New Constrained Random and Metric-Driven Verification Methodology using Python

Functional Verification is Software Engineering

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Agenda

- Functional verification scope – a different view
- Functional Coverage and Constrained Randomization
- Cocotb – Python-based verification environment
- New Functional Coverage architecture proposal
- New Constrained Randomization architecture proposal
- Working examples
- Summary

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What is Functional Verification?

- **Applying stimuli to the DUT and checking response**
  - **DUT as an RTL model – simulation or emulation**
  - **DUT as a (pseudo-)HLS model – pure software concern**

- **Testbench is a software program at the transaction level**
  - **Only Monitors and Drivers are time-aware**

Do we need *simulators* supporting verification process?

Functional Verification – a different approach

- Assume we only simulate DUT
  - Simulator not required to support HVLs
  - Free simulators can be used (e.g. Icarus Verilog)

- Testbench is a standalone application
  - API implementation needed to access simulator flow (e. g. VPI)

- Problem – VPI performance

Modern verification methodology

- **Constrained Randomization**
  - **Mechanisms that simplify applying random stimuli**
- **Functional Coverage**
  - **Need to observe whether all expected scenarios executed**
- **Regression Testing – Coverage Closure**
  - **A process that examines verification against a plan – meeting defined metrics**

Modern verification methodology

- High-level software verification - similar approach
- CRV an FC available as a part of HVLs syntax
- Regression Management – automated by EDA tools
- UVM – just a framework
  - Well understood only by UVM users
  - Resolves some typical use-case issues (like design patterns in software engineering)
  - UVM ≠ QUALITY

Constrained Random Verification

- Randomization of the data with given constraints:
  - Requires a constraint solver to be implemented
    - Part of the simulator – why here?

- System Verilog CRV syntax
  - Random variables
  - Constraints (soft constraints in SV2012)
  - Weighted distributions
  - *Constraint = function?*

```
constraint frame_sizes {
  size == NORMAL -> {
    length dist {
      [64  :  127 ] := 10,
      [128 :  511 ] := 10,
      [512 :  1500] := 10
    };
  }
  ...
}
```

source: http://www.asic-world.com/

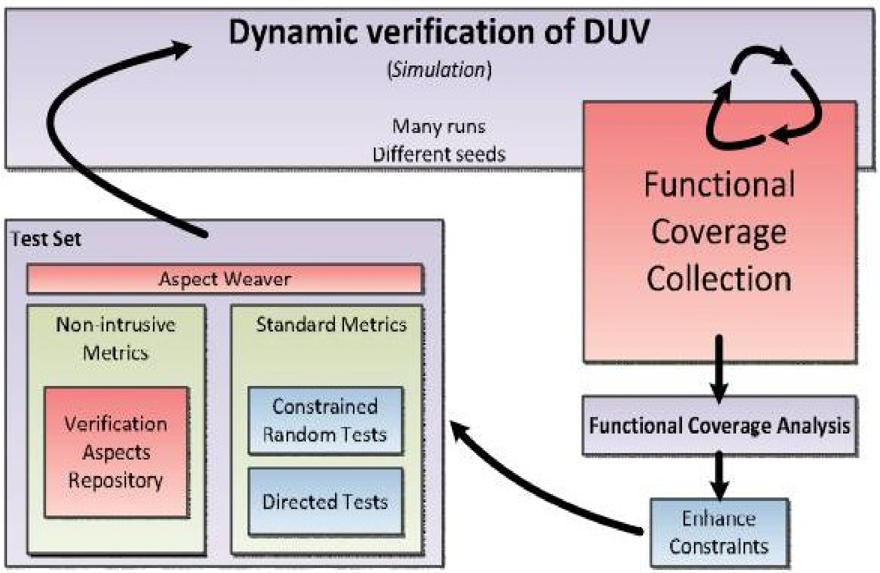
Metric-Driven Verification

- **Metrics need to be defined for verification process:**
  - **Test scenarios**
  - **Code Coverage**
  - **Functional Coverage**

- **SystemVerilog Functional Coverage syntax**
  - ***covergroup, coverpoint, cross***
    - ***bins*: signals, variables, sequences**
  - **Only countable features can be easily covered!**

Functional Coverage limitations

- Flat coverage structure
- Only naive bins matching
- Coverage data separated from the testbench data
- Example implementation issue: coverage driven test generation



