

COMS31700 Design Verification: Checking

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(Acknowledgement: Avi Ziv from the IBM Research Labs in Haifa has kindly permitted the re-use of some of his slides.)



Checking - Outline

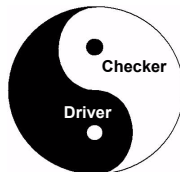
- Motivation
- Issues in checking
 - When to check
 - What to check
- Checking technologies
 - Reference models
 - Scoreboards
 - (Rule-based checking)
 - (Assertions)
 - Assertion-based verification (ABV) - later



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The Yin-Yang of Verification

- Driving and checking are the yin and yang of verification
 - We cannot find bugs without creating the failing conditions.
 - We cannot find bugs without detecting the incorrect behavior.



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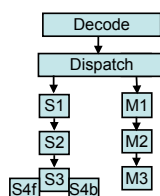
Ideal Checking

- In theory – detect deviation from expected behavior as soon as it happens and where it happens
 - No need to worry about “disappearing errors”
 - Easy to debug – the checker points to the bug
- This is not easy (even if we ignore many practical aspects) because in many cases we understand that something bad happened only in retrospect
 - Several “good” behaviors collide to create a bad behavior
- And what about the bugs we are not looking for?

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“Good” Behavior Collision

- At cycle 1000 **fdv** (F1) F2, F3 is dispatched to the M unit
 - It reaches stage M2 at cycle 1001
 - Its execution time is 60 cycles
- At cycle 1023 **fld** (F1) G2 is dispatched to the S unit
 - It reaches stage S2 at cycle 1024
- The data returns from the cache at cycle 1060
- At cycle 1061 the **fdv** is ready to write
 - It moves to stage M3
- At cycle 1061 the **fld** is ready to write
 - It moves to stage S3
- Both instruction write to the same register together



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“Good” Behavior Collision

- There are many possible causes for the problem

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Checking: Practical Aspects

Consider:

- The cost of *implementation and maintenance* of checkers

vs

- the cost of *debugging* (without checkers).
- The cost of mistakes
 - Missed detection
 - We failed to detect a bug that was exposed by the stimuli.
 - False alarm
 - We mistakenly flagged a good behavior as bad.

Which is more expensive?

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When to check

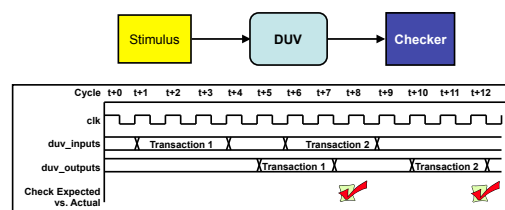
When to Check?

- Checking can be done at various stages of the verification job
 - During simulation
 - On-the-fly checking
 - At the end of simulation
 - End-of-test checking
 - After the verification job finishes
 - External checking
- Checking at each stage has its own advantages and disadvantages

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On-the-fly Checking

- Checking is done **while the simulation is running**
- The DUV is continuously monitored to detect erroneous behavior



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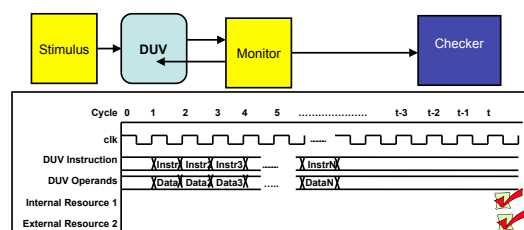
On-the-fly Checking

- **Advantages**
 - Detection can be as close as possible (in time and space) to the bug source
 - Can stop test as soon as bug occurs; no wasted simulation cycles
 - Do not require large traces and external tools to do the checking
- **Disadvantages**
 - May **slow down simulation**
 - Checking is limited to allowed time and space complexity
 - Need to **plan the checking in advance**
 - To add a new checker, we need to rerun simulation

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End-of-test Checking

- Checking is done **at the end of simulation**
- The checker checks the state of internal and external resources and makes sure that they are correct



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End-of-test Checking

Disadvantages

- Provides limited checking capabilities
 - Static look at the state of resources at the end of the test
- High probability of **masking bugs** by repeated writing to the resources
- Hard to detect performance bugs**
 - Correct things are happening, but not at the right time
- Hard to correlate symptoms to bugs
 - Hard to debug**

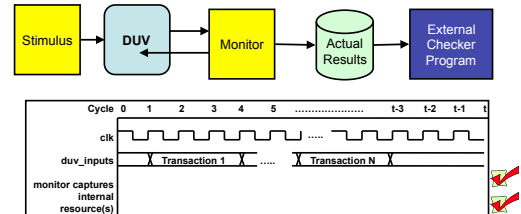
Advantages

- Simpler than other forms
 - May not require a deep understanding of the DUV
- Reduces probability of false alarms
 - (because bad effects may disappear)

