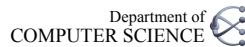


## COMS31700 Design Verification: Stimuli Generation

Kerstin Eder

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



## Last Time

- Coverage
  - Code
  - Structural
  - Functional
- Coverage analysis

2

## Outline

- Motivation
- Running example – PowerPC processor
- Issues in stimuli generation
  - Level of stimuli, test length, etc.
- Randomness
- Mapping stimuli generation to Constraints and Constraint Satisfaction Problems (CSP)

3

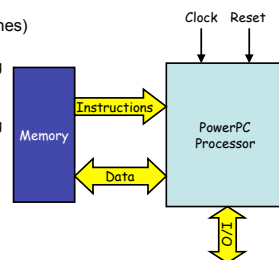
## Goals of Stimuli Generation

- Achieve all the items in the test scenarios matrix of the verification plan
  - Ensure that the scenario in the matrix is happening
  - Ensure that “bad effects” are propagating to an existing checker
    - Hitting a bug without exposing it is worth nothing
- But also
  - Hitting and exposing all the problems we did not think about in the verification plan
  - Provide information about the design and help recreate and understand problems
  - Ensure that nothing gets broken over time

4

## Running Example – PowerPC Processor

- Black box view
  - Interface to memory (via caches)
    - For instruction fetching
    - For data fetching and storing
  - Interface to I/O devices
    - For data fetching and storing
    - Interrupts
  - Miscellaneous interface
    - Clocks
    - Reset
    - ...



5

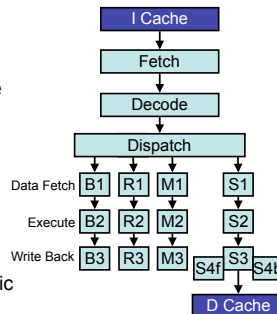
## Architectural View

- RISC (Reduced Instruction Set Computer) processor
  - “Small” number of instructions (~400)
  - One simple operation per instruction
  - Fixed length instructions (32 bits = 1 word)
  - Specific load and store instructions to access memory
    - All other instructions use registers for operands
- Large register files
  - 32 general purpose registers (GPR)
  - 32 floating-point registers (FPR)
    - Used only for floating-point operations
  - Several special purpose registers
    - Condition register, link register, status register, etc.
- Complex memory model
  - Multiple level address translation
  - Coherency rules
  - (not in the scope of the lecture)

6

## Microarchitectural View

- Multithreaded
- In-order execution
- Four instructions wide
  - Fetch
  - Decode
  - Dispatch
- Four execution units
  - B – Branch
  - S – Load Store
  - R – Simple Arithmetic
  - M – Complex Arithmetic



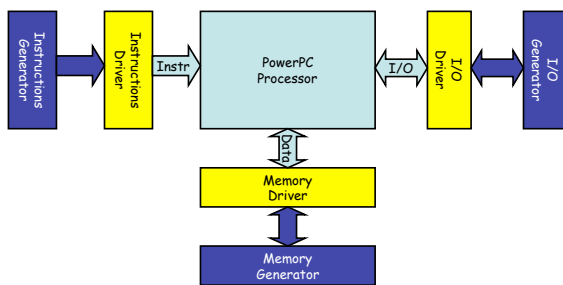
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## Extracts from the Verification Plan

- Check that **all pairs of instructions** are executed correctly together
  - Basic architectural requirement
  - Appears in most verification plans of processors
  - Fulfilling it is not as easy as it seems
- Check that all **forwarding mechanisms** between pipeline stages are working properly
  - Basic microarchitectural requirement
  - Source for many bugs in previous designs
- Check that **dispatch queue is not overfilled**
  - Hard to reach corner case

8

## Processor Verification Environment



9

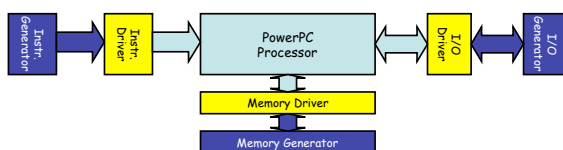
## Issues in Stimuli Generation

- How many generators?
- Level of abstraction
- Online vs. offline generation
- Dynamic vs. static generation
- Test length
- Randomness

