

COMS31700 Design Verification:

Block-level Case Study

(with demonstration of ABV and Formal Verification)

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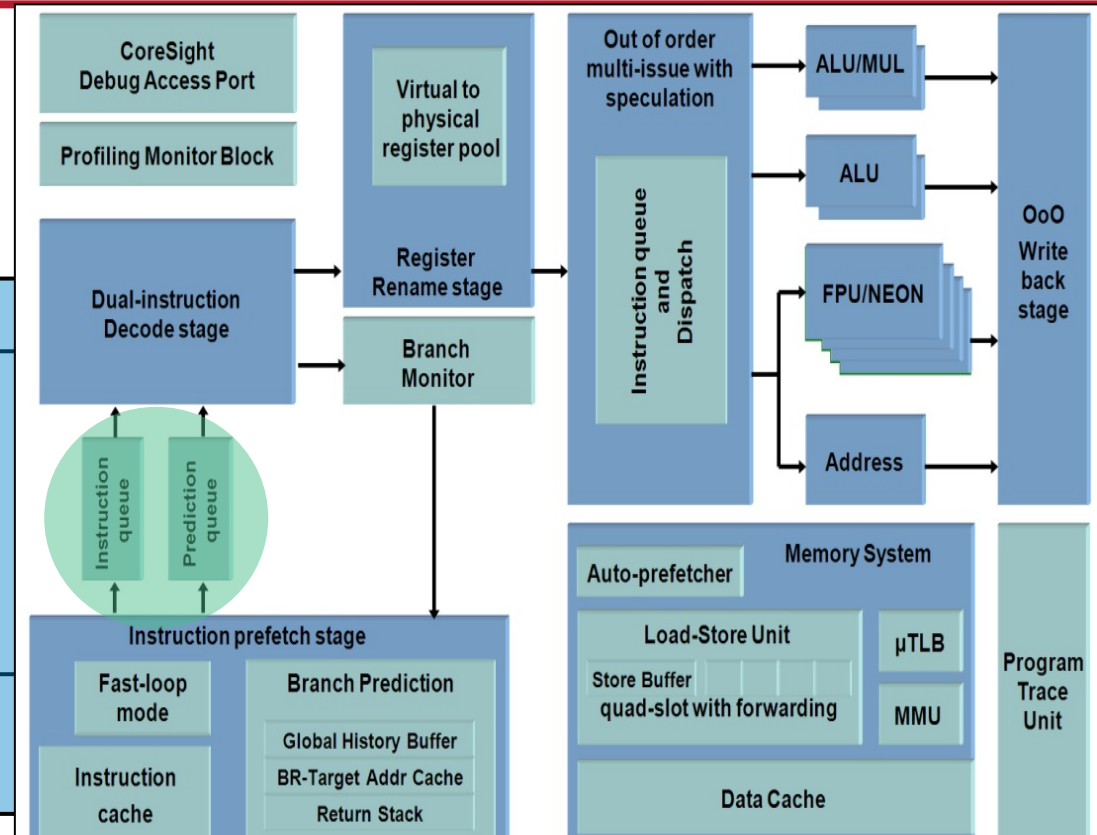
(Acknowledgement: I gratefully acknowledge the support from Jasper Design Automation who provide the licenses for the Formal Verification Tool demonstration.)

Case Study

Specification
Verification Plan
Directed Testing
(Code Coverage)
Functional Coverage
Assertion-based Verification
Formal Property Checking

Case Study: FIFO DUV

- Remember that the FIFO DUV is part of a larger unit which in turn is part of a larger system.
- The demo is focused on the verification of the FIFO at block level only.

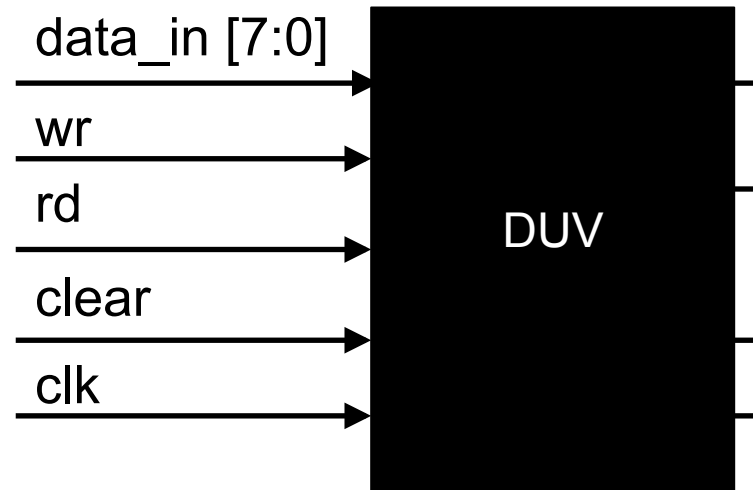


FIFO
DUV

FIFO
DUV

Specification

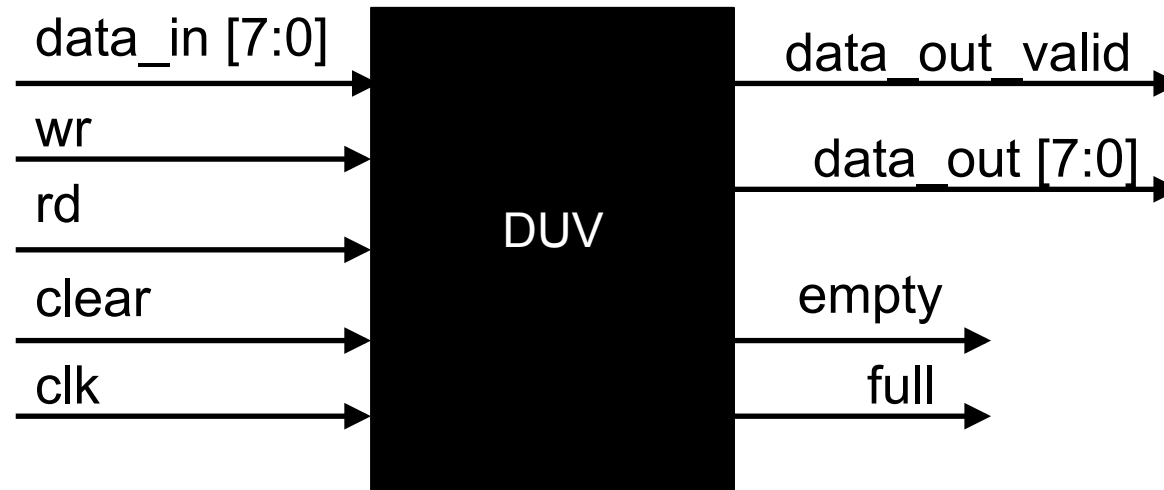
Example DUV Specification - Inputs



■ Inputs:

- wr indicates valid data is driven on the data_in bus
- data_in is the data to be pushed into the DUV
- rd pops the next data item from the DUV in the next cycle
- clear resets the DUV

Example DUV Specification - Outputs



■ Outputs:

- `data_out_valid` indicates that valid data is driven on the `data_out` bus
- `data_out` is the data item requested from the DUV
- `empty` indicates that the DUV is empty
- `full` indicates that the DUV is full

DUV Specification

- High-Level functional specification of DUV
 - The design is a FIFO.
 - Reading and writing can be done in the same cycle.
 - Data becomes valid for reading one cycle after it is written.
 - No data is returned for a read when the DUV is empty.
 - Clearing takes one cycle.
 - During clearing read and write are disabled.
 - Inputs arriving during a clear are ignored.
 - The FIFO is 8 entries deep.

Verification Plan

Those who fail to plan plan to fail.

The Verification Plan

- Functions to be verified:

- For each level in the design, specify what is verified at that level.
- In particular, identify corner cases.

Verification Plans are “live” documents. They change as our understanding of the DUV increases.

- Methods of verification:

- Define the range of conditions to be verified.

- Complete the verification plan:

- Define the verification strategy.
- In particular, identify the resources required.

**The Verification Plan is the
Specification
for the Verification Process**

directed or

complete.

- Resources required (people) and schedule details:

- Integrate the verification plan into the overall design plan and estimate the cost of verification.

- Required tools:

- List the software and hardware necessary to perform verification.

Test Scenarios Matrix - Basic

Test #	Description
1.1	Check the write functionality
1.2	Check the read functionality
1.3	Check the reset functionality
1.4	Check ...

Develop a Test Scenarios Matrix for our Case Study DUV.

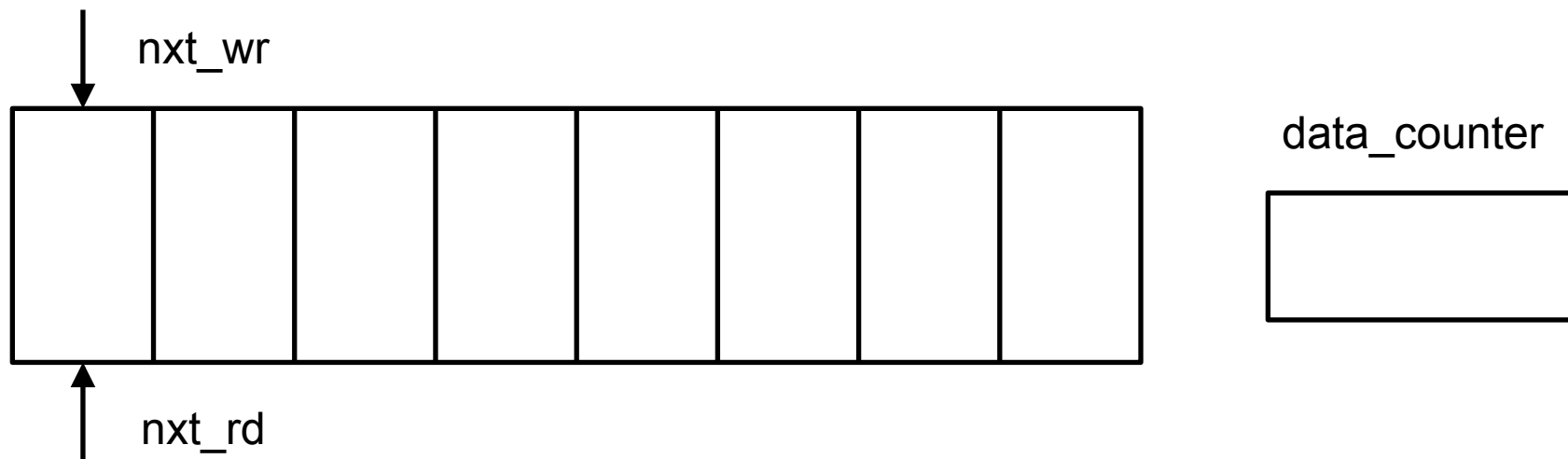
NOTE: “*Check that X*” should be read as “Create a scenario that allows checking X”.

- These generic tests should be broken to more specific tests
 - Test case 1.1.1: Check write when **empty**
 - Test case 1.1.2: Check write when **full**
 - Test case 1.1.3: Check write during **reset**
 - ...

White Box View DUV Implementation

Example DUV Implementation

- Implementation based on a circular buffer
 - `nxt_wr` and `nxt_rd` pointers indicate where the next entry will be written to or read from.
 - `data_counter` indicates the number of valid data items in the FIFO.
 - Complex control logic for pointers and counter.



Functional Coverage

Cross-Product Functional Coverage

[O Lachish, E Marcus, S Ur and A Ziv. Hole Analysis for Functional Coverage Data. In proceedings of the 2002 Design Automation Conference (DAC), June 10-14, 2002, New Orleans, US.]

A **cross-product coverage model** is composed of the following parts:

1. A **semantic description** of the model (**story**)
2. A list of the **attributes** mentioned in the story
3. A set of all the **possible values** for each attribute (**the attribute value domains**)
4. A **list of restrictions** on the **legal combinations** in the cross-product of attribute values

FIFO Cross Product Coverage Model

- From a “White Box” verification perspective:
 - The FIFO is implemented using a circular buffer.
 - The circular buffer implementation is based on the following control signals:
 - `nxt_rd`, `nxt_wr`, `data_counter`
 - These signals are used to control the data flow and also the empty and full signals.
 - **Verification Plan:**
 - Interactions of read and write transactions can create complex and unexpected conditions. All combinations need to be verified to gain confidence in the correctness of the FIFO.
- This is the **story**.

