

# COMS31700 Design Verification: Stimuli Generation

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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.)



Department of  
COMPUTER SCIENCE

## Last Time

- Coverage
  - Code
  - Structural
  - Functional
- Coverage analysis

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## 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)

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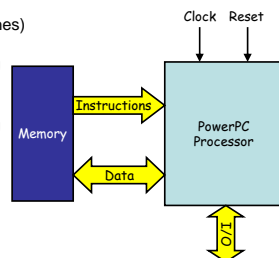
## Goals of Stimuli Generation

- 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

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## 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
    - ...



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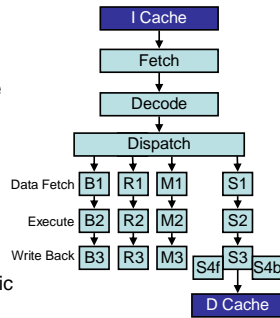
## Architectural View

- 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)

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## 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



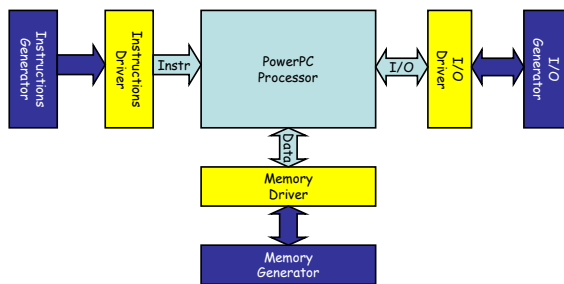
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## Extracts from the Verification Plan

- 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**

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## Processor Verification Environment



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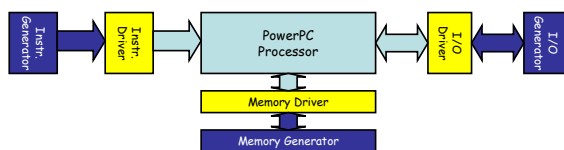
## Issues in Stimuli Generation

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

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## How Many Generators?

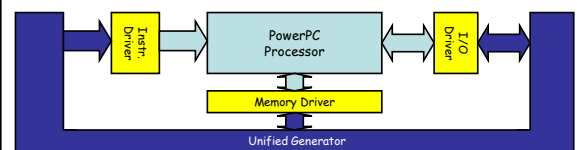
- Distributed generators
  - Each interface has its own generator
  - Each generator works on its own
  - Advantages
    - Simple
    - Easy to reuse
  - Disadvantages
    - **Hard to reach corner cases in coordinated fashion**



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## How Many Generators?

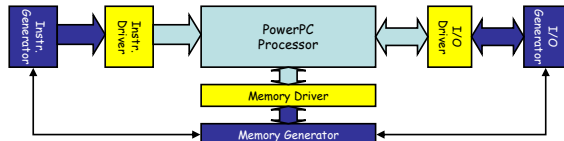
- Single generator
  - One generator controls all the interfaces
  - Advantages
    - All the interfaces can work together toward a common goal
  - Disadvantages
    - Complex
    - Hard to reuse



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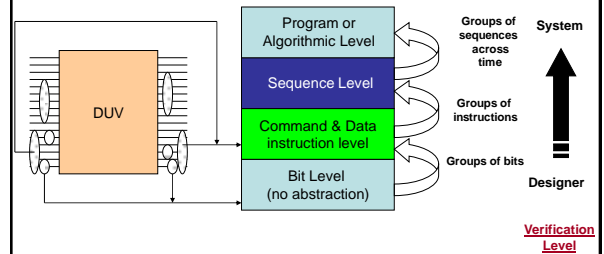
## How Many Generators?

- 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



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## Abstraction Level of Generation



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## 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

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## 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

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## 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

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## 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

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## 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

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## 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

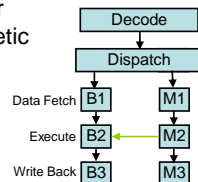
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## Generating Out Of Order

- 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

4	Lw G10, G0(G21)
4	Add G7, G9, G13
2	Mul G1, G2, G3
3	Div G4, G5, G6
1	Br 100(G1)

Generation Order



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## 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.)

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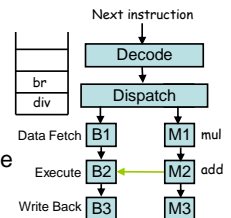
## Dynamic vs. Static Generation

- 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

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## 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



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## 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

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## 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

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## 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

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## 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

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## Why Short Tests?

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

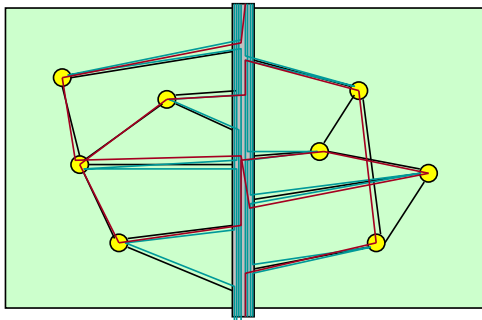
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## Why Long Tests?