10

## How Many Generators?

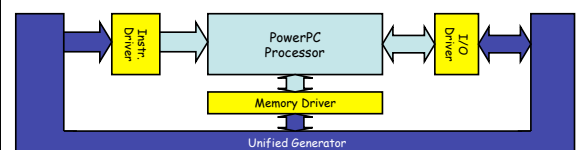
- Distributed generators
  - Each interface has its own generator
  - Each generator works on its own
  - Advantages
    - Simple
    - Easy to reuse
  - Disadvantages
    - Hard to reach corner cases in coordinated fashion



11

## How Many Generators?

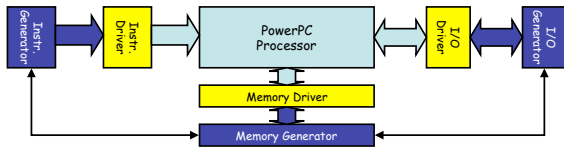
- Single generator
  - One generator controls all the interfaces
  - Advantages
    - All the interfaces can work together toward a common goal
  - Disadvantages
    - Complex
    - Hard to reuse



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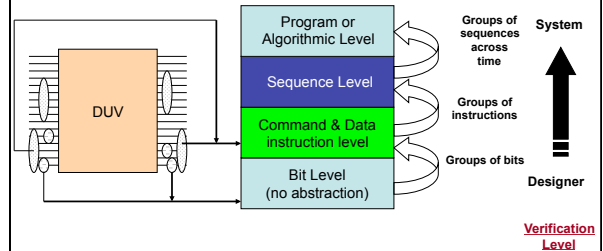
## How Many Generators?

- Synchronized generators
  - Each interface has its own generator
  - The generators share information and synchronize
  - Advantages
    - Can reuse each generator separately
    - Can work together towards a common goal



13

## Abstraction Level of Generation



14

## What Does Abstraction Level Mean?

- Communication between: **the user and the generator**
  - How the user specifies directives to the generator
- Internal representation and operation level in the generator
  - The level in which the generator generates the stimuli
- Communication between: **the generator and the driver**
  - The generator sends information at high level of abstraction
  - The driver translates into bits using the appropriate protocol

15

## Which Abstraction Level To Choose?

- Communication **between the user and the generator**
  - Use level similar to the level of the verification plan
  - In our case – the sequence level
- Internal representation and operation level in the generator
  - Conflicting requirements
    - Address user requests (at their level) → high level of abstraction
    - "Dxxxx is in the detail." → low level of abstraction
  - In many cases we use two or more levels of generation
    - First we build a high-level skeleton of the stimuli based on the user request
    - Next we add lower-level details
- Communication **between the generator and the driver**
  - Use the lowest level in which the generator operates
  - Special case – error injection

16

## Error Injection

- Error detection and recovery are very important mechanisms in hardware designs
  - They are also very hard to verify
- Error injection is usually **done at the lowest level of abstraction**
  - The value of a bit (or set of bits) is flipped when they are injected into the DUV
- To allow error injection, the generator needs to operate and **communicate with the driver at the bit level**
  - This creates extra burden and unnecessarily increases complexity for normal cases
- Possible solution – create **separate error injection interface** between the generator and driver
  - At the **low level** of the error injection
  - At the **normal level** with instructions on how to inject the error

17

## Online Vs Offline Generation

### When to generate stimuli?

- **Online** generation (on-the-fly):
  - the stimuli generation generates the stimuli **during simulation**
    - The next element is generated when needed by the driver
    - The generator must be part of the verification environment
- **Offline** generation (pre-run) – the entire stimuli is generated **before the simulation** begins
  - The generation and simulation can be two separated processes

18

## Online Generation

- Why
  - The generator is part of the verification environment
  - It can use information about the [state](#) of the environment and DUV for improving the quality of generation
    - Makes reaching corner cases easier
  - The only solution for responders
  - Generally small memory footprint
- Why not
  - Must generate items in order
  - Limited complexity