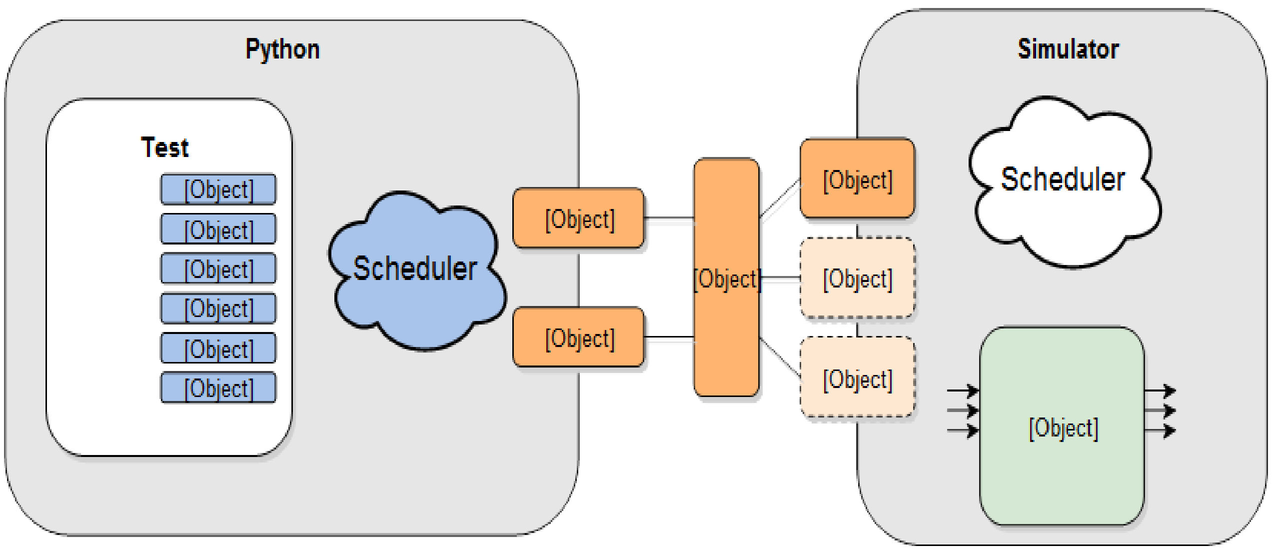
source: C. Kuznik and W. Mueller: Aspect enhanced functional coverage driven verification in the SystemC HDVL

Motivation for work

- Functional Verification as a software engineering
- Slow evolution of HVLs (and then – simulators)
- Lack of the „agility" of the verification process
- Expensive digital simulation environments

Cocotb

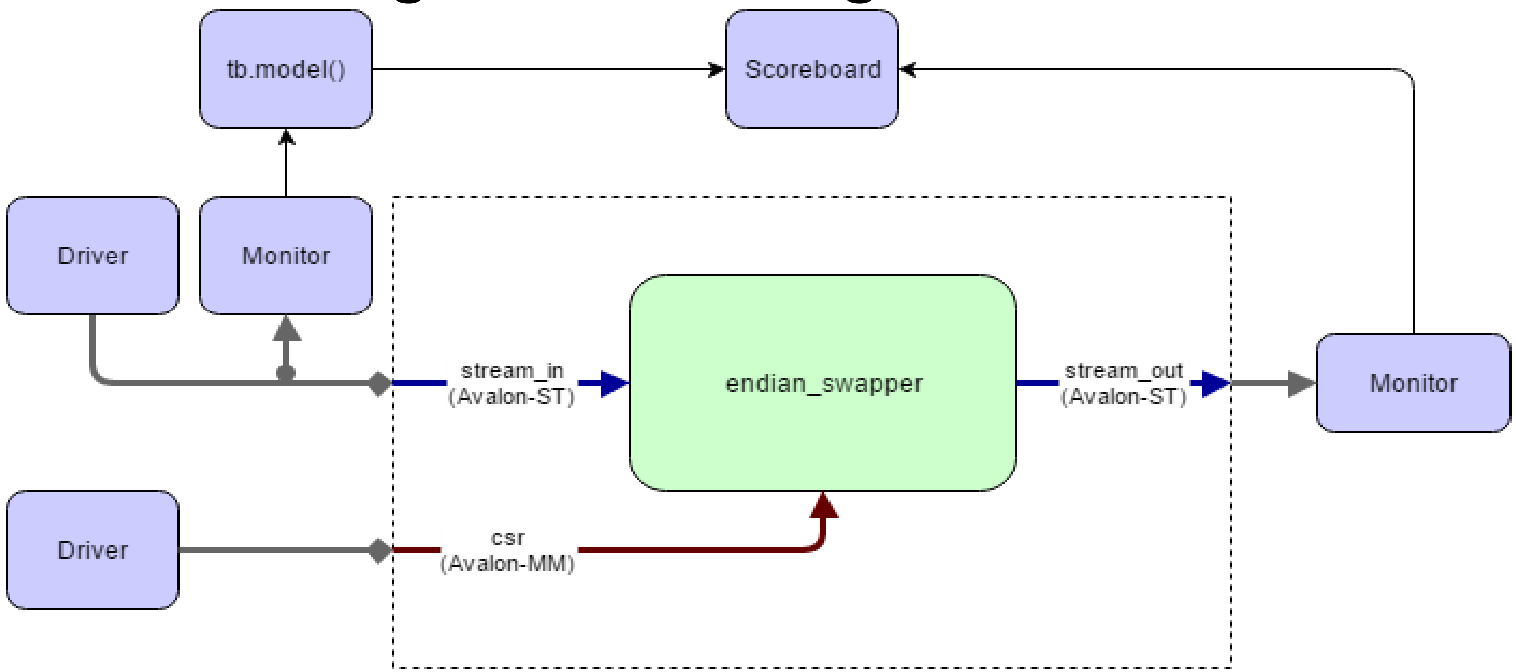
- **Cocotb is a COroutine based COsimulation TestBench environment for verifying VHDL/Verilog RTL using Python**
- **Cocotb is completely free, open source (under the BSD License) and hosted on GitHub**
- **Cocotb requires a simulator to simulate the RTL**