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External Checking (Monitors)

- Monitors** keep internal resources' values and behaviors in trace files
- Checking is done by an external program that examines these files



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External Checking

External checking **separates the checking from the simulation**

- We can perform any check we want without rerunning the simulation
 - As long as the data is in the trace files
- We can perform more complicated checks
 - Use longer history, process events out-of-order
- We can combine information coming from different sources
 - For example, different verification environments

In theory, external checking has all the powers of on-the-fly checking plus end-of-test checking - plus more

(Trace size and amount of traced facilities is a practical limitation.)

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What to check

What to Check

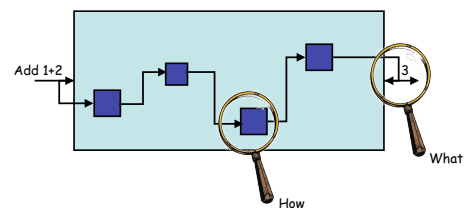
There are five main sources of checkers

- The **inputs and outputs** of the design (specification)
- The **architecture** of the design
- The **microarchitecture** of the design
- The **implementation** of the design
- The **context** of the design
 - e.g. protocol compliance

(Slide from a previous lecture to remind us of where we can get inspiration for checkers from.)

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Coarser Classification – The What and the How



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Checking the What

- Check the **final outcome** of a behavior
 - **Data oriented**
 - But not limited to data
 - **Usually based on higher level of abstraction**
 - Checking is less tight
 - Requires less familiarity with the DUV
 - **Low correlation between **failure**, the observed behavior that violates the spec, and **bugs/faults**, the root cause of the failure**
 - Harder for debugging
 - Can find “unexpected” bugs

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Checking the How

- Check **how things are done internally**
 - **Control oriented**
 - **Usually at lower levels of abstraction**
 - Closer to implementation
 - **Tighter correlation between failure and bugs**

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Stimuli Generation and Checking

- In general, **checking should be isolated from the stimuli generation**
 - **Modularity** – ability to replace the stimuli generator
 - **Reusability** – ability to use the checkers at higher level of the design hierarchy
 - **Independence of Checking from Generation**
- Exceptions
 - Self-checking tests
 - Golden vectors
- **Can stimuli generation assist checking?**
 - The **stimuli generation can assist checking** by improving observability
 - Help transfer events from dark corners to the spotlight

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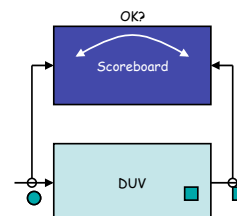
Checking Technologies

Scoreboards

- Scoreboards are **smart data structures** that keep track of events in the DUV during simulation
- Usually, scoreboards are global
 - **One scoreboard per verification environment**
- Scoreboards are not checking mechanisms, but
 - The main purpose of using scoreboards is for checking
 - In practice, many checkers are implemented inside scoreboards
 - There are many typical checks that are done with scoreboards

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Scoreboard Operation



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Scoreboards Overview

- Scoreboards source information from
 - the inputs and outputs of the DUV, and
 - occasionally also from internal events in the DUV.
- **Scoreboards are very useful in dataflow designs**
 - Routers, cache designs, queues
- Types of checks enabled using a scoreboard:
 - Matching outputs with inputs
 - No loss of data
 - Detect inputs with no matching output.
 - No creation of data
 - Detect output with no matching input.
 - No unintended modification of data
 - Timing specification
 - Delay from input to output remains within specified limits.
 - Data order

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Scoreboarding in e - 1

- Assume: DUV does not change order of packets.
 - Hence, first packet on scoreboard has to match received packet.

```
import packet_s;
unit scoreboard {
  !expected_packets : list of packet_s;
  add_packet(p_in : packet_s) is {
    expected_packets.add(p_in);
  };
  check_packet(p_out : packet_s) is {
    var diff : list of string;
    -- Compare physical fields of first packet on scb with p_out.
    -- Report up to 10 differences.
    diff = deep_compare_physical(expected_packets[0], p_out, 10);
    check that (diff.is_empty())
    else dut_error("'Packet not found on scoreboard'",
    diff);
    -- If match was successful, continue.
    out('Found received packet on scoreboard.'');
    expected_packets.delete(0);
  };
};
```

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Scoreboarding in e - 2

Recording a packet on the scoreboard:

- Extend driver such that
- When packet is driven into DUV call `add_packet` method of scoreboard.
 - Current packet is copied to scoreboard.
 - It is useful to define an `event` that indicates when packet is being driven.