19

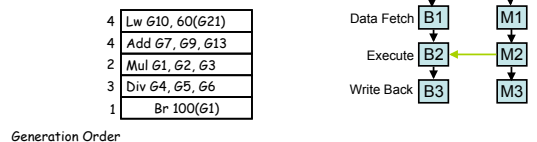
## Offline Generation

- Why
  - Can separate the generation from simulation
    - Use external tools, emulation, ...
  - Can use more complex algorithms for generation
    - For example, [generate](#) out of order
  - May be compulsory (Where?)
- Why not
  - Need to integrate generator to the verification environment
  - Cannot use information from the DUV and environment
  - Hard to create responders

20

## Generating Out Of Order

- Goal – forward data from M2 to B2
  - Branch is dispatched after arithmetic instruction
  - Both reach stage 2 together
  - Branch waits for the arithmetic instruction to complete



21

## Mixing online and offline Generation

- Online and offline generation can be mixed within a verification environment
- Which designs would benefit from this combination?
  - (Example will be discussed in lecture.)

22

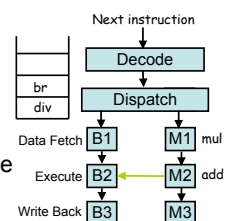
## Dynamic vs. Static Generation

- In [static generation](#) the generator is not aware of the state of the DUV and the environment
  - Generation decisions are based entirely on the internal state of the generator
  - Less restrictive definition – the generator is aware of what and when it is allowed to generate
    - In calc1 the generator knows not to generate a new command before a response is received
- In [dynamic generation](#) the generator is fully aware of the state of the DUV and the environment and generates based on this information
  - The generator can react to interesting states in the DUV

23

## Dynamic Generation Example

- Goal – forward data from M2 to B2
  - The generator identifies potential forwarding condition
  - Generates instruction that will block the branch from dispatching with mul
  - Generates br instruction with same register to create dependency



24

## Does This Example Work?

- This example may not work!
- Main reason:
  - The distance from the entry point of instructions to the processor to the dispatch queue
  - Many bad things can happen while the br instruction travels this distance
    - For example, exceptions that flush the pipes
  - By the time it reaches the relevant stage in the pipe, the interesting condition is already gone

25

## Dynamic Vs. Static Generation

- **Dynamic generation** is based on **reaction** while **static generation** is based on **planning**
- In general, reaction is harder than planning
  - Time is a factor
  - Unexpected events
- **Most generators use dynamic features lightly**
  - Observe and react to shallow or stable states and resources
    - For example, architectural registers

26

## Offline Dynamic Generation

- Dynamic and static generation should not be confused with online and offline generation
- Offline generator can use dynamic generation by using a **reference model** that provides information about the state of the DUV
  - The level and accuracy of the information depends on the abstraction level and accuracy of the reference model

27

## Test Length

- Two extreme approaches for selecting the test length
- Use **short tests**
  - The shortest tests that can fulfill the requirement in the verification plan
  - For the instruction pairs requirement use tests with just two instructions ☺
- Use **long tests**
  - Combine many requirements in a single test
  - Wrap a test with initial and ending sequences

28

## Why Short Tests?

- Easy to create
- Easy to debug
- Easy to maintain
- Short time to simulate

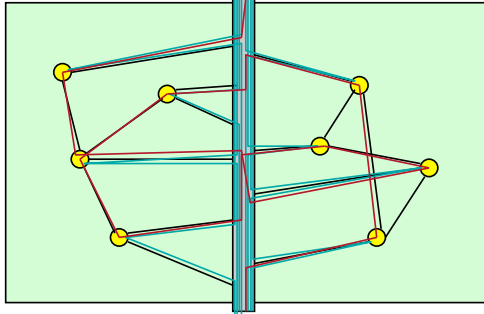
29

## Why Long Tests?

- Need fewer tests
- Less time to simulate
  - Do not need to repeat initialization sequence for every requirement
- Test is not at or near the initial state most of the time
- Use less traveled paths
- Reach target in more ways
  - Often leads to reaching the target in unexpected ways

30

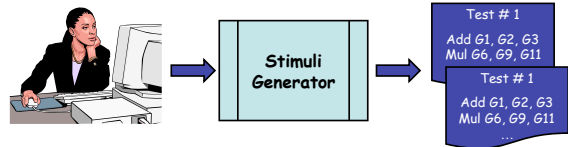
## Short Vs. Long



31

## Randomness - Motivation

- The first time we press the button a test is created
- What happen when we press the button a second time?
  - **The same test appears**
  - our stimuli generator is deterministic



32

## Why Deterministic?

(Do not confuse deterministic with manual!)