source: http://cocotb.readthedocs.io

Cocotb

- **Base testbench classes: Driver, Monitor, Scoreboard**
- **Easy interfacing to other languages**
- **Missing features: functional coverage, randomization mechanisms, regression management**



Python *functions*

- A function – first class citizen in Python (and many other modern languages)
  - Assigned or passed as an argument
  - Any object that is *callable*
  - Defined anywhere (inside other functions)
  - Lambda expressions
- Decorator design pattern

```
@decorator(x,y)
def my_func(f1, w, z):
      def inside_func(a,b):
        return a + b

      f2 = lambda a,b: a - b

      if (w < z):
        return f1(w, z)
      elif (w > z):
        return inside_func(w,z)
      else:
        return f2(w, z)
```

```
my_func = decorator(my_func, x, y)
```

New Constrained Randomization Mechanism

- A constraint – an arbitrary function
  - Returns true/false – hard constraint
  - Returns numeric value – distribution
    - Can be used for soft constraints
- API:
  - addRand(var), addConstraint(function)
  - post/pre_randomize(), randomize[_with]()
  - SolveOrder (solve … before)

Example: SV vs. Cocotb – randomization

```
class rand_frame;
  typedef enum {SMALL,MED,BIG}
    size_t;
  rand logic [15:0] length;
  rand logic [15:0] pld;
  rand size_t size;
  constraint frame_sizes {
    if (size == MED) {
      length >= 64;
      length < 2000;
    } else if (size == SMALL)  {
      length > 0;
      length < 64;
    } else if (size == BIG) {
      length >= 2000;
      length < 5000;
    }
    pld < length;
    pld % 2 == 0;
  }
endclass
```

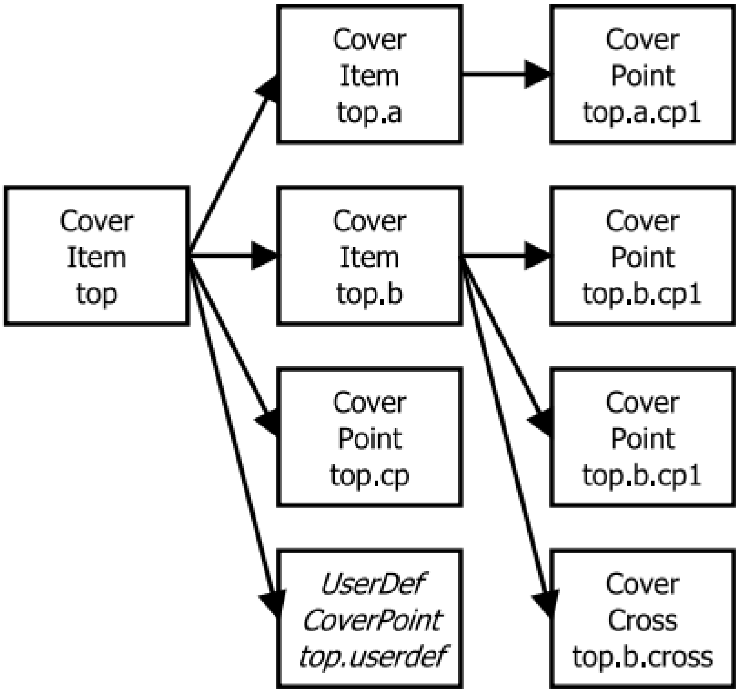
```
class rand_frame(crv.Randomized):
  def __init__(self):
    crv.Randomized.__init__(self)

    self.length = 0
    self.pld = 0
    self.size = "SMALL"

    self.addRand("size",["SMALL", "MED", "BIG"])
    self.addRand("length", list(range(1, 5000)))
    self.addRand("pld", list(range(0, 4999)))
    def frame_sizes(length, size):
      if (size == "SMALL") length < 64
      elif (size == "MED") 64 <= length < 2000
      else length >= 2000

    self.addConstraint(frame_sizes)
    self.addConstraint(
      lambda length, pld : pld < length
    )
    self.addConstraint(lambda pld : pld %2 == 0)
```