FIFO Cross Product Coverage Model

- **Attributes** relevant to the coverage model:
 - `nxt_rd`, `nxt_wr`, `data_counter`, `empty`, `full` signals
- **Attribute value domains:**
 - `nxt_rd` $\in \{0,1,2,3,4,5,6,7\}$
 - `nxt_wr` $\in \{0,1,2,3,4,5,6,7\}$
 - `data_counter` $\in \{0,1,2,3,4,5,6,7,8\}$
 - `empty` $\in \{0,1\}$
 - `full` $\in \{0,1\}$
- **Full coverage space:**
 - $8*8*9*2*2 = \mathbf{2304 \text{ coverage tasks}}$
 - Format: (`nxt_rd`, `nxt_wr`, `data_counter`, `empty`, `full`)
 - Find some legal and some illegal examples

FIFO Cross Product Coverage Model

- **Attributes** relevant to the coverage model:

- `nxt_rd`, `nxt_wr`, `data_counter`, `empty`, `full` signals

- **Attributes**

- `nxt_rd`
- `nxt_wr`
- `data_counter`
- `empty`
- `full` $\in \{0,1\}$

Legal Coverage Tasks:

(0,0,0,1,0)
(2,2,8,0,1)
(3,7,4,0,0)

Illegal Coverage Tasks:

(0,0,0,1,1)
(1,1,4,0,0)
(1,5,0,1,1)

- **Full coverage space:**

- $8*8*9*2*2 = \mathbf{2304 \text{ coverage tasks}}$
- Format: (`nxt_rd`, `nxt_wr`, `data_counter`, `empty`, `full`)
- Find some legal and some illegal examples

FIFO Cross Product Coverage Model

- Restrictions

- data_counter is only important when $\text{nxt_rd} == \text{nxt_wr}$ so that one can tell the difference between empty and full
- 64 combinations of nxt_rd and nxt_wr
- 56 cases are for $\text{nxt_rd} \neq \text{nxt_wr}$, so empty and full are not both asserted at the same time
- 8 cases are for $\text{nxt_rd} == \text{nxt_wr}$
- one set of 8 is for $\text{data_counter} == 0$, so empty is asserted
- one set of 8 is for $\text{data_counter} == 8$, so full is asserted
- empty and full are not both asserted at the same time

Defining meaningful functional coverage requires design understanding and engineering skill.

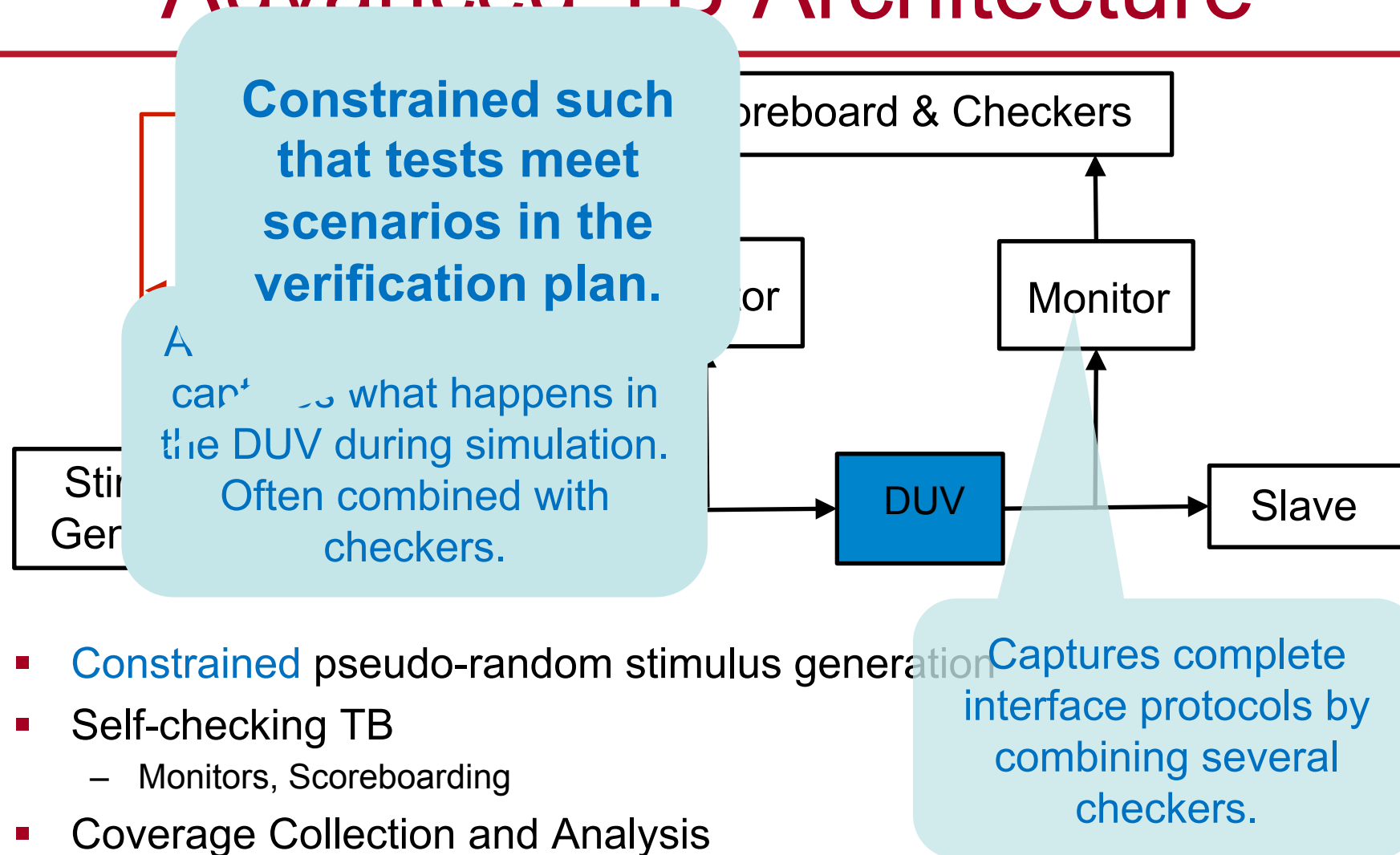
- Revised format of coverage model:

- (nxt_rd , nxt_wr , empty, full)
- total size of coverage space: $8 \times 8 \times 2 \times 2 = 256$ coverage tasks
- Encode assumptions into properties
- Only $56 + 8 + 8 = 72$ coverage tasks are legal and meaningful.

- It is worth noting the close link of the above coverage model to the properties for formal verification.

