Don’t over-constrain in formal property verification (FPV) flows


Formal property verification (FPV) is increasingly being used to complement simulation for system-on-chip (SoC) verification. Adding FPV to your verification flow can greatly accelerate verification closure and find tough corner-case bugs, but it is important to understand the differences between the technologies. The main difference is that FPV uses properties, i.e., assertions and constraints, instead of a testbench. Assertions are used in simulation as well, but the role of constraints is different. An understanding of constraints is necessary for successful use of FPV.

Constraints

Constraints play a central role in FPV. They define what is legal stimulus to the design under test, i.e., what state space can be reached. Assertions define the desired behavior of the DUT for the legal stimulus.

Constraints describe how inputs to the DUT are allowed to behave, what values should be taken, and temporal relationships between inputs. Constraints can be thought of as the stimulus in simulation. In constrained random simulation, the constraint solver generates an input vector for the next cycle that satisfies all constraints. It will continue to generate cycle after cycle of stimulus until the end of simulation, or until it reaches a situation where no legal stimulus can be generated.

In contrast, constraints for formal verification can describe, for example, how to legally communicate within a given protocol.

Over and under-constraining

Writing constraints that exactly describe all legal stimuli is difficult and often undesirable. This means that the formal environment is either under- or over-constrained. Under-constrained means that there are fewer constraints than required to exactly model the stimulus. This means that some potentially illegal inputs will be driven to the device under test (DUT). Over-constrained means that there are more constraints than required, and not all legal behaviors will be allowed.

Having a slightly under-constrained environment is usually the best approach. Many designs can handle inputs and behaviors not defined in the specification, and a larger state space in the design will be verified if fewer constraints are used. An under-constrained environment may lead to failing assertions, and if this is the case, additional constraints need to be added. For example, let’s say we have a 4-bit multiplier to verify:
The specification says it can multiply positive integers $A$ and $B > 0$, but the verification engineer assumes $A$ and $B >= 0$. The constraints and the assertion to check the multiplier is simply:

```plaintext
assume property (@posedge clk) A >= 0;
assume property (@posedge clk) B >= 0;
assert property (@posedge clk) C == A * B;
```

If the property is proven in this case – for either or both $A$ and $B$ being zero as well as for positive integers – then obviously it will hold for $A$ and $B$ only being greater than zero. The constraints allowed for additional behaviors, which means the environment is under-constrained. Having fewer constraints usually also improves run time of formal tools. If the properties pass, we don’t have to worry about the under constraining case anymore.

Over-constraining the formal environment is a much bigger problem as it may hide bugs in the design. In effect you are not verifying as much as you think you are. For example, assume the case of a multiplier that can multiply both positive and negative numbers, but the verification engineer misinterprets the specification and writes constraints to restrict $A$ and $B$ to $>= 0$. Assuming the multiplier works, the property above will pass, and you think verification is done because all properties pass.

Over-constraining is only a problem when it is unintentional. Intentional over-constraining is a useful method to break up verification of a design into cases. One example is verification of a memory controller. First constrain the stimulus to do only write transactions, and then constrain it to do only read transactions. Each of these cases is clearly over-constrained.

In the first case, read transactions, which are legal transactions, are not allowed, and in the second case, write transactions are not allowed. This is not a problem because the two cases together cover all legal stimulus. It is the case where only one of the cases is exercised and not the other, leading the verification engineer to think that verification is done. A risk with intentionally over-constraining is that legal input values are missed, and sequences such as read followed by write (in the case of the memory controller) are not verified.

### Conflicting constraints

Constraints limit the set of inputs and the state space explored in formal property verification. If the verification environment has constraints that conflict with each other or with statements in the design, no legal inputs may be possible, and none of the state space in the design will be reachable. For example, the two constraints below can be satisfied individually, but together they produce a conflict:

```plaintext
equal: assume property (@posedge clk) (wb_stb_i == wb_cyc_i)
```
not_equal: assume property (@ posedge clk) (wb_stb_i != wb_cyc_i)

Conflicting constraints can be seen as the most extreme form of an over-constrained environment that is so constrained that there are no legal inputs. This means that no assertions can fail, in effect because no checking is done. It is analogous to saying that none of my test cases fail in simulation when the reason is that you have not executed any test cases. The statement is true, but it is misleading in terms of verification completeness.