- Useful before random environment is ready
  - It is much easier to create a driver that reads deterministic tests and injects them into the DUV
- Previously developed test suite
  - For example, architectural compliance suite
- Known quality
- Avoid extremely long generation time

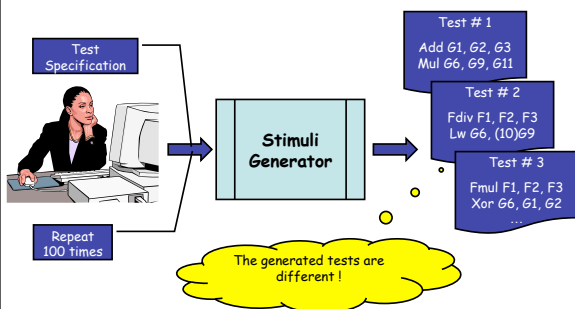
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## Why Not Deterministic?

- A given test can be used only once
  - It is useless unless something has changed in the
    - DUV
    - Environment
- The test specification has limited reuse capabilities
- Modern verification methodology employs many workstations that simulate many test cases
  - We cannot afford to provide different test specifications for each test case simulated
- What about hitting and exposing all the problems we did not think about in the verification plan?

34

## Random Stimuli Generation



35

## Pure Random Generation

- The opposite end of the spectrum to deterministic generation
- The generator generates random sequences of '0' and '1' that are packed into instructions
- Theoretically, this might seem like the ideal solution
  - Avoid blind spots in the verification plan
- BUT practically,
  - not very useful for verification
    - Most generated test cases are invalid
    - Most valid test cases are not interesting



36

## Side Note – Pseudo Random

- Random decisions are controlled by a **seed**
  - Given the value of the seed, random decisions are deterministic
  - Each random decision updates the value of the seed (in a deterministic fashion)
- **Pseudo random** is essential in verification because of the need to reproduce specific tests
  - For example, to reproduce bugs
- Requirement for **Pseudo Random Test Generator**:
  - Need (at least) **repeatability!**
    - Achieved by using same seed to seed generator.

37

## Constrained Random Generation

- The stimuli generator is **constrained** to generate
  - Valid tests
  - Tests that meet the user requests
- There are many (infinite) number of tests that fulfill these constraints
- The generator can choose any such test



38

## Example – Instruction Pair Generation

- The test specification is a test with an **add** instruction followed by an **xor** instruction
  - Comes from the first extract of the verification plan
- The test should look like
- Everything else can be randomized

```
add_xor_test
Start:
...
Add ??, ??, ??
Xor ??, ??, ??
...
```

39

## Random Decisions for add\_xor\_test

- Processor operation mode
- Start address of the program
- Prelude sequence
- Epilogue sequence
- Registers of add instruction
- Data of add instruction
- Registers of xor instruction
- Data of xor instruction
- Behavior of caches, I/O, ...
- ...

40

## How To Make Random Decisions

- **Pure random** decisions
  - Most tests will be invalid
- **Constrained random** decisions
  - Limit random decisions to those that lead to **valid tests**
  - Choose uniformly among valid possibilities
  - Result
    - Generated tests are valid
    - Most random decisions are not interesting
    - Small gain in test quality
- **“Smart” constrained random** decisions
  - **Bias** decision toward interesting cases
  - Can lead to significant **improvement in test quality**



41

## “Smart” Decisions for add\_xor\_test

- Start address of the program
  - Page 0
  - Start of page
  - Near end of page
- Registers of add instruction
  - G0
- Data of add instruction
  - Result = 0
  - Overflow
  - Long sequences of ‘1’ (long carry chains)
- Registers of xor instruction
  - Same registers as add instruction

42

## Smart Decisions

- These decisions usually represent **generic knowledge of what is interesting in verification**
  - Add with result 0 is interesting in all addition operations
  - Interdependency between registers is interesting in all processors
  - G0 is an interesting operand in all PowerPC processors
- This collection of knowledge is often called **"Testing Knowledge"**
- The testing knowledge is usually **incorporated in the generation environment**
  - The generation tool you buy
  - The generation driver you develop