Checking for a packet on the scoreboard:

- Extend receiver such that
- When a packet was received from DUV call `check_packet`.
 - Try to find the matching packet on scoreboard.
 - It is useful to define an `event` that indicates when a packet is being received.

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Side Note – Graceful End-of-test

- **Checking that nothing is lost is very important**
- If an input does not have a matching output, how can we distinguish between these two cases:
 - The input is lost or hopelessly stuck in the DUV
 - The DUV did not have enough time to handle the input
- Possible solution – Start a timer when a new input enters the DUV
 - If the timer expires, that input is lost or stuck
 - But, what if the delay cannot be bound?
- Alternative (or complementary) solution – stop the inputs before the end of the test and let the design clean itself
 - Because there are no new inputs, things that are stuck inside have a chance to get free

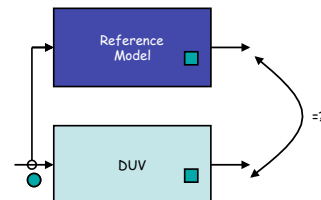
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Reference Models

- **A reference model is an oracle that tells how the DUV should behave**
 - Usually in the form of an alternative implementation
- It runs in parallel to the DUV, using the same inputs and provides the checking mechanisms with information about the expected behavior
 - Checking is done by comparing the expected behavior to the actual one
- Pure reference models can run independently of the DUV
 - But not all reference models are pure (example later)

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Reference Model Operation



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Reference Models

- Reference models have many uses
 - Checking
 - Aids for stimuli generation
 - "Smart" protocol models – imitate the function of the DUV (When?)
 - Vehicles for SW development
- What can we check with a reference model
 - In principle, anything
 - In practice it depends on the level of detail and accuracy of the reference model
 - And how much of its behavior we are willing to expose

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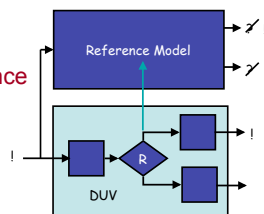
Levels of Abstraction

- The level of abstraction in a reference model dictates the type of information we can get out of it for checking
 - Functionally accurate models can be used only to check correctness of data, usually at the end of the test or at well defined points in time
 - Timing, order, and other checks need other means
 - Cycle accurate models can be used for checking all aspects of I/O behavior
 - Cycle accurate and latch accurate models can be used also for checking the internal state of the DUV
 - This type of model is sometimes called deep function reference model

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Impure Reference Model

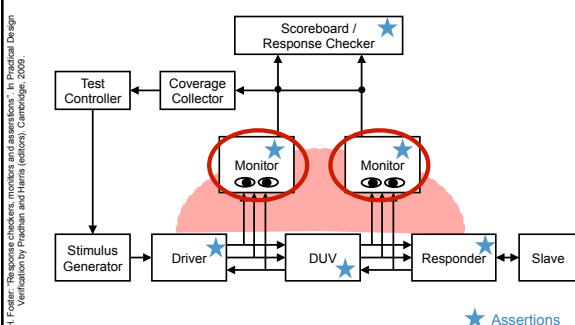
- Sometimes it is impossible (or very hard) for the reference model to duplicate significant decisions made by the DUV
- Possible solution:
Use information from the DUV to assist the reference model!



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Contemporary TB Architecture

Contemporary Testbench Architecture



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Monitors

- Monitors are TB components that observe the inputs, outputs, or internals of the DUV.
 - Monitors watch activity of the DUV.
 - Black box: DUV inputs and outputs
 - Grey box: potentially selected internals
 - Monitors can convert low-level signals to transactions.
 - Monitors can flag simple timing and protocol errors.
 - Monitors collect functional coverage.
 - Monitors update the scoreboard.
 - Monitors don't drive DUV pins; they are "passive".
 - Monitors are self-contained and don't cause "side effects".
 - Monitors are re-usable at different levels of abstraction.

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Types of Monitors

- Input monitors:
 - Collect inputs to the DUV and pass them to scoreboard.
 - Can have checker components.
- Output monitors:
 - Observe the outputs from the DUV and pass them to the scoreboard.
 - Can have checker components.
- Coverage monitors:
 - Collects inputs, outputs and selected internal signals.
 - Permit analysis of stimulus and functionality coverage.