Constraint Pseudo Random Test Generation

Advanced TB Architecture



- **Constrained** pseudo-random stimulus generation
- Self-checking TB
 - Monitors, Scoreboarding
- Coverage Collection and Analysis

Promote a **Coverage-Driven Verification Methodology**

Test Scenarios Matrix – Advanced

Topic	Test #	Description
Data checking	2.1	Data is not modified
	2.2	
	2.3	
	2.4	

Test Cases Matrix – Advanced

Basic scoreboard
functionality.

Topic	Description	
Data checking	2.1	Data is not modified
	2.2	Data is not lost
	2.3	Data is not duplicated
	2.4	Data order is maintained

Test Scenarios Matrix – Advanced

Topic	Test #	Description
Data checking	2.1	Data is not modified
	2.2	Data is not lost
	2.3	Data is not duplicated
	2.4	Data order is maintained
Corner cases	2.3	Reading and writing at the same time
	2.3.1	
	2.3.2	
	...	
	...	
	...	

Test Scenarios Matrix – Advanced

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	...	
	...	
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Test Scenarios Matrix – Advanced

Topic	Test #	Description
Data checking	2.1	Data is not modified
	2.2	Data is not lost
	2.3	Data is not duplicated
	2.4	Data order is maintained
Corner cases	2.3	Reading and writing at the same time
	2.3.1	Reading and writing at the same time when empty
	2.3.2	Reading and writing at the same time when full
 at the same time as clearing
	...	
	...	

**These make
interesting functional
coverage scenarios.**

How?

Should we rely on random generation by
constraining stimulus to make these rare
events happen more often?

Bug Hunting

Given the following bug...

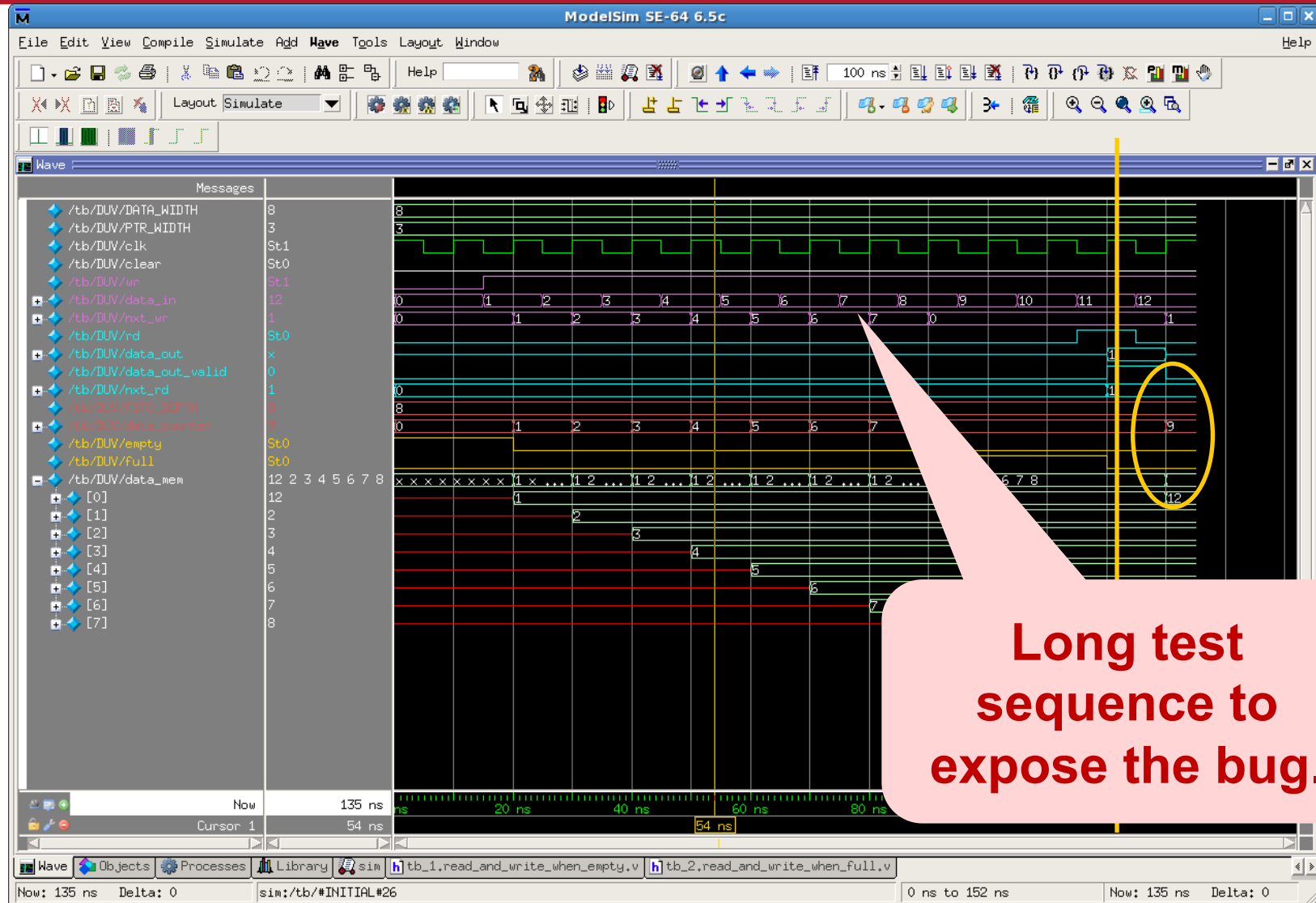
- Concurrent reading from and writing to FIFO
 - Should the data counter change its value?

Given the following bug...

- **Concurrent reading from and writing to FIFO**
 - ok, the data counter should not change its value
 - unless reading from and writing to the same data slot
 - this only happens when the FIFO is
 - **empty:** When the FIFO is empty and there is a write at the same time as a read (from empty), then the read should be ignored.
 - **full:** When the FIFO is full and there is a read at the same time as a write, then the write (to full) should be ignored.
 - But the logic that controls the value of the data counter does not distinguish these special cases.
 - **What do we need to do to find these bugs?**



Read and Write when FIFO is full



ABV

Properties of the DUV

Black box view:

- Empty and full are never asserted together.
- After clear the FIFO is empty.
- After writing 8 data items the FIFO is full.
- Data items are moving through the FIFO unchanged in terms of data content and in terms of data order.
- No data is duplicated.
- No data is lost.
- data_out_valid only for valid data, i.e. no x's in data.

