



Gisselquist
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An Introduction to Formal Methods

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Lessons



▷ Welcome

Motivation

Basics

Clocked and \$past

k Induction

Bus Properties

Free Variables

Abstraction

Invariants

Multiple-Clocks

Cover

Sequences

Quizzes

Day one

1. Motivation
2. Basic Operators
3. Clocked Operators
4. Induction
5. Bus Properties

Day two

6. Free Variables
7. Abstraction
8. Invariants
9. Multiple-Clocks
10. Cover
11. Sequences
12. Final Thoughts



Course Structure



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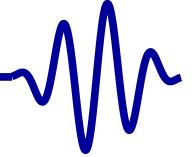
Multiple-Clocks

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- We'll be primarily using the *immediate assertion* subset of the full SystemVerilog assertion language
 - It's easier to understand
 - Concurrent assertions are built on top of immediate assertions under the hood
- Each lesson will be followed by an exercise
There are 12 exercises
- My goal is to have 50% lecture, 50% exercises
- Leading up to building a bus arbiter and testing an synchronous FIFO



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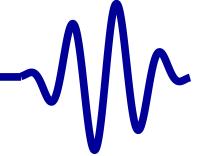
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Motivation



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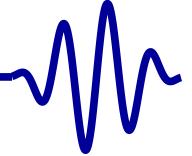
1. Why are you here?
2. What can I provide?
3. What have I learned from formal methods?

Our Objectives

- Get to know a little bit about each other
- Motivate further discussion



Your expectations



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What do you want to learn and get out of this course?



From an ARM dev.



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- “I think the main difference between FPGA and ASIC development is the level of verification you have to go through. Shipping a CPU or GPU to Samsung or whoever, and then telling them once they’ve taped out that you have a Cat1 bug that requires a respin is going to set them back \$1M per mask.”
- “... But our main verification is still done *with constrained random test benches written in SV*.
- “Overall, you are looking at 50 man years per project minimum for an average project size.”



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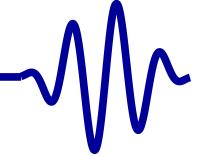
Quizzes

“If we would not do formal verification, we would
no longer exist.”

– Shahar Ariel, now the former Head of VLSI design at Mellanox



Pentium FDIV



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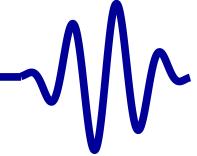
One little mistake . . .

. . . \$475M later.

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I have proven such things as,

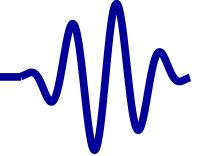
- Formal bus properties (Wishbone, Avalon, AXI, etc.)
- Bus bridges (WB-AXI, Avalon-WB)
- AXI DMA's, firewalls, crossbars
- Prefetches, cache controllers, memory controllers, MMU
- SPI slaves and masters
- UART, both TX and RX
- FIFO's, signal processing flows, FFT
- Display (VGA) Controller
- Flash controllers
- Formal proof of the ZipCPU

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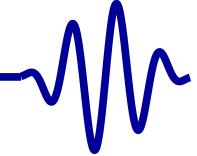
I've found bugs in things I thought were working.

1. FIFO
2. Pre-fetch and Instruction cache
3. SDRAM
4. A peripheral timer

Just how hard can a timer be to get right? It's just a counter!

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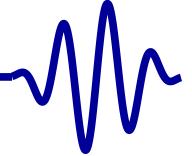
- *It worked in my test bench*
- Failed when reading and writing on the same clock while empty
 - Write first then read worked
 - R+W on full FIFO is okay
 - R+W on an empty FIFO

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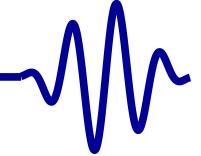
- *It worked in my test bench*
- Failed when reading and writing on the same clock while empty
 - Write first then read worked
 - R+W on full FIFO is okay
 - R+W on an empty FIFO . . . **not so much**
- My test bench didn't check that, formal did

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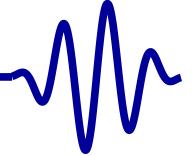
- *It worked in my test bench*
- Ugliest bug I ever came across was in the prefetch cache
It passed test-bench muster, but failed in the hardware with a
strange set of symptoms
- When I learned formal, it was easy to prove that this would
never happen again.
- Low logic has always been one of my goals.
Always asking, “will it work if I get rid of this condition?”
Formal helps to answer that question for me.

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- *It worked in my test bench*
- It passed my hardware testing
 - Test S/W: Week+, no bugs

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- *It worked in my test bench*
- **It passed my hardware testing**
 - Test S/W: Week+, no bugs
 - Formal methods found the bug
 - Full proof took less than < 30 min



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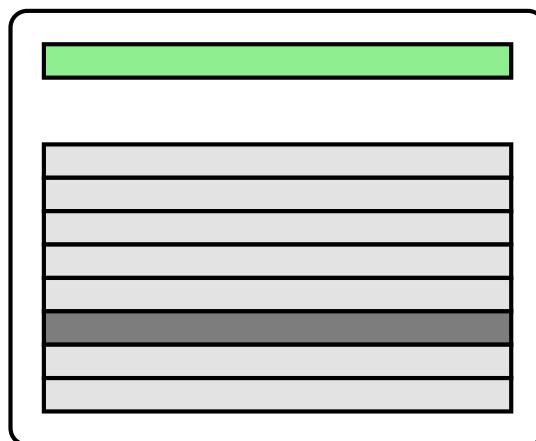
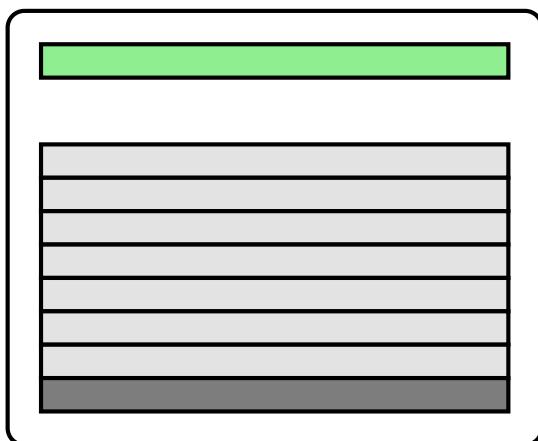
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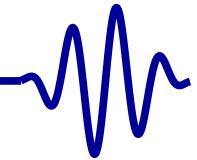
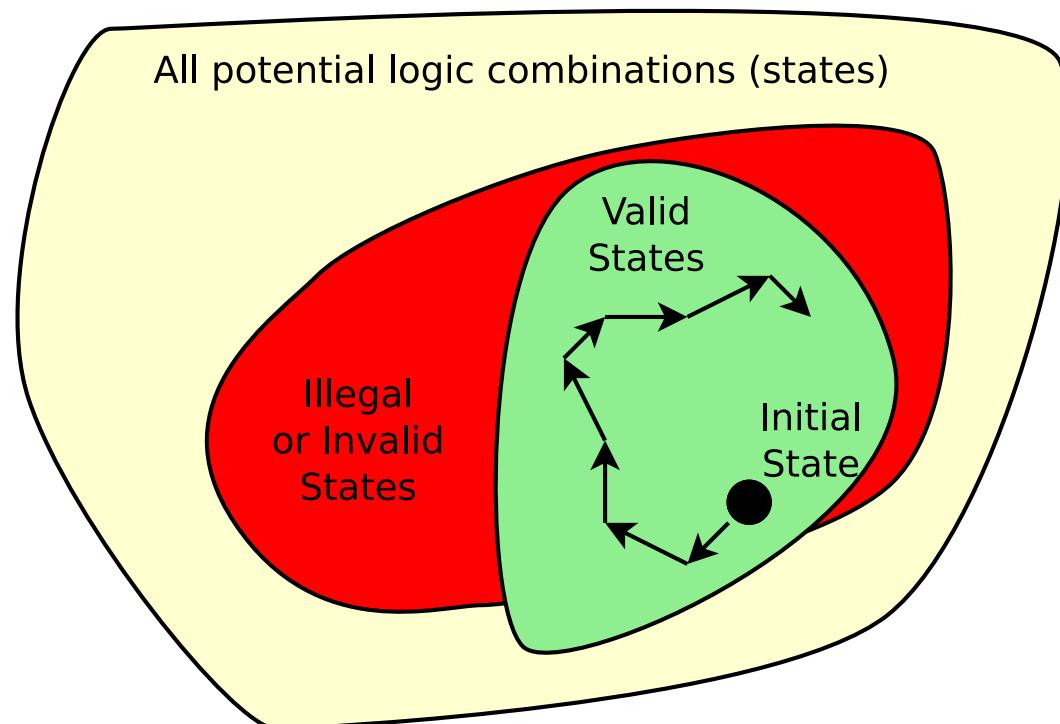
- *It worked in my test bench*
- It passed my hardware testing
- Background