Example: Cocotb – advanced randomization

```
class TripleInt(Randomized)
  def __init__(self, x):
    Randomized.__init__(self)
    #this is a non-random value, determined at class instance creation
    self.x = x
    self.y = 0
    self.z = 0
    addRand(y, list(range(1000))) #0 to 999
    addRand(z, list(range(1000))) #0 to 999
    #HARD CONSTRAINT
    addConstraint(lambda x, y, z : x + y + z == 1000)
    #TRIANGULAR DISTRIBUTION
    addConstraint(lambda z: 500 - abs(500 - z))
    #MULTI-DIMENSIONAL DISTRIBUTION
    addConstraint(lambda y, z : 100 + abs(y - z))
    #SOFT CONSTRAINT
    addConstraint(lambda x, y : 0.01 if (y > x) else 1)
```

New Functional Coverage Mechanism

- **A tree (trie) sctructure**
- **Coverage primitive – a function decorator**
  - **Called each time at the function call**
  - **User can define own coverage types**
  - **SystemVerilog originated:**
    - **CoverPoint**
    - **CoverCross**



Example: SV vs. Cocotb – functional coverage

```
covergroup transfer;
  direction : coverpoint dir {
    bins read       = {0};
    bins write      = {1};
  }
  length : coverpoint length {
    bins short      = {[1:10]};
    bins long       = {[10:100]};
  }
  type : coverpoint type {
    bins type_a     = {A};
    bins type_b     = {B};
  }
  tr_cross : cross
    direction, length, type {
    ignore_bins ign =
      binsof(type) intersect {A};
  }
```

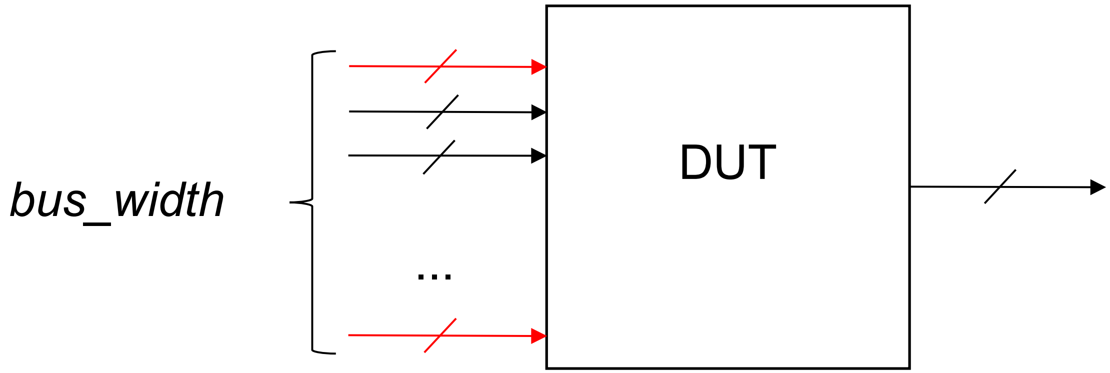
```
@CoverPoint( "transfer.direction",
  xf = lambda xfer : xfer.dir, bins = [0, 1]
  )
@CoverPoint( "transfer.length",
  xf = lambda xfer.length,
  bins = [(1,10), (10,100)],
  rel = lambda val, b: b(0) <= val <= b(1)
  )
@CoverPoint( "transfer.type",
  xf = lambda xfer.type, bins = [A, B]
  )
@CoverCross( "transfer.tr_cross", items =
  ["transfer.direction", "transfer.length",
   "transfer.type"],
  ign_bins = [(None, None, A)]
  )
def decorated_function(xfer):
  ...
```