An invariant property.

Properties of the DUV

- White box view:
 - The value range of the read and write pointers is between 0 and 7.
 - The data_counter ranges from 0 to 8.
 - The data in the FIFO is not changed during a clear.
 - For each valid read the read pointer is incremented.
 - For each valid write the write pointer is incremented.
 - Data is written only to the slot indicated by `nxt_wr`.
 - Data is read only from the slot indicated by `nxt_rd`.
 - When reading and writing the data_counter remains unchanged.
 - What about a RW from an empty/full FIFO?

Property Formalization

Formalization of key DUV Assertions

- **System Verilog Assertions (SVA) for:**

- Empty and full are never asserted together.

```
property not_empty_and_full;
```

```
@ (posedge
```

```
endprop
```

```
assert
```

- After c

```
property
```

```
@ (posedge
```

```
endprop
```

```
assert property (empty_after_clear);
```

- On empty after one write the FIFO is no longer empty.

```
property not_empty_after_write_on_empty;
```

```
@ (posedge clk) (empty && wr ==> !empty);
```

```
endproperty
```

```
assert property (not_empty_after_write_on_empty);
```

Challenge:
There are many more
interesting
assertions.

Assertions can be
monitored during
simulation.

Assertions can also
be used for formal
property checking.

Corner case properties

- **FIFO empty:** When the FIFO is empty and there is a write at the same time as a read (from empty), then the read should be ignored.

```
property empty_write_ignore_read;
@ (posedge clk) {empty && wr && rd ==>
    data_counter == $past(data_counter)+1};

endproperty
assert property (empty_write_ignore_read);
cover property (empty_write_ignore_read);
```

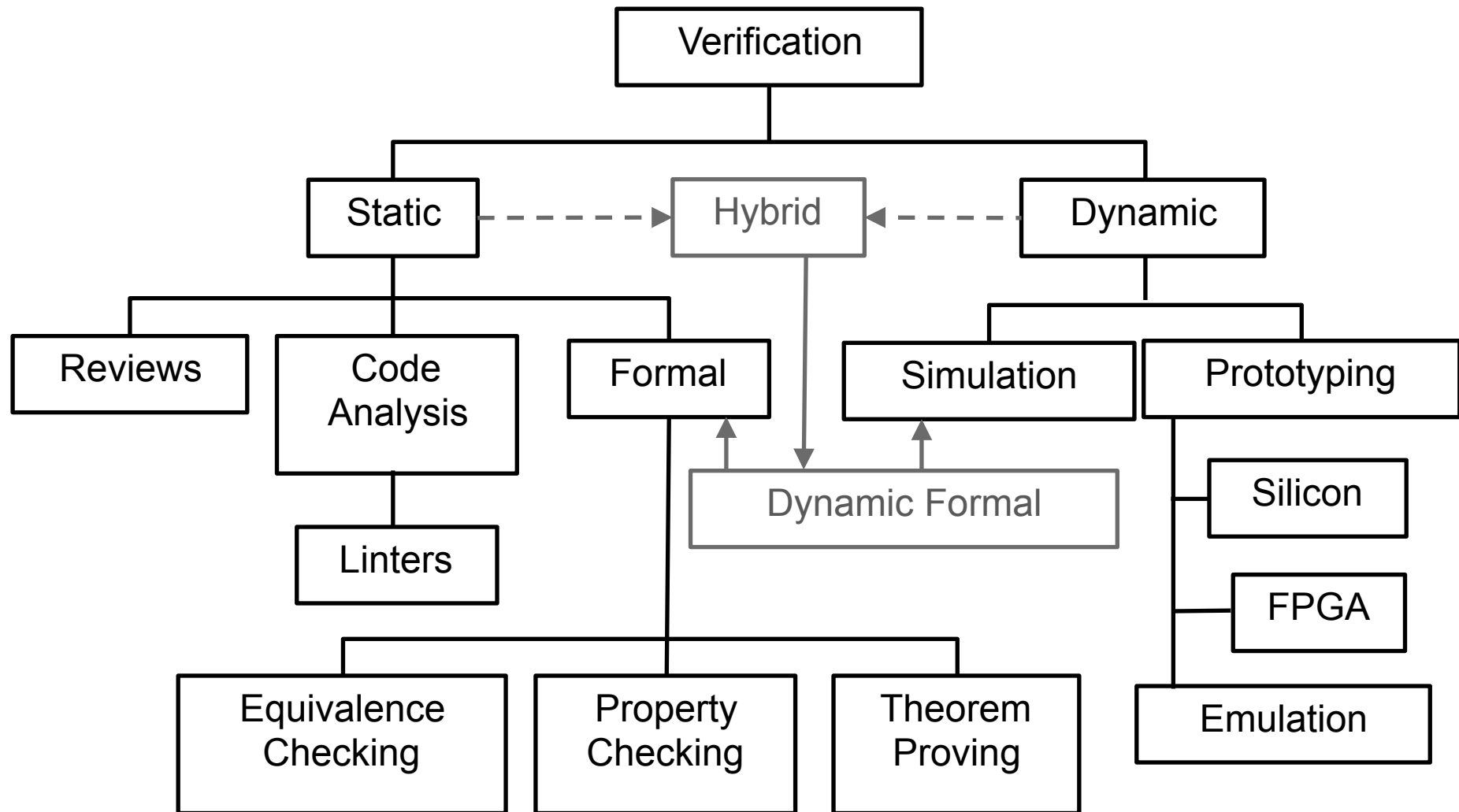
- **FIFO full:** When the FIFO is full and there is a read at the same time as a write, then the write (to full) should be ignored.

```
property full_read_ignore_write
@ (posedge clk) {full && rd && wr ==>
    data_counter == $past(data_counter)-1};

endproperty
assert property (full_read_ignore_write);
cover property (full_read_ignore_write);
```