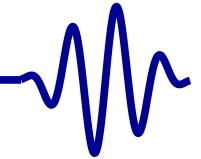
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- *It worked in my test bench*
- It passed my hardware testing
- Background
 - SDRAM's are organized into separate banks, each having rows and columns
 - A row must be “activated” before it can be used.
 - The controller must keep track of which row is activated.
 - If a request comes in for a row that isn't activated, the active row must be deactivated, and the proper row must be activated.
- A subtle bug in my SDRAM controller compared the active row address against the immediately previous (1-clock ago) required row address, not the currently requested address. This bug had lived in my design for years. Formal methods caught it.

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- Only examines a known good branch
- Cannot check for every out of bounds conditions

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- Demonstrate design works
- Through a *normal* working path
 - or a limited number of extraneous paths
- Never rigorous enough to check everything
- Not uniform in rigour

For the FIFO,

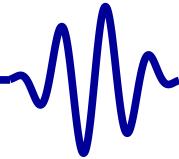
- I only read when I knew it wasn't empty

For the Prefetch,

- I never tested jumping to the last location in a cache line

For the SDRAM,

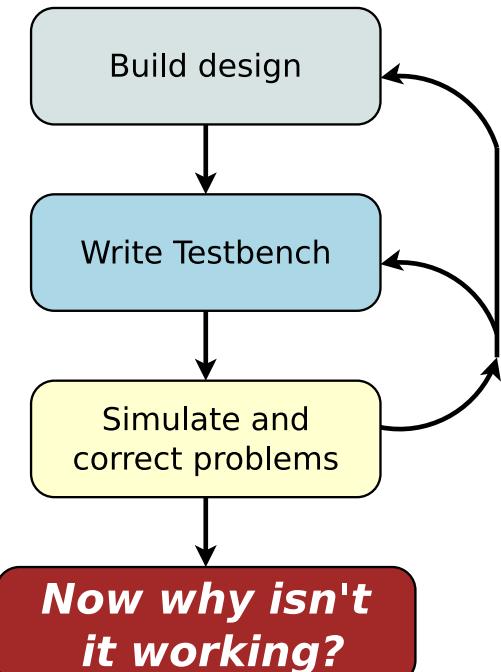
- The error was so obscure, it would be hard to trigger

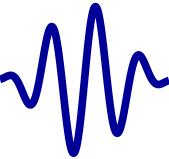
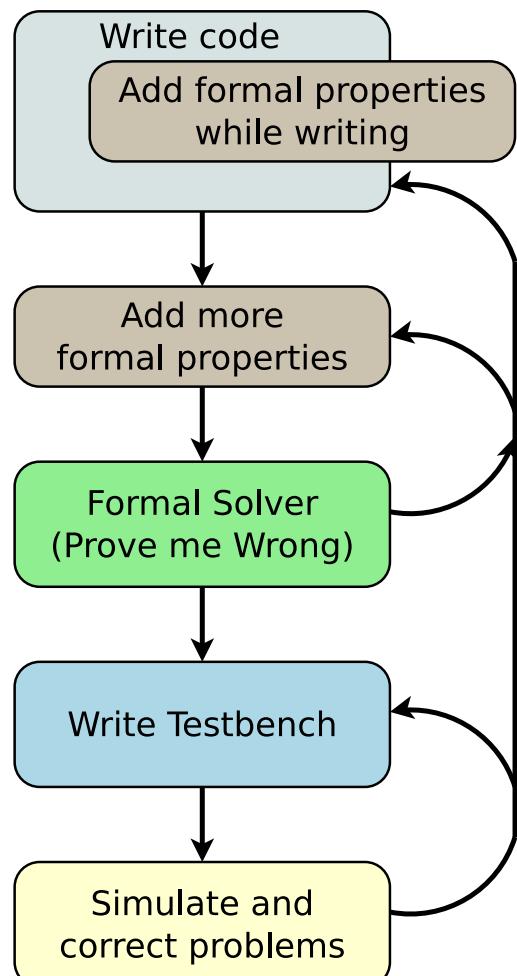
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This was my method before starting to work with formal.

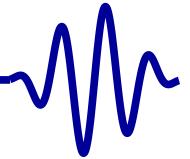
- After . . .
 - Proving my design with test benches
 - Directed simulation
- I was still chasing bugs in hardware

I still use this approach for DSP algorithms.



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- After finding the bug in my FIFO ... I was hooked.
- Rebuilding everything ... now using formal
- Formal found more bugs ... in example after example
- *I'm hooked!*



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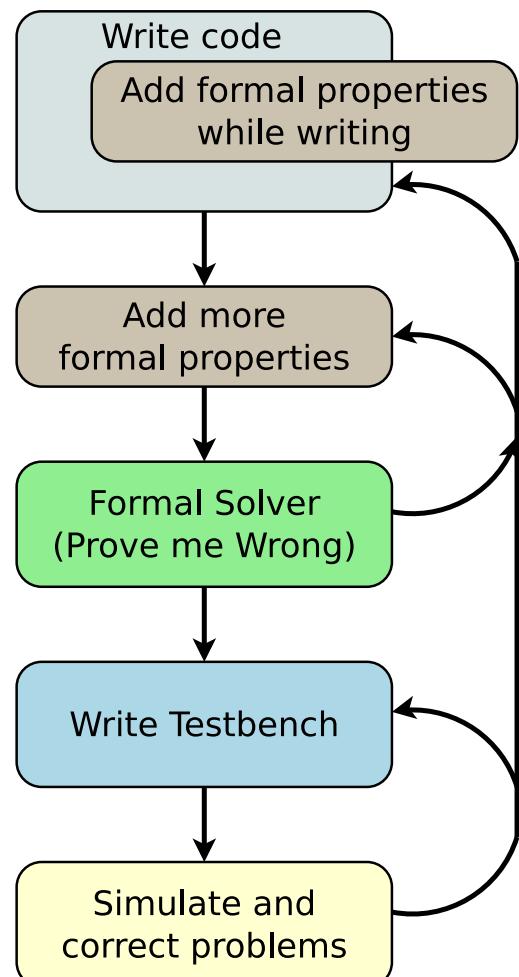
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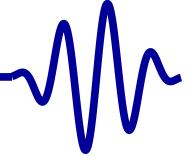


- Bus component

I would not build a bus component without formal any more

- Multiplies

Formal struggles with multiplication



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Formal Verification

Basics: assert and assume



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Let's start at the beginning, and look at the very basics of formal verification.

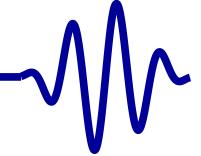
Our Objective:

- To learn the basic two operators used in formal verification,
 - **assert()**
 - **assume()**
- To understand how these affect a design from a state space perspective
- We'll also look at several examples

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Formal methods are built around looking for redundancies.

- Basic difference between mediocre and excellent:
Double checking your work
- Two separate and distinct fashions
 - First method calculates the answer
 - Second method proved it was right
- Example: Division
 - $89,321/499 = 179$
 - Does it? Let's check: $179 * 499 = 89,321$ — Yes
- Formal methods are similar
 - Your design is the first method
 - Formal properties describe the second

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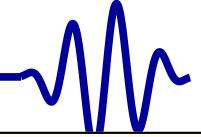
Let's start with the two basic operators

1. **assume()**

An **assume(X)** statement will limit the state space that the formal verification engine examines.