- 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

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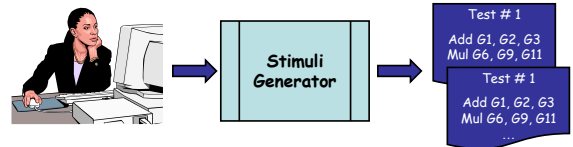
## Short Vs. Long



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## 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



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## 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

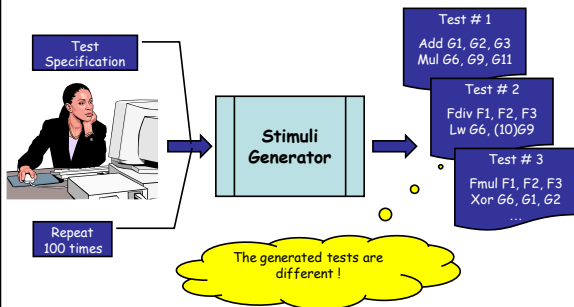
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## Why Not Deterministic?

- 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?

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## Random Stimuli Generation



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## 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



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## 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.

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## 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



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## 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 ??, ??, ??
...
```

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## 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, ...
- ...

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## 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**



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## “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

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## 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

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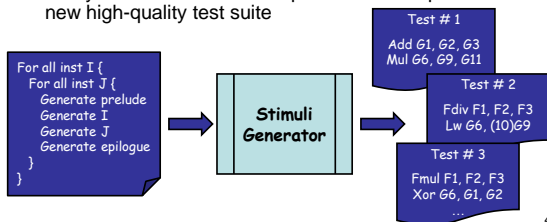
## Using Testing Knowledge

- 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. ☺

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## 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



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## 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

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## 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

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## 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

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## “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**

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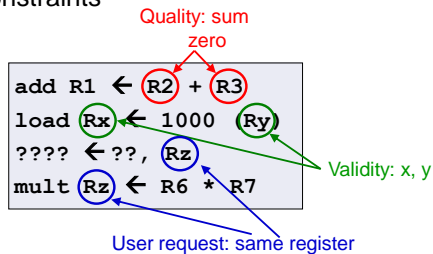
## Summary: Requirements from Stimuli Generator

- 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

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## Test program constraints

All requirements can be expressed as constraints



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## 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

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## Solution for Constraint Satisfaction Problem

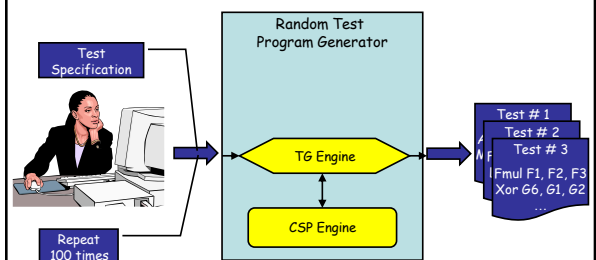
- Every variable is assigned a value from its domain, such that all constraints are satisfied
  - All solutions are born equal.
  - There is no better or best solution!

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:
  - $a = 1$  ;  $b = 4$  ;  $c = 3$

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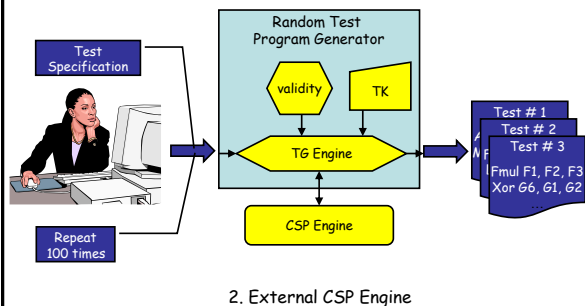
## Putting It All Together: Building a Random Test Program Generator - I



1. Everything included

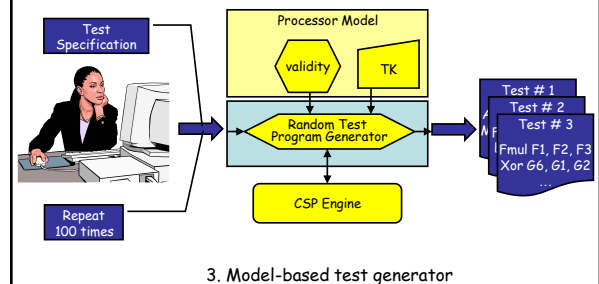
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## Putting It All Together: Building a Random Test Program Generator - II



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



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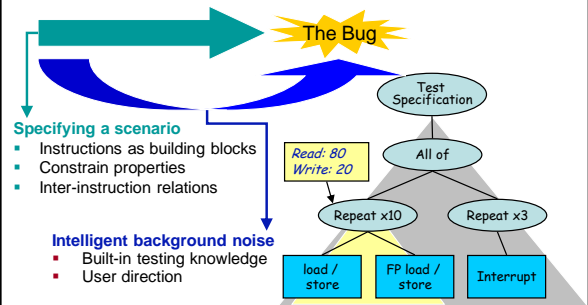
## Model-based Test Generator

### 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

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## Bug Detection: Dual Attack Approach



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

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