Most formal tools detect conflicting constraints before attempting to run proofs of properties. Manually determining which properties conflict is difficult, and it is better to rely on tools to report it. For example:

[Info] CONFLICT_DBG: Conflict occurs at depth 0
[Info] CONFLICT_DBG: List of assumptions involved in conflict
  equal (id=51)
  not_equal (id=582)

Detection of an over-constrained environment

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Having an unintentionally over-constrained environment may hide bugs in the DUT, so it is important to have a methodology to detect it. Methods described below to detect over-constrain include:

1. Cover properties
2. Vacuity checks
3. Formal coverage analysis

Cover properties

Cover properties describe expected behaviors in the design. If they fail, it may indicate an over-constrained environment. Cover properties are unique to each design and are written by design or verification engineers to ensure sequences of events can happen. For example:

cover property @(posedge clk) empty ##4 full;

The cover property ensures that it is possible to fill a four-deep FIFO in the design. This means that some write logic must be working. If the property fails, it could be caused by a design bug or a constraint that prevents four data values from being written to the FIFO.

Cover properties are a useful tool to detect an over-constrained environment, but the main drawback is that the designer must write them. If a cover property is missing, nothing is detected.

Vacuity checks
Vacuity checks are a type of cover property automatically generated by formal tools. The tool creates a check on the antecedent expression of an assertion with an implication – where the left-hand side of an assertion implies that the right-hand side must hold true at some point. For example:

```
assert property @(posedge clk) REQ && ACTIVE |-> ##2 DONE;
```

The vacuity check for the property above would be equivalent to:

```
cover property @(posedge clk) REQ && ACTIVE;
```

If the vacuity check (cover property above) fails, it means that the property can never fail because the antecedent is never true. The vacuity check may fail because of a design bug or because of a constraint. For example:

```
assume property @(posedge clk) ACTIVE |-> !REQ;
```

As we have seen in the example above, vacuity checks can also be useful in detecting an over-constrained environment. Their main advantage over cover properties is that they are generated automatically by formal tools, but they rely on the existence of properties with implications and do not check areas of the design where properties are sparse or missing.

**Formal coverage analysis**

The most effective method to detect an over-constrained environment is to use formal coverage analysis (FCA). FCA uses simulation-type coverage goals such as line, expression, toggle, and FSM coverage to determine which parts of the design are reachable. This is similar to the use of coverage in simulation, where you track and measure which lines and expressions have been executed or reached by the set of test cases. If a line of code is not reached in simulation, it may be because a test has not yet been written, or constrained-random simulation didn’t run long enough to reach it. Or, it may simply be impossible to reach a particular line of code.

Some parts of the design may be unreachable regardless of the constraints. The structure of the RTL may prevent some lines from being reached. For example:

```
if (A && B)
    data <= 32’hdeadbeef;
if (!B)
    data <=32’h00000000;
```

The assignment

```
data <= 32’b00000000;
```

will never be executed in simulation and is unreachable in formal analysis because it is impossible to reach it. If (A && B) is true, !B cannot be true at the same time. This means that it is necessary to first find the coverage goals that are structurally unreachable so they can be distinguished from goals that are unreachable because of constraints.

If a design is over-constrained, it means part of it is structurally reachable, yet still unreachable because of the constraints. This can be detected by FCA. Any line, expression, toggle, or FSM coverage goal that is unreachable in the presence of constraints but is reachable when no
constraints are applied is a potential problem due to over-constraining. The designer needs to
determine if the over-constraining in each case is intended or harmless, or if it needs to be
addressed and constraints changed.

For example, if we have the constraint and finite-state machine:

```vhdl
assume always @(posedge clk) B <= 4'b5;

case (state)
  IDLE: begin if (B == 0) next_state <= ACTIVE;
  end
  ACTIVE: begin if (B<= 4'b6) next_state <= ACTIVE;
    end
    else next_state <= END;
    end
  END: begin next_state <= IDLE;
    end
endstate
```

The state END will never be reached because of the constraint, and we have an over-constrained
environment. The FSM coverage and line coverage goal will fail for the state END.

**Conclusion**

Constraints are needed for FPV since they ensure that only legal input values are used. Care must be
taken when creating constraints to avoid over-constraining as this may hide bugs in the design
because some parts of the design are not explored. Several methods exist to aid in the detection of
this situation, and are an important part of the methodology when adopting FPV on a project. FCA is
the most effective method to detect an over-constrained environment. It does not rely on the user to
write checks, and hence is straightforward to adopt, and is more complete. Proper and intelligent
selection and creation of constraints will ensure that the FPV flow is both effective and efficient.