2. **assert()**

An **assert(X)** statement indicates that X *must* be true, or the design will fail to prove.

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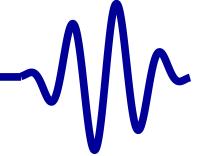
```
always @(*)  
    assert(x);
```

// Use when your property has clock dependencies,
// such as referencing an items value in the past

```
always @(posedge clk)  
    assert(x);
```

As an example,

```
always @(*)  
    assert(counter < 20);
```



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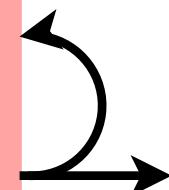
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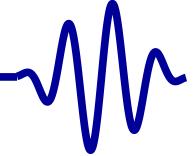
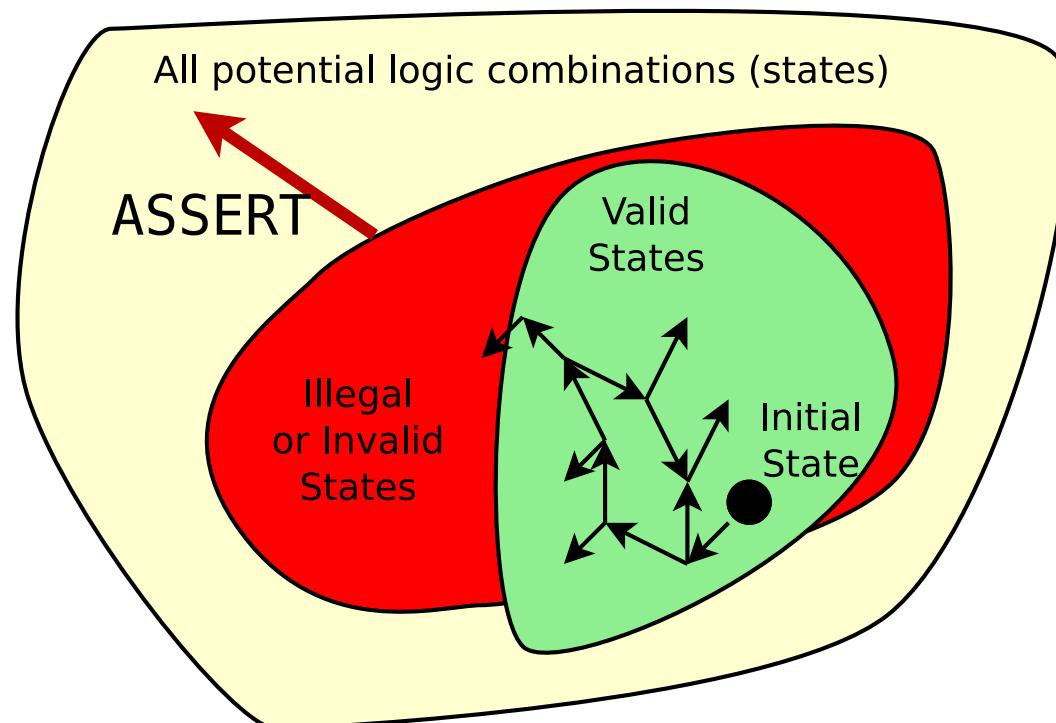
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Master FV Rule

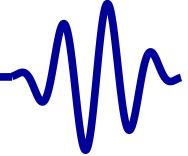
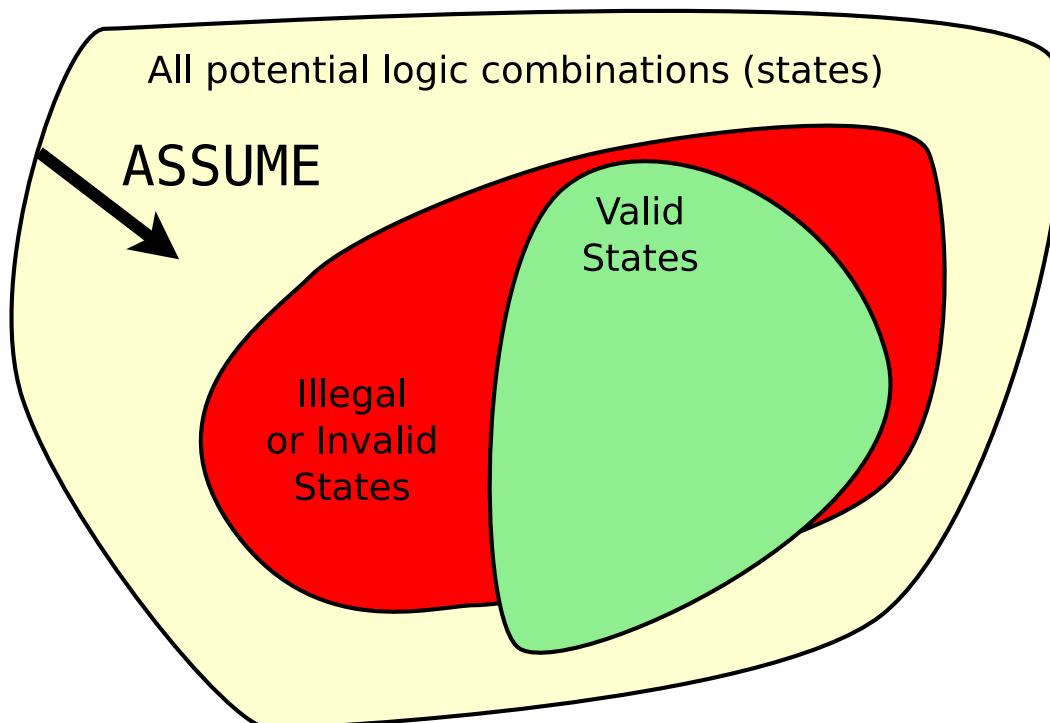
→ assume(inputs);

assert(local state);
assert(outputs);

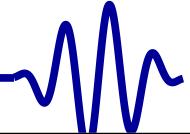


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- Assertions define the *illegal* state space.
- Additional assertions will increase the size of the *illegal* state space.

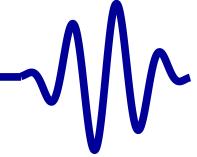
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- Assumptions limit the universe of all possibilities
- Additional assumptions will decrease the size of the *total* state space
- *Caution:* One careless assumption can void the proof

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```
reg [15:0] counter;  
  
initial counter = 0;  
always @ (posedge clk)  
    counter <= counter + 1'b1;  
  