43

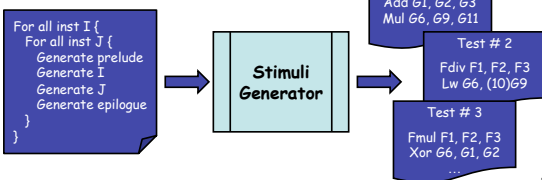
## Using Testing Knowledge

- Testing knowledge is applied automatically to generated stimuli where possible
- The generator **biases random decisions towards interesting scenarios using the testing knowledge**
  - Other cases are not shut-down completely to avoid missing cases we never thought about.
- Stimuli generators that use testing knowledge are often called **"biased random stimuli generators"**
- Users can **change the bias** of items in the testing knowledge as part of the test specification
  - We will see examples later and can explore how this works when developing the testbench for A2. ☺

44

## All Instruction Pairs Generation

- With biased random stimuli generator we can generate tests that cover all the specific items of the **all instruction pairs** extract from the verification plan
- Every activation of the test specification will produce a new high-quality test suite



45

## Forwarding Path Generation

- The same approach cannot work for the forwarding path requirement
  - There is a difference between the language of the test and the language of the requirement
    - The test language is instructions, registers, memory
    - The requirement language is **microarchitectural** events
- Three possible solutions
  - Manual translation
  - Automatic translation
  - "Loose" generation

46

## Manual Translation

- The user provides a description of an instruction sequence that creates the event
  - For example, mul followed by div followed by br, where br uses same register as target of mul
- The generator randomly fills in missing details
  - For example, registers and data of div
- Suffers from all the **disadvantages of manual test creation**
  - Labor intensive
  - Error prone
  - Hard to maintain

47

## Automatic Generation

- The generator is aware of the microarchitecture of the processor and knows how to translate a microarchitectural request to a sequence of instructions
  - Such generators are often called **"Deep Knowledge"** test generators
- Advantages
  - Generated tests cover the requested event with high probability
- Disadvantages
  - High development cost
  - Potentially long generation time
  - Sensitive to changes in the design → high maintenance cost

48



## "Loose" Generation

Rely on the power of **massive** generation

- Use the "normal" test vocabulary to **bias** the generated tests **toward tests that improve the probability of hitting the requested event**
  - Increase probability of complex arithmetic and branch instructions
  - Increase probability of read after write dependency
- Coverage** is used to ensure that the requested events did occur
- Usually, **one test specification** will be used to cover **many items in the verification plan**

49

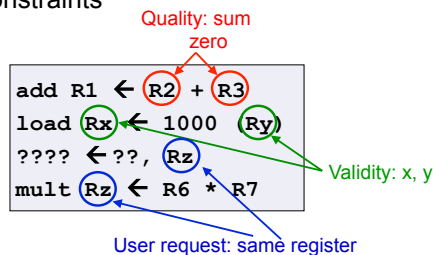
## Summary: Requirements from Stimuli Generator

- Generated stimuli need to be
  - Valid
    - Behavior of DUV under the test is fully specified
      - NOTE: Valid is not necessarily legal
    - The verification environment can determine if the DUV behaved correctly
  - Interesting
    - Improve coverage
    - Reach corner cases
    - Find bugs
  - Meet specific user requirements
    - Resource reuse, interdependencies

50

## Test program constraints

All requirements can be expressed as constraints



51

## Constraint Satisfaction Problem Definition

[ Mackworth, Freuder, Montanari, Dechter, Rossi, ... ]

- CSP  $P = \{V, D, C\}$
- Variables  $V$ 
  - Address
  - Register\_value
- Domains  $D$  (finite sets) for each variable
  - Address: 0x0000 - 0xFFFF
  - Number of bytes in a 'load': { 1, 2, 4, 8, 16 }
- Constraints  $C$  (relations) over variables
  - (load n bytes)  $\rightarrow$  (align address to n bytes boundary)
  - value(base\_reg) + displacement = address

52

## Solution for Constraint Satisfaction Problem

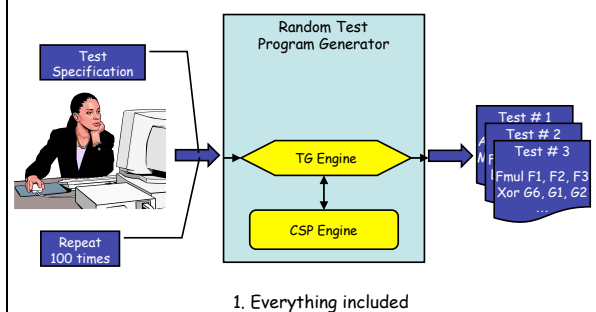
- Every variable is assigned a value from its domain, such that all constraints are satisfied
  - All solutions are born equal.
  - There is no better or best solution!