Example: Cocotb – advanced functional coverage

```
simple_bins = [] #bins generation for coverage.tuple:
for i in range (1, 21): #for i = 1 to 20
  simple_bins.extend([(i, 'y'), (i, 'n')])

#transition function for coverage.transition
prev_value = 0; #previous value defined outside the function
def transition_inta(inta, intb, string): #function definition
  transition = (prev_value, inta) #transition as a tuple of (int, int)
  prev_value = inta #update previous value
  return transition

@CoverPoint("coverage.transition", xf = transition_inta,
  bins = [(1,2), (2,3), (3,4)])
@CoverPoint("coverage.primefactors",
  xf = lambda inta, intb, string : inta,
  rel = has_prime_factor, inj = True, bins = [2, 3, 5, 7, 11, 13, 17])
@CoverPoint("coverage.tuple",
  xf = lambda inta, intb, string : (inta + intb, string),
  bins = simple_bins)
def decorated_function(inta, intb, string):
  ...
```

Working test example

- **DUT: calculates mean value of *bus_width* inputs**
- **Verification requirement: check all possible data combinations on first and last input**
- **Random data order, radom data on other inputs**



Working test example

```
class StreamTransaction(Randomized):
    """
    randomized transaction
    """
    def __init__(self, bus_width, data_width):
        Randomized.__init__(self)
        self.bus_width = bus_width
        self.data_width = data_width
        self.data = ()

        list_data = range(0, 2**data_width)

        combs = list(itertools.product(list_data, repeat=bus_width))

        self.addRand("data", combs)

    def mean_value(self):
        return sum(self.data) // self.bus_width
```

Working test example

```
#functional coverage - check if all possible data values were
#sampled at first and last input
@cocotb.coverage.CoverPoint("top.data1",
  xf = lambda transaction : transaction.data[0],
      bins = range(0, 2**transaction.data_width)
    )
@cocotb.coverage.CoverPoint("top.dataN",
  xf = lambda transaction : transaction.data[transaction.bus_width-1],
      bins = range(0, 2**transaction.data_width)
    )
def sample_coverage(transaction):
      """
      We need this sampling function inside the class function, as
      transaction object needs to exist (required for bins creation).
      If not needed, just "send" could be decorated.
      """
      pass

sample_coverage(transaction)
```

Working test example

```
@cocotb.test()
def mean_mdv_test(dut):
    """ Test using functional coverage measurements and
        Constrained-Random mechanisms. Generates random transactions
        until coverage defined in Driver reaches 100% """


    dut_out = StreamBusMonitor(dut, "o", dut.clk)
    dut_in = StreamBusDriver(dut, "i", dut.clk)

    exp_out = []

    scoreboard = Scoreboard(dut)
    scoreboard.add_interface(dut_out, exp_out)

    data_width = int(dut.DATA_WIDTH.value)
    bus_width = int(dut.BUS_WIDTH.value)

    cocotb.fork(clock_gen(dut.clk, period=clock_period))
```

Working test example

```
dut.rst <= 1
for i in range(bus_width):
    dut.i_data[i] = 0
dut.i_valid <= 0

yield RisingEdge(dut.clk)
yield RisingEdge(dut.clk)
dut.rst <= 0

coverage1_hits = []
coverageN_hits = []

#define a constraint function, which prevents
#from picking already covered data
def data_constraint(data):
    return (not data[0] in coverage1_hits) &
           (not data[bus_width-1] in coverageN_hits)
```

Working test example

```
coverage = 0
xaction = StreamTransaction(bus_width, data_width)
while coverage < 100:
    #randomize with constraint
    if not "top.data1" in coverage_db:
        xaction.randomize()
    else:
        coverage1_new_bins = coverage_db["top.data1"].new_hits
        coverageN_new_bins = coverage_db["top.dataN"].new_hits
        coverage1_hits.extend(coverage1_new_bins)
        coverageN_hits.extend(coverageN_new_bins)
        xaction.randomize_with(data_constraint)

    yield dut_in.send(xaction)
    exp_out.append(xaction.mean_value())

    coverage = coverage_db["top"].coverage*100/
               coverage_db["top"].size

    dut._log.info("Current Coverage = %d %%", coverage)
```

Summary

- Verification is software engineering!
- SystemVerilog/UVM-based implementation is not efficient for complex programming tasks
- Cocotb may be an alternative for expensive simulators
  - Less code
  - Fast ramp-up

Cocotb with presented extensions is available online:
https://github.com/mciepluc/cocotb

Thank you!

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