always @ (*)  
begin  
    assert(counter <= 100);  
    assume(counter <= 90);  
end
```

Question: Will counter ever reach 120?

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restrict () is very similar to **assume()**

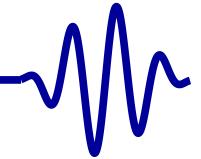
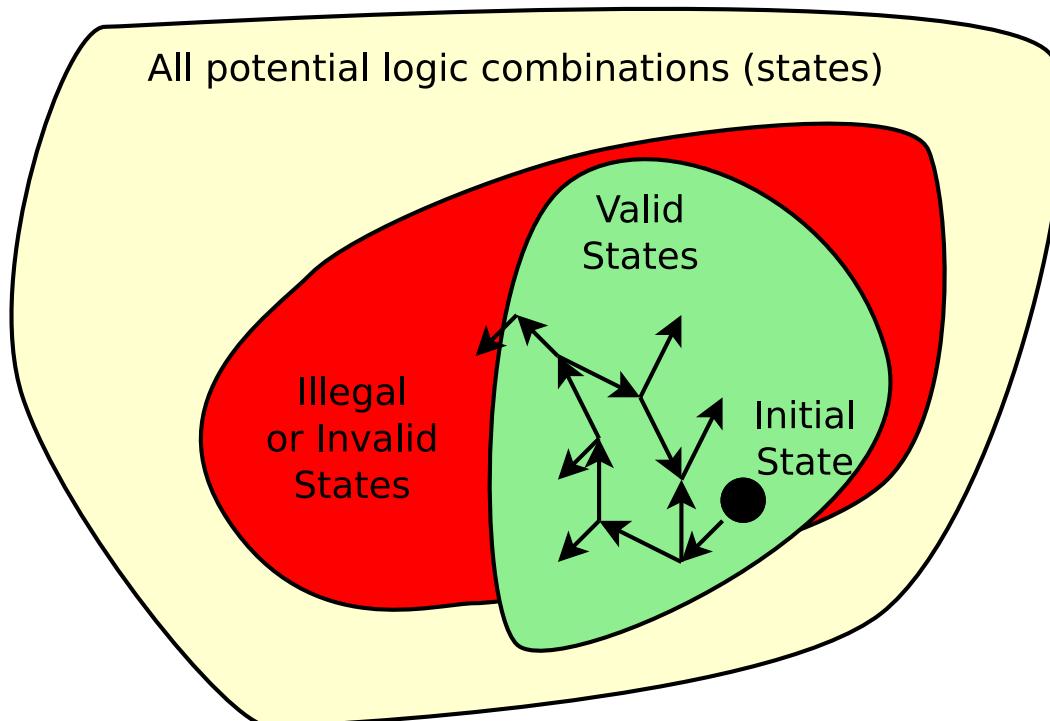
Operator	Formal Verification	Traditional Simulation
restrict ()	Restricts search space	Ignored
assume()		Halts simulation with an error
assert()	Illegal state	

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restrict () is very similar to **assume()**

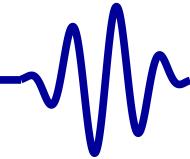
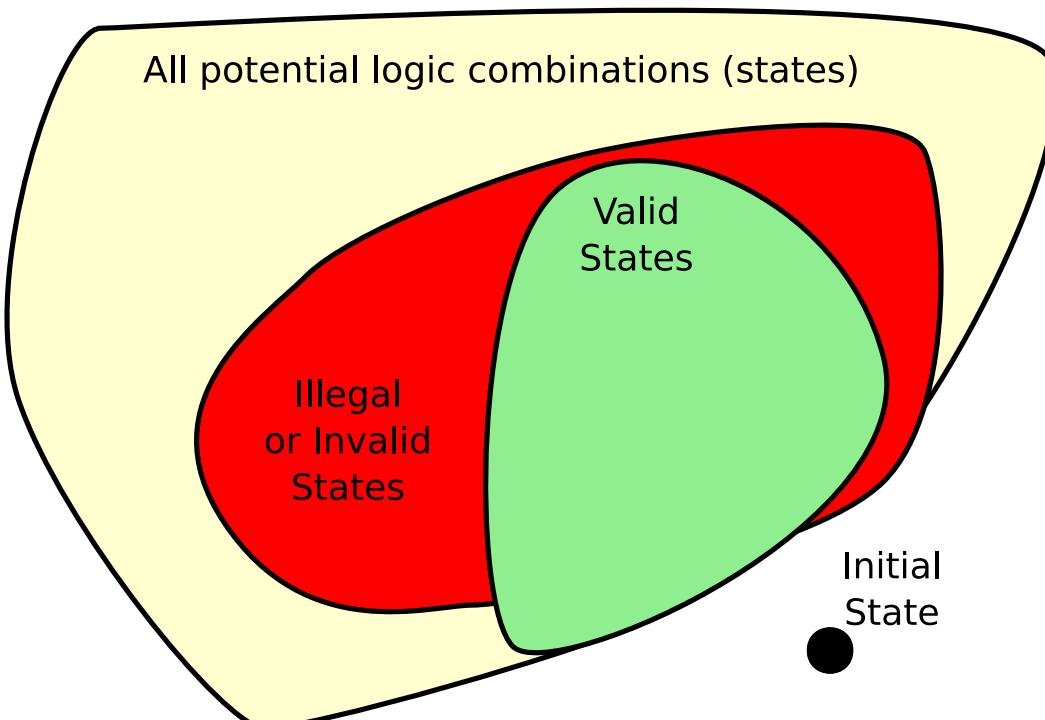
Operator	Formal Verification	Traditional Simulation
restrict ()	Restricts search space	Ignored
assume()		Halts simulation with an error
assert()	Illegal state	

- **restrict ()**: Like **assume(x)**, it also limits the state space
- But in a traditional simulation ...
 - **restrict ()** is ignored
 - **assume()** is turned into an **assert()**

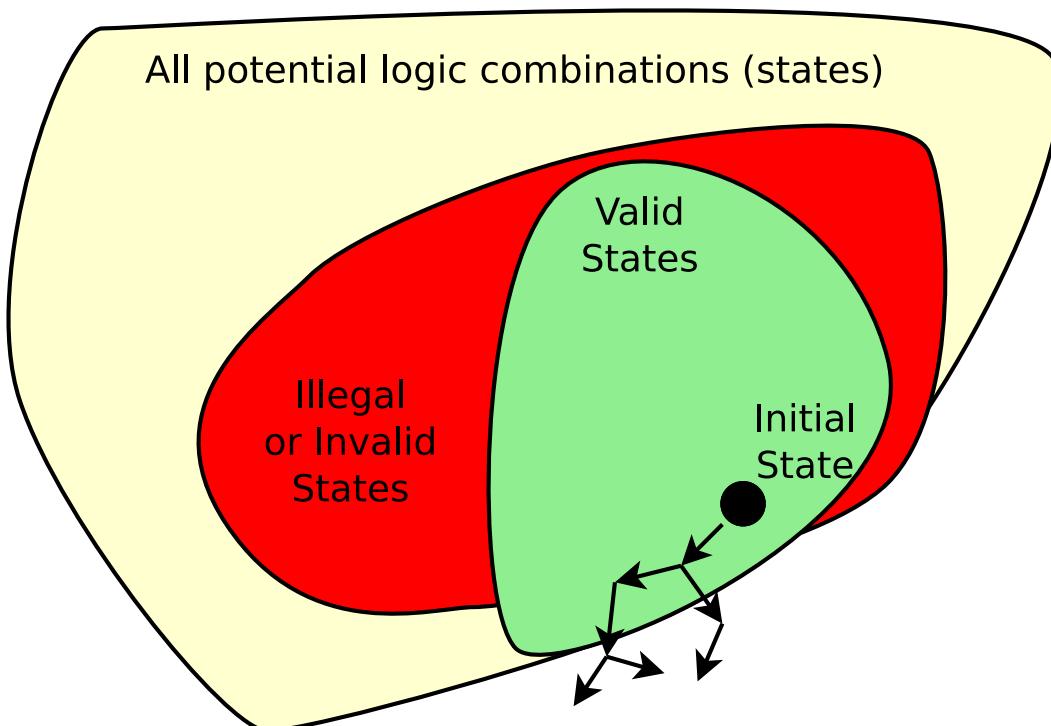
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For bounded model checking,

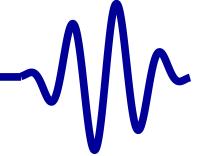
1. Start at the initial state
2. Examine *all* possible states for N clocks
3. Try to find a way to make an **assert**(); fail
4. If it's not possible in N clocks, then *pass*

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Problem: **initial assume(!initial_state);**
Model fails, *no line number given.*

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Problem: **assume(!reachable_state);**
Model fails, *no line number given.*