Formal Property Checking

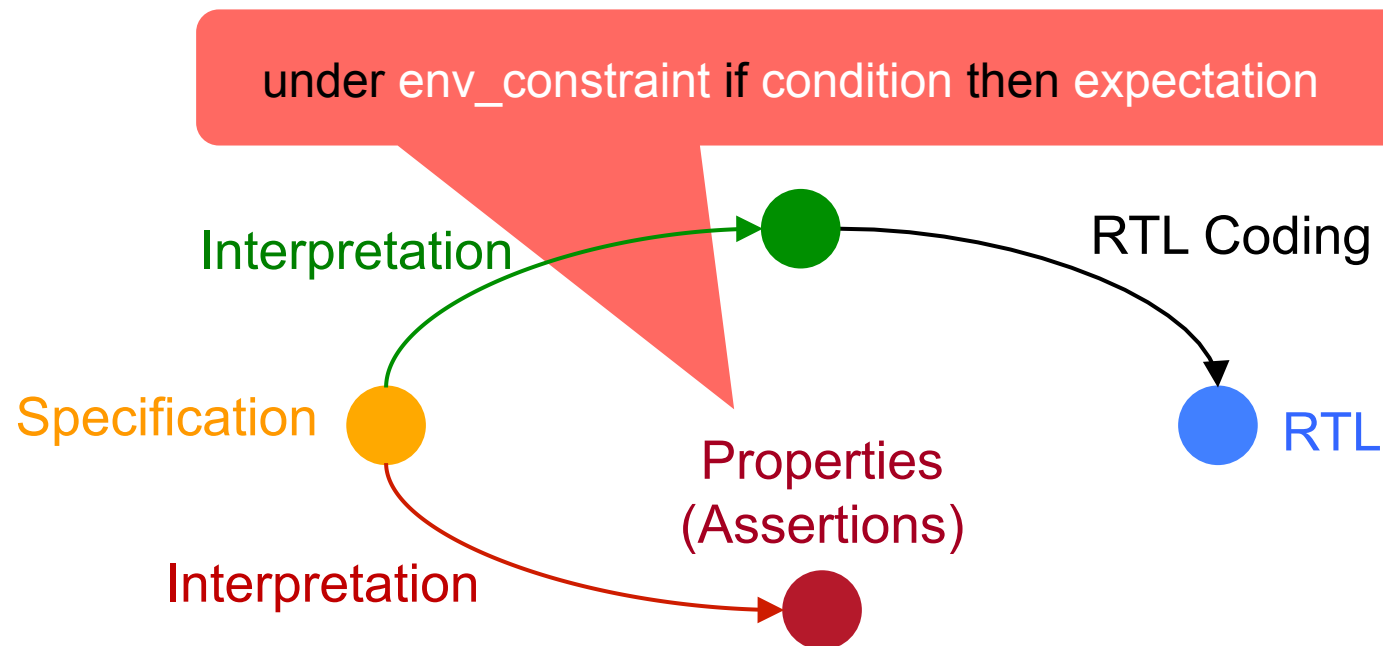
Functional Verification Approaches



Formal Property Checking

Properties of a design are formally proven or disproved.

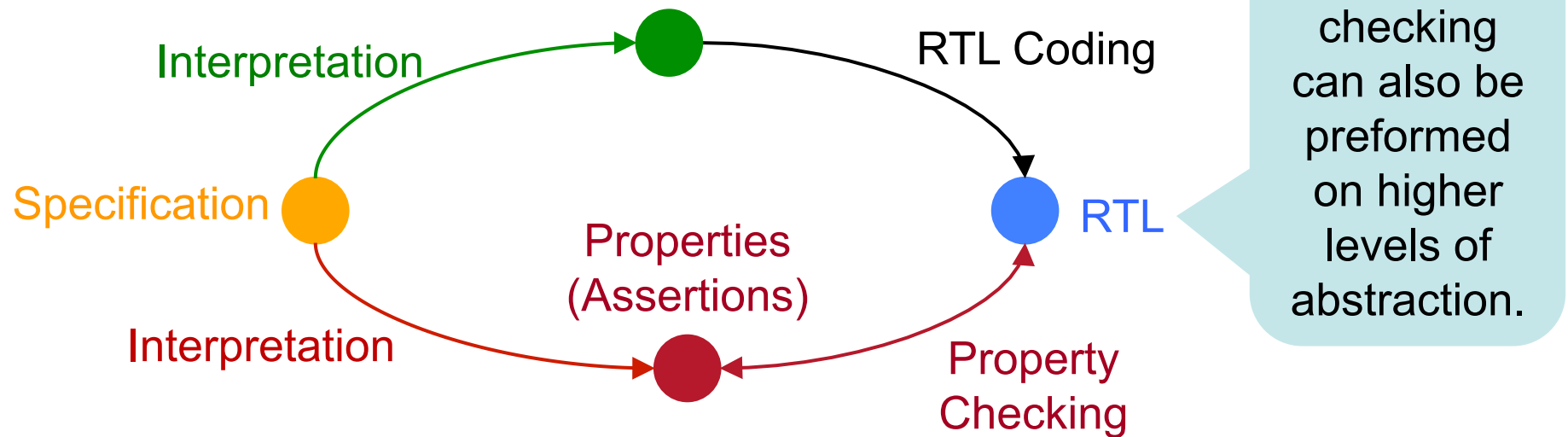
- Used to check for generic problems or violations of user-defined properties of the behaviour of the design.
- Usually employed at **higher levels** of abstractions.
- **Properties** are derived from the specification.
- **Properties** are expressed as formulae in some (temporal) logic.



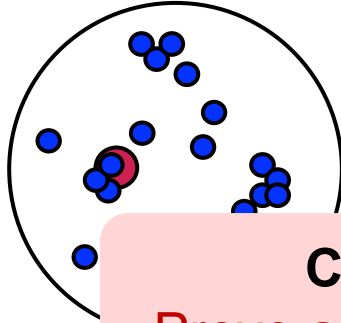
Formal Property Checking

Properties of a design are formally proven or disproved.

- Used to check for generic problems or violations of user-defined properties of the behaviour of the design.
- Usually employed at **higher levels** of abstractions.
- **Properties** are derived from the specification.
- **Properties** are expressed as formulae in some (temporal) logic.
- Checking is typically performed on a Finite State Machine model of the design.
 - This may be the RTL.



Simulation vs Functional Formal Verification



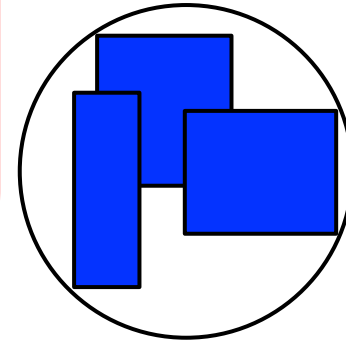
Challenge 2:
Prove all these properties.

Only selected parts
of the design can be
covered during
simulation.

Naïve interpretation
of exhaustive formal
verification:

Verify ALL properties.

