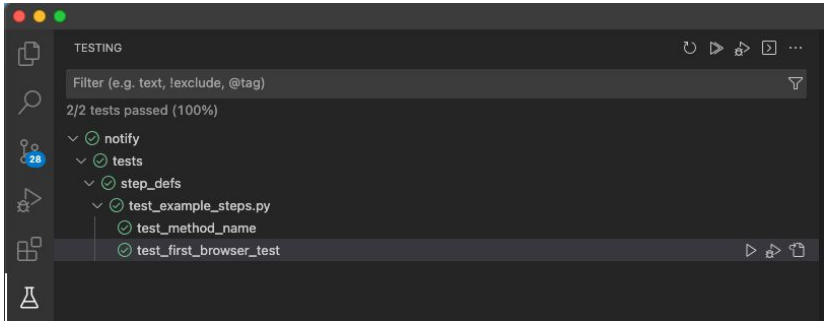
Easy to enable pytest:

- `pip install pytest`
- Open Command Palette: Ctrl+Shift+P
- Search for Python: Configure Tests
- Select pytest as your test framework.
- Specify Test Folder

VS code integration with pytest

Test Explorer View:

- Click the "Testing" icon in activity bar.
- See all your tests listed.
- Run test or multiple tests with a single click.
- "Debug Test" icon to start debugging.



Conclusion

- Pytest framework - unified testing approach
- Standardized but still customizable
- No need to reinvent the wheel
- Future work - pytest framework, plugins can be standardized to be used with HDL testing, and made open-source

Thank you

Questions?