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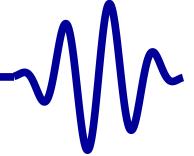
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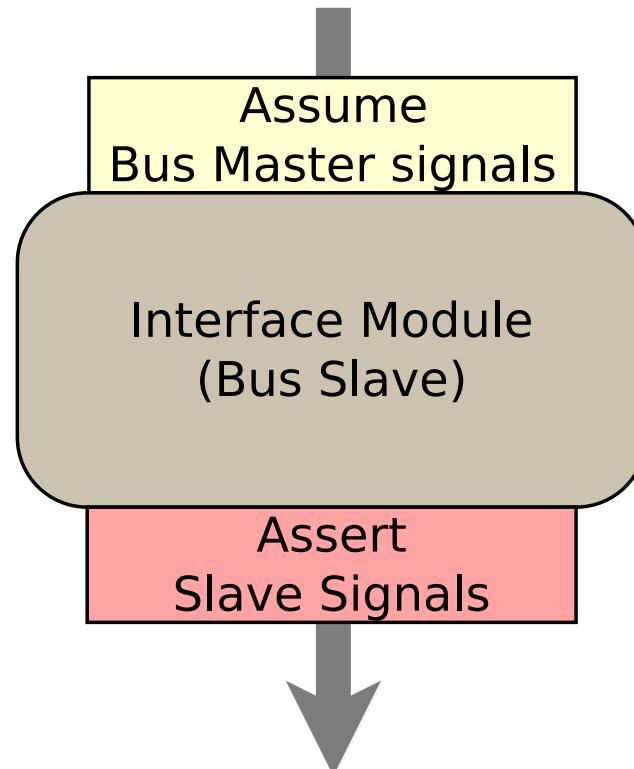
Unlike the rest of your digital design, formal properties . . .

- don't need to meet timing
- don't need to meet a minimum logic requirement

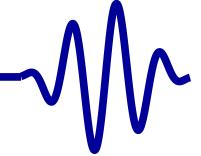
We'll discuss this more as we go along.

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Here's an example of a bus slave



- Inputs are assumed
- Outputs are asserted



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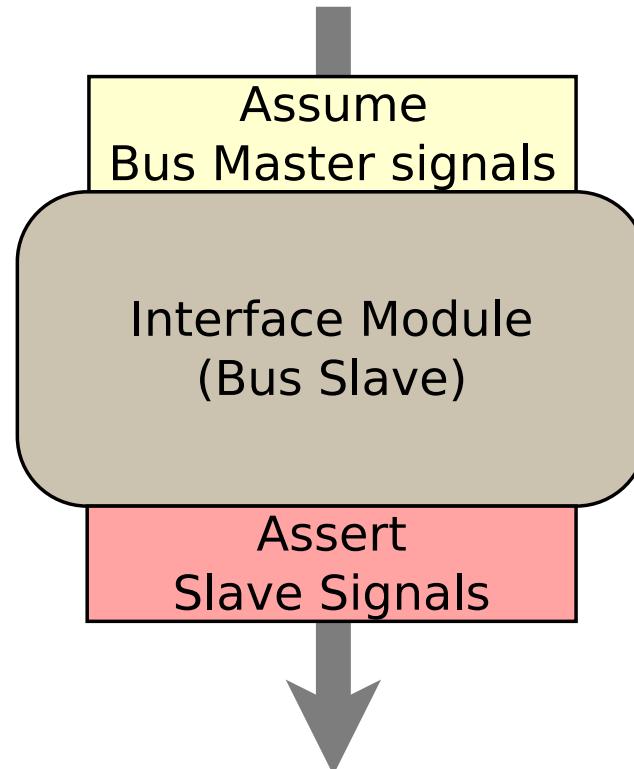
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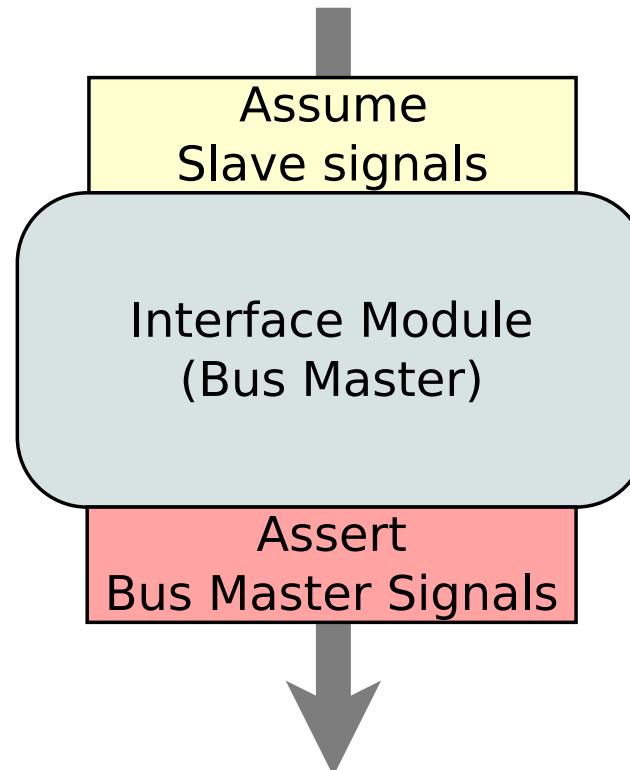
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Question: How would a bus master be different?



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Question: How would a bus master be different?

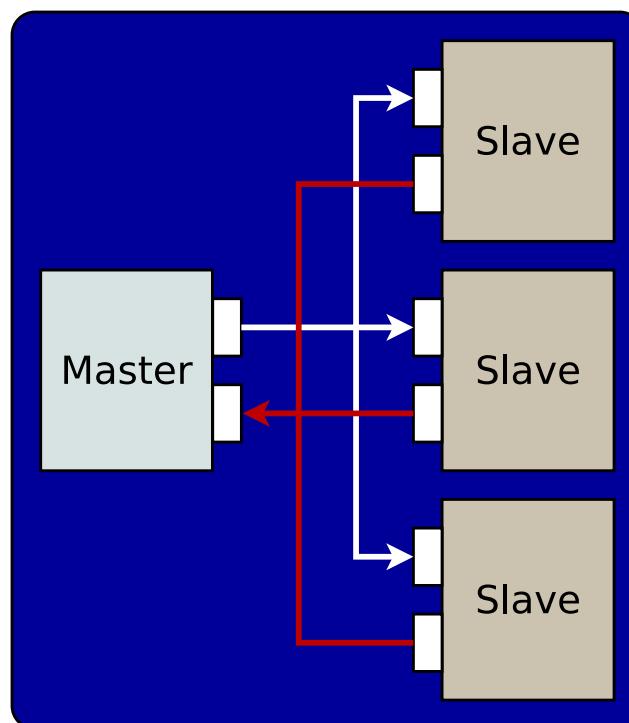


The slave's outputs are the master's inputs

- **assume()** the inputs from the slave
- **assert()** the outputs from the master

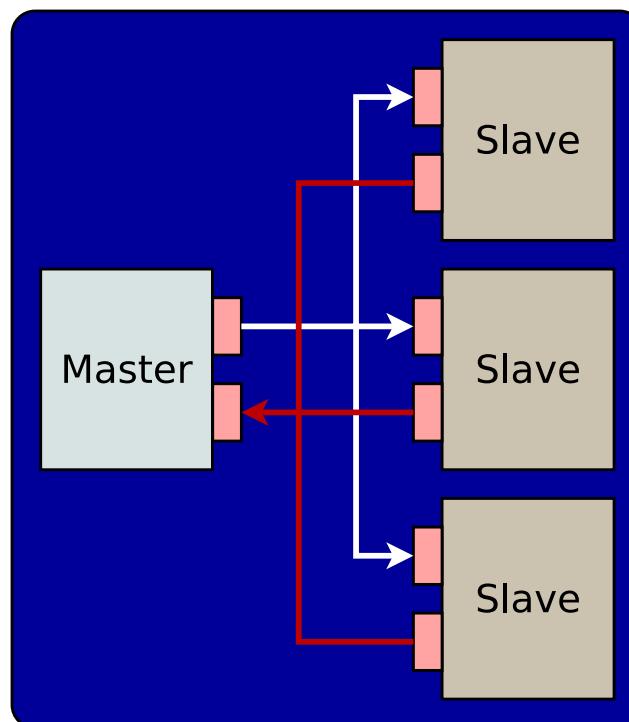
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Question: What if both slave and master signals were part of the same design?



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Question: What if both slave and master signals were part of the same design?



- All of the wires are now internal
- They should therefore be **assert()**ed

Serial Port Transmitter



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- Whenever the serial port is idle, the output line should be high