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Rule-based Checking

- Checks that a set of rules hold in the DUV
- Essentially, all checking is rule-based, e.g.

```
if (not "something") then error
```

- where the “something” can be
 - Value of a register matches value in reference model
 - Data in a packet at the DUV output matches data in the input as stored in the scoreboard
 - `response_out == 0 → data_out == 0`

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Rule-based Checking

- Rules can come from many sources
 - All levels of the design process
 - Spec, high-level design, implementation
 - Behavior of neighboring units
- Rules checking can be implemented in many places
 - External checking tools
 - Various places in the verification environment
 - Interface monitors
 - Scoreboards
 - End-of-test checkers
 - In the DUV itself
- Rule-based checkers embedded in the DUV code are called **assertions**
 - Lecture on **Assertion-Based Verification**

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Self-Checking Testbenches

- Knowledge of the DUV functionality can be built into the TB.
 - This *automates* the checking process.
 - Verification engineers encode their knowledge of correct DUV functionality into the checkers, monitors and scoreboard using:
 - Golden Vectors,
 - Reference Models,
 - Protocols or Transactions,
 - Assertions.
- This results in a **“self-checking” TB**.
 - Checkers are “always” active.

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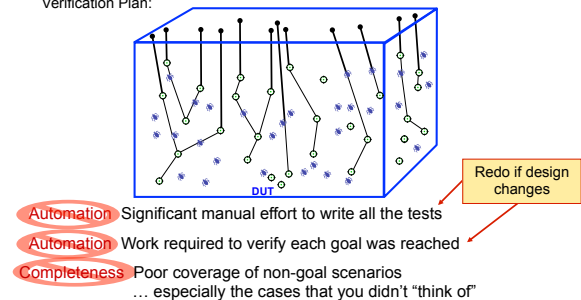
Putting Coverage, Generation and Checking together:

The Verification Environment

(With many thanks to Cadence for providing the animations in this section.)

Traditional Approach: Directed Testing

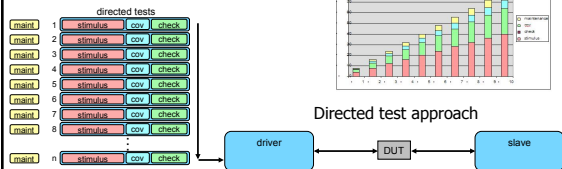
Verification engineer sets goals and writes directed test for each item in the Verification Plan:



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Directed Test Environment

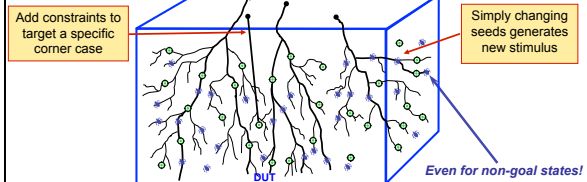
- Composition of a directed test
 - Directed tests contain more than just stimulus.
 - Checks are embedded into the tests to verify correct behavior.
 - The passing of each test is the indicator that a functionality has been exercised.
- Reusability and maintenance
 - Tests can become quite complex and difficult to understand the intent of what functionality is being verified.
 - Since the checking is distributed throughout the test suite, it is a lot of maintenance to keep checks updated.
 - It is usually difficult or impossible to reuse the tests across projects or from module to system level.
- The more tests you have the more effort is required to develop and maintain them.



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Coverage Driven Verification Methodology: Defining Coverage "Goals" Enables Automation

Focuses on reaching **goal areas** (versus execution of test lists):



Constrained-random stimulus **generation** explores goal areas (& beyond).

Coverage shows which **goals** have been exercised and which need attention.

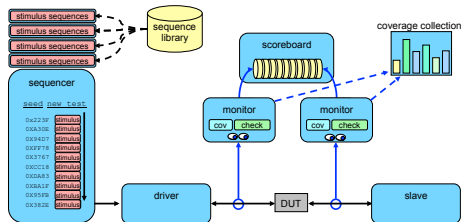
(Checking needs to be in place to assess DUT response.)

Automation – Constrained-random stimulus accelerates hitting coverage goals and exposing bugs. Coverage and checking results indicate effectiveness of each simulation, which enables scaling many parallel runs.

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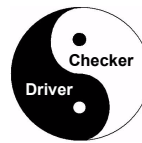
Coverage Driven Environment

- Composition of a coverage driven environment
 - Reusable stimulus sequences developed with "constrained random" generation
 - Running unique seeds allows the environment to exercise different functionality
 - Monitors independently watch the environment
 - Independent checks ensure correct behavior.
 - Independent coverage points indicate which functionality has been exercised.



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Summary



- Stimuli Generation
- Coverage and
- Checking

Coverage Driven Verification Methodology

→ Coverage Directed Test Generation

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