Challenge 1:
Specify
properties to
cover the entire
design.

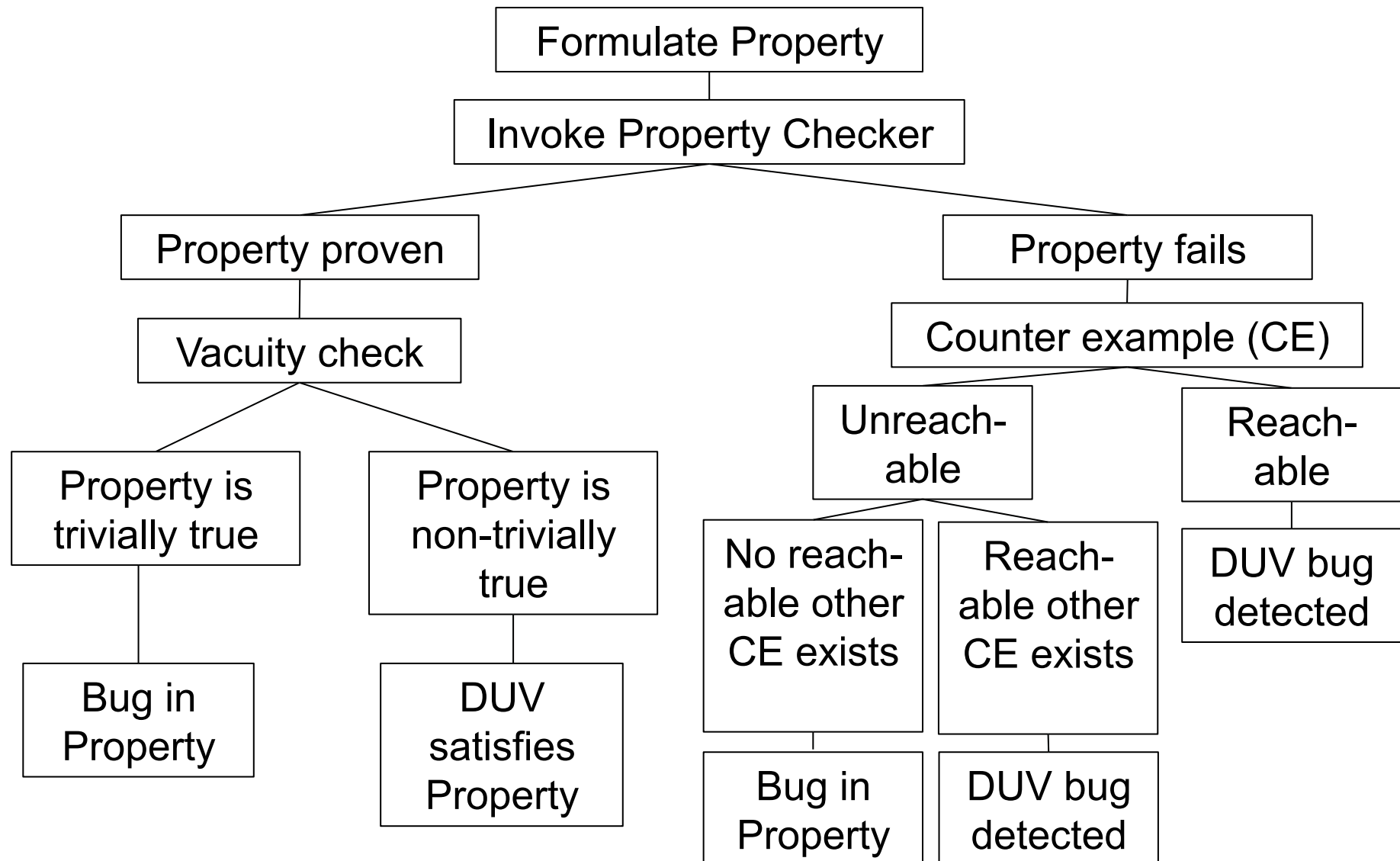


In practice, **completeness issues** and **capacity limits** restrict formal verification to selected parts of the design.