```
if (state == IDLE)
    assert(o_uart_tx);
```

- Whenever the serial port is not idle, busy should be high

```
if (state != IDLE)
    assert(o_busy);
else
    assert(!o_busy);
```

- The design can only ever be in a valid state

```
assert((state <= TXUL_STOP)
    ||(state == TXUL_IDLE));
```

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- Arbiter cannot grant both A and B access

```
always @(*)  
    assert ((!grant_A) || (!grant_B));
```

- While one has access, the other must be stalled

```
always @(*)  
if (grant_A)  
    assert(stall_B);
```

```
always @(*)  
if (grant_B)  
    assert(stall_A);
```

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- While one is stalled, its outstanding requests must be zero

```
always @(*)  
  if (grant_A)  
    begin  
      assert(f_nreqs_B == 0);  
      assert(f_nacks_B == 0);  
      assert(f_outstanding_B == 0);  
    end
```

I use the prefix f_ to indicate a variable that is

- Not part of the design
- But only used for Formal Verification

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- Avalon bus: will never issue a read and write request at the same time

always @(*)**assume**((!i_av_read)||(!i_av_write));

- The bus is initially idle

initial assume(!i_av_read);**initial assume**(!i_av_write);**initial assume**(!i_av_lock);**initial assert**(!o_av_readdatavalid);**initial assert**(!o_av_writeresponsevalid);

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- Cannot respond to both read and write in the same clock

```
always @(*)  
    assume((!i_av_readdatavalid)  
           ||(!i_av_writeresponsevalid));
```

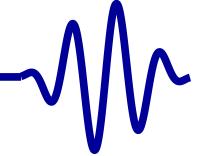
Remember ! (A&&B) is equivalent to (!A)||(! B)

- Cannot respond if no request is outstanding

```
always @(*)  
begin  
    if (f_wr_outstanding == 0)  
        assert(!o_av_writeresponsevalid);  
    if (f_rd_outstanding == 0)  
        assert(!o_av_readdatavalid);  
end
```



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- o_STB can only be high if o_CYC is also high

```
always @(*)  
if (o_STB)  
    assert(o_CYC);
```

- Count the number of outstanding requests:

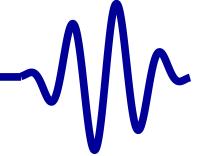
```
assign f_outstanding = (i_reset) ? 0  
    : f_nreqs - f_nacks;
```

- Acks can only respond to valid requests

```
if (f_outstanding == 0)  
    assume (!i_wb_ack);
```



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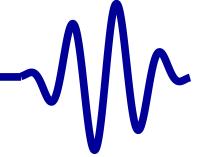
- Well, what if a request is being made now?

```
if ((f_outstanding == 0)
    &&(!o_wb_stb) || (i_wb_stall))
assume (!i_wb_ack);
```

- If not within a bus request, the ACK and ERR lines must be low

```
if (!o_CYC)
begin
    assume (!i_ACK);
    assume (!i_ERR);
end
```

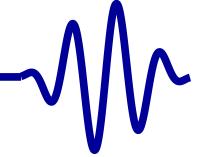
- Following any reset, the bus will be idle
- Requests remain unchanged until accepted

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Want a guarantee that the cache response is consistent?

- A valid cache entry must ...

```
always @(posedge i_clk)
  if (o_valid)
    begin
      // Be marked valid in the cache
      assert(cache_valid[f_addr[CW-1:LW]]);
      // Have the same cache tag as address
      assert(f_addr[AW-1:LW] ==
             cache_tag[f_addr[CW-1:LW]]);
      // Match the value in the cache
      assert(o_data ==
             cache_data[f_addr[CW-1:0]]);
      // Must be in response to a valid
      // request
      assert(waiting_requests != 0);
    end
```



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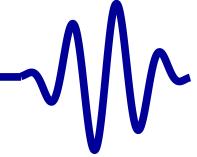
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Consider a multiply

- Just because an algorithm doesn't meet timing

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Consider a multiply

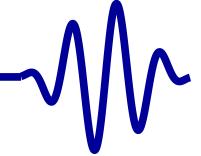
- Just because an algorithm doesn't meet timing, or
- Just because it take up logic your FPGA doesn't have

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Consider a multiply

- Just because an algorithm doesn't meet timing, or
- Just because it take up logic your FPGA doesn't have, doesn't mean you can't use it now

```
always @ (posedge i_clk)
begin
    f_answer = 0;
    for (k=0; k<NA; k=k+1)
        begin
            if (i_a[k])
                f_answer = f_answer + (i_b<<k);
        end
    assert(o_result == f_answer);
end
```



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Let's talk about that multiply some more . . .

- The one thing formal solver's don't handle well is multiplies



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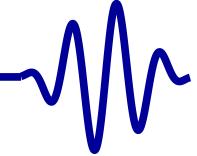
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Let's talk about that multiply some more . . .

- The one thing formal solver's don't handle well is multiplies

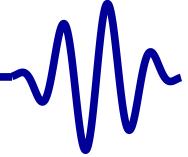
Abstraction offers alternatives

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- For a page result to be valid, it must match the TLB

```
always @(*)
  if (last_page_valid)
    begin
      assert(tlb_valid[f_last_page]);
      assert(last_ppage ==
             tlb_pdata[f_last_page]);
      assert(last_vpage ==
             tlb_vdata[f_last_page]);
      assert(last_ro ==
             tlb_flags[f_last_page][ROFLAG]);
      assert(last_exe ==
             tlb_flags[f_last_page][EXEFLG]);
      assert(r_context_word[LGCTXT-1:1]
             == tlb_cdata[f_last_page]);
    end
```

GT SDRAM



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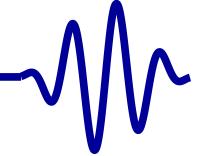
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- Writing requires the right row of the right bank to be activated

```
always @(posedge i_clk)
  if ((f_past_valid)&&(!maintenance_mode))
    case(f_cmd)
      // ...
      F_WRITE: begin
        // Response to a write request
        assert(f_we);
        // Bank in question must be active
        assert(bank_active[o_ram_bs] == 3'b111);
        // Active row must be for this address
        assert(bank_row[o_ram_bs]
              == f_addr[22:10]);
        // Must be selecting the right bank
        assert(o_ram_bs == f_addr[9:8]);
      end
    // ...
  
```



Ex: Counter



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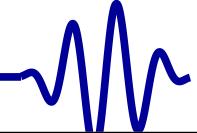
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Let's work through a counter as an example.

- | | |
|---------------------------|--|
| <code>exercise-01/</code> | Contains two files |
| <code>counter.v</code> | This will be the HDL source for our demo. |
| <code>counter.sby</code> | This is the SymbiYosys script for the demo |

Our Objectives:

- Walk through the steps in the tool-flow
- Hands on experience with SymbiYosys
- Ensure everyone has a working version of SymbiYosys
- Find and fix a design bug

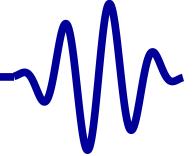
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```
parameter [15:0] MAX_AMOUNT = 22;
reg [15:0] counter;

always @ (posedge i_clk)
if ((i_start_signal)&&(counter == 0))
    counter <= MAX_AMOUNT - 1'b1;
else if (counter != 0)
    counter <= counter - 1'b1;

always @ (*)
o_busy = (counter != 0);

`ifdef FORMAL
always @ (*)
    assert(counter < MAX_AMOUNT);
`endif
```

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In the file, exercise-01/counter.sby, you'll find:

[**options**]

mode bmc

[**engines**]

smtbmc

[**script**]

read –formal counter.v

... other files would go here

prep –top counter

[**files**]

counter.v

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In the file, exercise-01/counter.sby, you'll find:

[options]

mode bmc ← Bounded model checking mode

[engines]

smtbmc

[script]

read -formal counter.v

... other files would go here

prep -top counter

[files]

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In the file, exercise-01/counter.sby, you'll find:

[options]

mode bmc

[engines]

smtbmc ← Run, using yosys-smtbmc

[script]

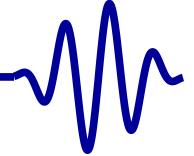
read -formal counter.v

... other files would go here

prep -top counter

[files]

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In the file, exercise-01/counter.sby, you'll find:

[**options**]

mode bmc

[**engines**]

smtbmc

[**script**] ← Yosys commands

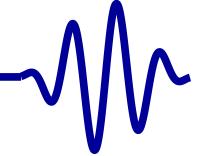
read -formal counter.v

... other files would go here

prep -top counter

[**files**]

counter.v

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In the file, exercise-01/counter.sby, you'll find:

[**options**]

mode bmc

[**engines**]

smtbmc

[**script**]

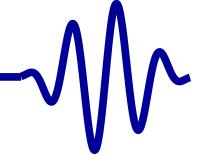
read -formal counter.v ← Read file

... other files would go here

prep -top counter

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In the file, exercise-01/counter.sby, you'll find:

```
[ options ]
```

```
mode bmc
```

```
[ engines ]
```

```
smtbmc
```

```
[ script ]
```

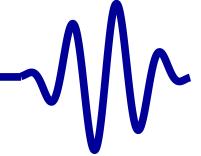
```
read -formal counter.v
```

```
# ... other files would go here
```

```
prep -top counter ← Prepare the file for formal
```

```
[ files ]
```

```
counter.v
```

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In the file, exercise-01/counter.sby, you'll find:

[**options**]

mode bmc

[**engines**]

smtbmc

[**script**]

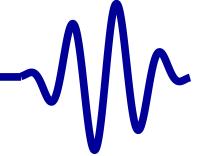
read –formal counter.v

... other files would go here

prep –top counter

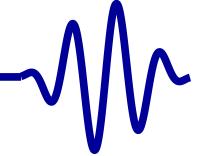
[**files**] ← List of files to be used

counter.v

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Other usefull yosys commands

```
[options]
mode bmc
depth 20
[engines]
smtbmc yices
# smtbmc boolector
# smtbmc z3
[script]
read -formal counter.v
# ... other files would go here
prep -top counter
opt_merge -share_all
[files]
counter.v
```

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Other usefull yosys commands

[options]**mode bmc** ← Other modes: prove, cover, live**depth 20****[engines]****smtbmc** yices

smtbmc boolector

smtbmc z3

[script]**read** -formal counter.v

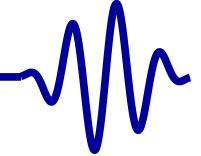
... other files would go here

prep -top counter

opt_merge -share_all

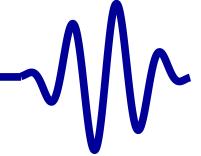
[files]

counter.v

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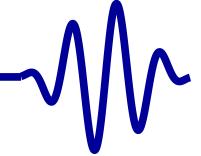
Other usefull yosys commands

```
[options]
mode bmc
depth 20 ← # of Steps to examine
[engines]
smtbmc yices
# smtbmc boolector
# smtbmc z3
[script]
read -formal counter.v
# ... other files would go here
prep -top counter
opt_merge -share_all
[files]
counter.v
```

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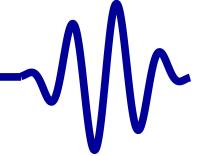
Other usefull yosys commands

```
[options]
mode bmc
depth 20
[engines]
smtbmc yices ← Yices theorem prover (default)
# smtbmc boolector
# smtbmc z3
[script]
read -formal counter.v
# ... other files would go here
prep -top counter
opt_merge -share_all
[files]
counter.v
```

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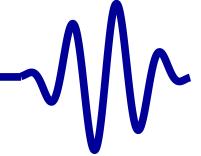
Other usefull yosys commands

```
[options]
mode bmc
depth 20
[engines]
smtbmc yices
# smtbmc boolector ← Other potential solvers
# smtbmc z3
[script]
read -formal counter.v
# ... other files would go here
prep -top counter
opt_merge -share_all
[files]
counter.v
```

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Other usefull yosys commands

```
[options]
mode bmc
depth 20
[engines]
smtbmc yices
# smtbmc boolector
# smtbmc z3
[script]
read -formal counter.v
# ... other files would go here
prep -top counter
opt_merge -share_all ← We'll discuss this later
[files]
counter.v
```

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Other usefull yosys commands

```
[options]
```

```
mode bmc
```

```
depth 20
```

```
[engines]
```

```
smtbmc yices
```

```
# smtbmc boolector
```

```
# smtbmc z3
```

```
[script]
```

```
read -formal counter.v
```

```
# ... other files would go here
```

```
prep -top counter
```

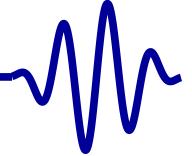
```
opt_merge -share_all
```

```
[files]
```

```
counter.v ← Full or relative pathnames go here
```



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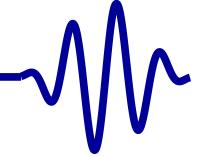
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Run: % sby -f counter.sby



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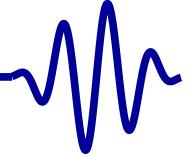
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Run: % sbt -f counter.sbt

```
:~/.../exercise-01$ sbt -f counter.sbt
SBY 11:26:17 [counter] Removing directory 'counter'.
SBY 11:26:17 [counter] Copy 'counter.v' to 'counter/src/counter.v'.
SBY 11:26:17 [counter] engine_0: smtbmc
SBY 11:26:17 [counter] base: starting process "cd counter/src; yosys -ql ../model/design.log ../model/design.yos"
SBY 11:26:17 [counter] base: finished (returncode=0)
SBY 11:26:17 [counter] smt2: starting process "cd counter/model; yosys -ql design_smt2.log design_smt2.ys"
SBY 11:26:17 [counter] smt2: finished (returncode=0)
SBY 11:26:17 [counter] engine_0: starting process "cd counter; yosys-smtbmc --presat --unroll --nopress -t 20 --append 0 --dump-vcd engine_0/trace.vcd --dump-vlogtb engine_0/trace_tb.v --dump-smtc engine_0/trace.sm
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Solver: yices
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Checking assumptions in step 0..
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Checking assertions in step 0..
SBY 11:26:17 [counter] engine_0: ## 0:00:00 BMC failed!
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Assert failed in counter: counter.v:63.13-64.31
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to VCD file: engine_0/trace.vcd
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to Verilog testbench: engine_0/trace_tb.v
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to constraints file: engine_0/trace.sm
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Status: failed
SBY 11:26:17 [counter] engine_0: finished (returncode=1)
SBY 11:26:17 [counter] engine_0: Status returned by engine: FAIL
SBY 11:26:17 [counter] summary: Elapsed clock time [H:MM:SS (secs)]: 0:00:00 (0)
SBY 11:26:17 [counter] summary: Elapsed process time [H:MM:SS (secs)]: 0:00:00 (0)
SBY 11:26:17 [counter] summary: engine_0 (smtbmc) returned FAIL
SBY 11:26:17 [counter] summary: counterexample trace: counter/engine_0/trace.vcd
SBY 11:26:17 [counter] DONE (FAIL, rc=2)
```