Example

- Variables: a, b, c
- Domains:  $A = \{1,2,3\}$ ;  $B = \{2,3,4,5\}$ ;  $C = \{1,3,5\}$
- Constraints:
  - $a^2 < b$  ;  $c \neq b$  ;  $a < c - 1$
- (One) Solution:
  - $a = 1$  ;  $b = 4$  ;  $c = 3$

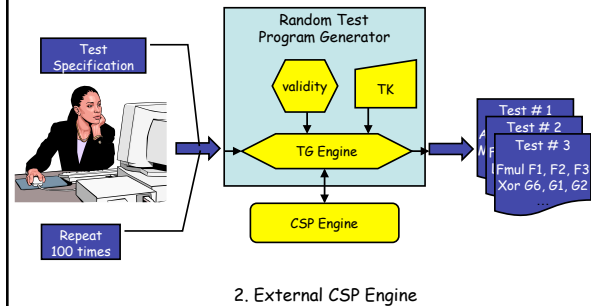
53

## Putting It All Together: Building a Random Test Program Generator - I



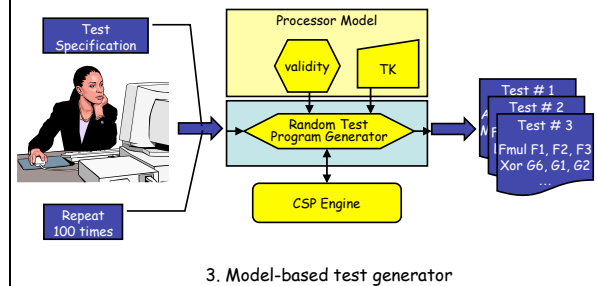
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## Putting It All Together: Building a Random Test Program Generator - II



55

## Putting It All Together: Building a Random Test Program Generator - III



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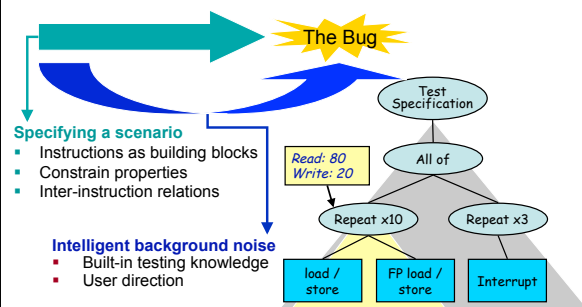
## Model-based Test Generator

### Three main layers:

- **General purpose CSP engine (solver)**
  - May be specific for stimuli generation, but can be shared among various tools
- **Processor model**
  - Description of a specific processor
    - Instruction set, registers, memory model, etc.
  - Testing knowledge specific to the processor
- **Processor generation engine**
  - Knows about the concept, vocabulary of processors
  - Generic testing knowledge of processors
  - Can translate the user request, processor model, and testing knowledge into CSP and CSP solution into a test program

57

## Bug Detection: Dual Attack Approach



58

## Summary: Main Principles of Test Generation

	Mainly Deterministic (i.e. written for a specific scenario)	Mainly Biased Pseudo Random (i.e. created using bias control)
Offline Generation (prior to sim)	Single scenario test. Usually written by hand to verify a specific scenario. Most often early in verification process.	Test case generators using random parameters to bias the stimulus. Architecturally correct tests are created and then exercised via simulation.
Online Generation (during sim)	Single scenario test cases with some random generation of peripheral inputs. Random generations used only for inputs not critical to the test case intent.	Stimulus generated each cycle using parameter biasing to determine that cycle's input. The environment must have the knowledge of legal and illegal scenarios.

59