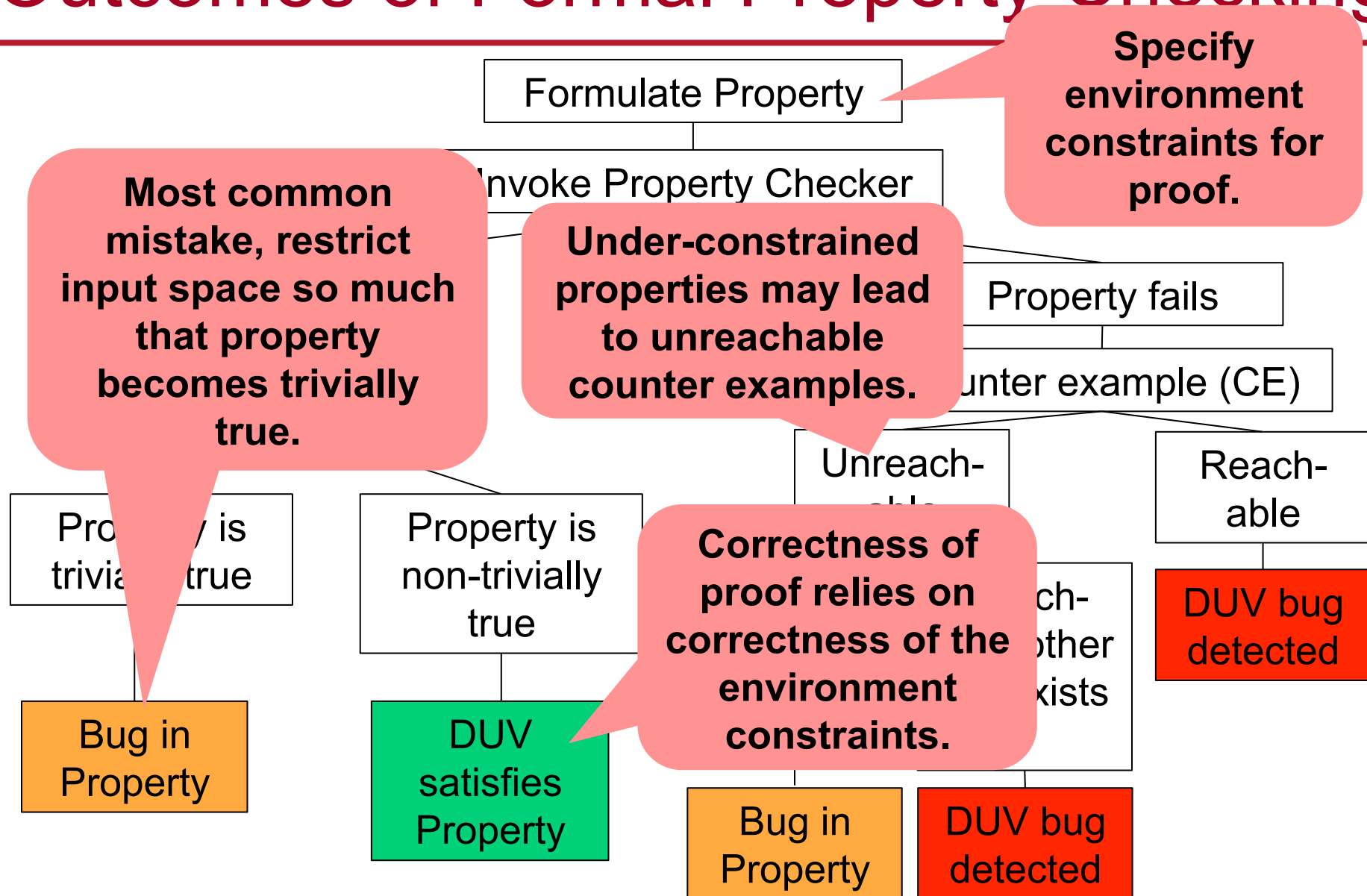
The Role of Formal Property Checking

- Property Checking is the most common form of high-level formal verification used in practice.
 - Property checking is fully automatic.
 - Requires the properties to be written.
 - It performs exhaustive verification of the design wrt the specified properties.
 - It provides proofs and can demonstrate the absence of bugs.
 - A counter example is presented for failed properties.
 - Used for critical well specified parts of the design
 - Cache coherence protocols, Bus protocols, Interrupt controllers
- Formal Methods can suffer from **capacity limits**
 - There are tried and trusted techniques to overcome these:
 - Restrict property checking to work over finite small time windows.
 - Limit environment behaviour by strengthening constraints.
 - Case splits over a set of properties, partitioning and black boxing.

Outcomes of Formal Property Checking



Outcomes of Formal Property Checking



How do you know you've encoded the property right?

- Keep properties and sequences simple.
 - Build complex properties from simple, short properties
- **Peer review properties you write.**
- **If the property fails, you can investigate the counter example:**
 - Is it reachable or not?
- **But if the property succeeds, how do you know whether you've encoded the property right?**



Formal Property Checking

- Property checking tools can formally verify assertions.
 - **Basic properties (visualize):**
 - Basic functionality
 - Range checks
 - **Re-use SV Assertions as properties (check):**
 - Empty and full are never asserted together.
 - After clear the FIFO is empty.
 - On empty after one write the FIFO is no longer empty.
 - Understanding counter examples:
 - Debug an assumption
 - Debug a design property

Note:

- Closely related to functional coverage.
- Link from [env_constraints](#) to simulation assertions.

Formal Property Checking

- Jasper DEMO

- Formal verification of selected FIFO properties from ABV

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How big is Exhaustive?

- Consider simulating a typical CPU design
 - 500k gates, 20k DFFs, 500 inputs
 - 70 billion sim cycles, running on 200 linux boxes for a week
 - **How big: 2^{36} cycles**
- Consider formally verifying this design
 - Input sequences: cycles $2^{(\text{inputs}+\text{state})} = 2^{20500}$
 - What about X's: 2^{15000} (5,000 X-assignments + 10,000 non-reset DFFs)
 - **How big: 2^{20500} cycles** (2^{15000} combinations of X is not significant here!)
- That's a big number!

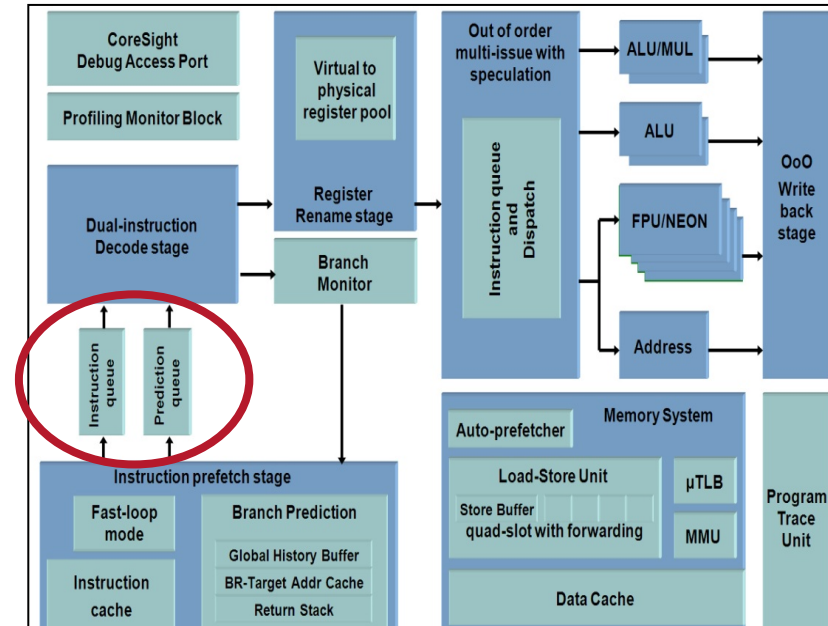
– Cycles to simulate the 500k design:	2^{36}	(70 billion)
– Cycles to formally verify a 32-bit adder:	2^{64}	(18 billion billion)
– Number of stars in universe:	2^{70}	(10^{21})
– Number of atoms in the universe:	2^{260}	(10^{78})
– Possible X combinations in 500k design:	2^{15000}	($10^{4515} \times 3$)
– Cycles to formally verify the 500k design:	2^{20500}	(10^{6171})



Summary

■ Block-level Case Study

- Specification
- Verification Plan
- Directed Testing
- (Code Coverage)
- Functional Coverage
- Assertion-based Verification
- Formal Property Checking



■ No single method is adequate to cover a whole design in practice.

- Carefully select the verification methods that maximize ROI.
- Complement simulation with formal: Integrated approach

Merry Christmas and a Happy New Year



Why red wine is so important for Christmas