BMC Failed



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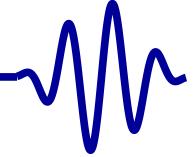
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Run: % sbt -f counter.sbt

```
exercise-01$ sbt -f counter.sbt
SBY 11:26:17 [counter] Removing directory 'counter'.
SBY 11:26:17 [counter] Copy 'counter.v' to 'counter/src/counter.v'.
SBY 11:26:17 [counter] engine_0: smtbmc
SBY 11:26:17 [counter] base: starting process "cd counter/src; yosys -ql ../model/design.log ../model/design.yos"
SBY 11:26:17 [counter] base: finished (returncode=0)
SBY 11:26:17 [counter] smt2: starting process "cd counter/model; yosys -ql design_smt2.log design_smt2.ys"
SBY 11:26:17 [counter] smt2: finished (returncode=0)
SBY 11:26:17 [counter] engine_0: starting process "cd counter; yosys-smtbmc --presat --unroll --noprecision -t 20 --append 0 --dump-vcd engine_0/trace.vcd --dump-vlogtb engine_0/trace_tb.v --dump-smtc engine_0/trace.smvc model/design_smt2.smt2"
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Solver: yices
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Checking assumptions in step 0..
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Checking assertions in step 0..
SBY 11:26:17 [counter] engine_0: ## 0:00:00 BMC failed!
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Assert failed in counter: counter.v:63.13-64.31
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to VCD file: engine_0/trace.vcd
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to Verilog testbench: engine_0/trace_tb.v
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to constraints file: engine_0/trace.smvc
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Status: failed
SBY 11:26:17 [counter] engine_0: finished (returncode=-1)
SBY 11:26:17 [counter] engine_0: Status returned by engine: FAIL
SBY 11:26:17 [counter] summary: Elapsed clock time [H:MM:SS (secs)]: 0:00:00 (0)
SBY 11:26:17 [counter] summary: Elapsed process time [H:MM:SS (secs)]: 0:00:00 (0)
SBY 11:26:17 [counter] summary: engine_0 (smtbmc) returned FAIL
SBY 11:26:17 [counter] summary: counter example trace: counter/engine_0/trace.vcd
SBY 11:26:17 [counter] DONE (FAIL, rc=2)
```

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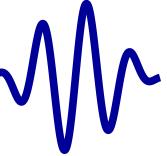
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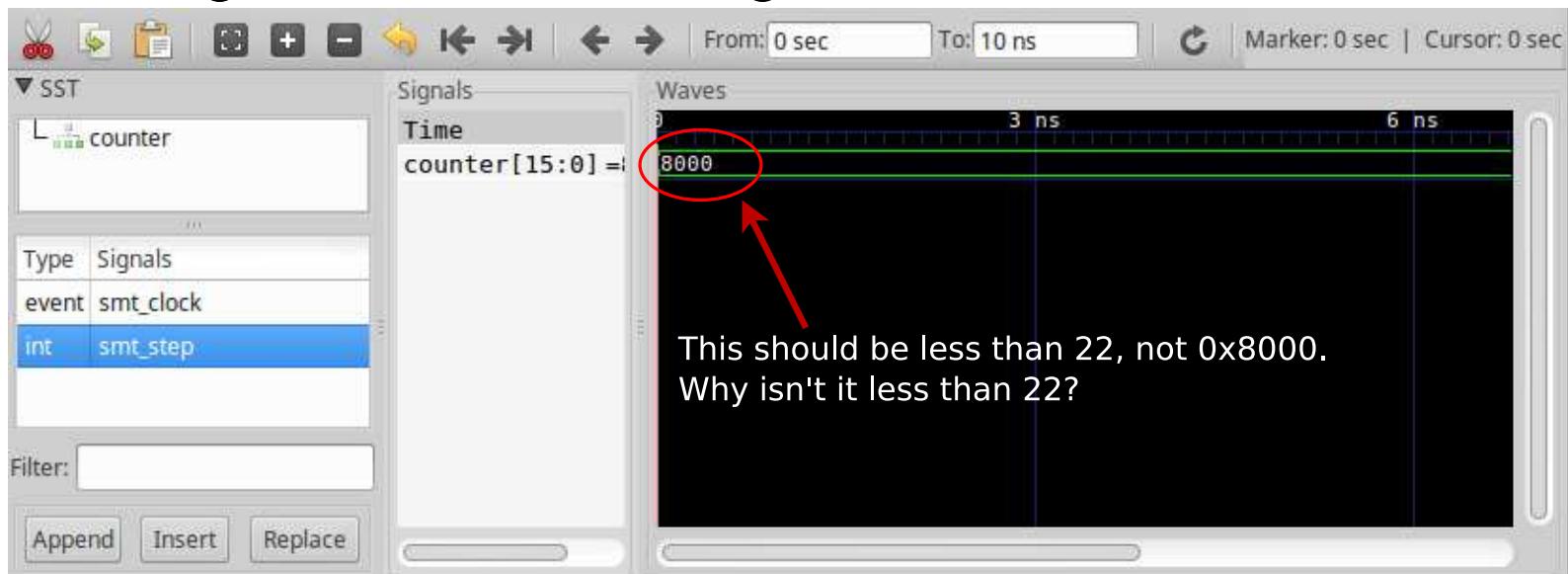
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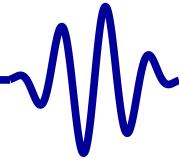
Look at source line 63, and fire up gtkwave

```
:~/          exercise-01$ sby -f counter.sby
SBY 11:26:17 [counter] Removing directory 'counter'.
SBY 11:26:17 [counter] Copy 'counter.v' to 'counter/src/counter.v'.
SBY 11:26:17 [counter] engine_0: smtbmc
SBY 11:26:17 [counter] base: starting process "cd counter/src; yosys -ql ../model/design.log ../model/design.yos"
SBY 11:26:17 [counter] base: finished (returncode=0)
SBY 11:26:17 [counter] smt2: starting process "cd counter/model; yosys -ql design_smt2.log design_smt2.ys"
SBY 11:26:17 [counter] smt2: finished (returncode=0)
SBY 11:26:17 [counter] engine_0: starting process "cd counter; yosys-smtbmc --presat --unroll --noprogress -t 20 --append 0 --dump-vcd engine_0/trace.vcd --dump-vlogtb engine_0/trace_tb.v --dump-smtc engine_0/trace.smfc model/design_smt2.smt2"
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Solver: yices
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Checking assumptions in step 0..
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Checking assertions in step 0..
SBY 11:26:17 [counter] engine_0: ## 0:00:00 BMC failed!
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Assert failed in counter: counter.v:63.13-64.31
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to VCD file: engine_0/trace.vcd
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to Verilog testbench: engine_0/trace_tb.v
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Writing trace to constraints file: engine_0/trace.smfc
SBY 11:26:17 [counter] engine_0: ## 0:00:00 Status: failed
SBY 11:26:17 [counter] engine_0: finished (returncode=1)
SBY 11:26:17 [counter] engine_0: Status returned by engine: FAIL
SBY 11:26:17 [counter] summary: Elapsed clock time [H:MM:SS (secs)]: 0:00:00 (0)
SBY 11:26:17 [counter] summary: Elapsed process time [H:MM:SS (secs)]: 0:00:00 (0)
SBY 11:26:17 [counter] summary: engine_0 (smtbmc) returned FAIL
SBY 11:26:17 [counter] summary: counterexample trace: counter/engine_0/trace.vcd
SBY 11:26:17 [counter] DONE (FAIL, rc=2)
```

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Run: % gtkwave counter/engine_0/trace.vcd



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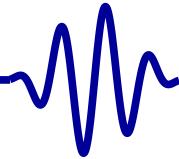
Run: % gvim demo-rtl/counter.v

What did we do wrong?

```
File Edit Tools Syntax Buffers Window Help
39 // 
40 `default_nettype none
41 //
42 module counter(i_clk, i_start_signal, o_busy);
43     parameter [15:0] MAX_AMOUNT = 22;
44     //
45     input wire i_clk;
46     //
47     input wire i_start_signal;
48     output reg o_busy;
49
50     reg [15:0] counter;
51
52     always @(posedge i_clk)
53         if ((i_start_signal)&&(counter == 0))
54             counter <= MAX_AMOUNT-1'b1;
55         else if (counter != 0)
56             counter <= counter - 1'b1;
57
58     always @(*)
59         o_busy <= (counter != 0);
60
61 `ifdef FORMAL
62     always @(*)
63         assert(counter < MAX_AMOUNT);
64 `endif
65 endmodule
```

Line 63, Here's the assertion that failed

53,37-51 Bot

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Run: % gvim demo-rtl/counter.v

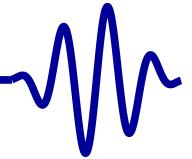
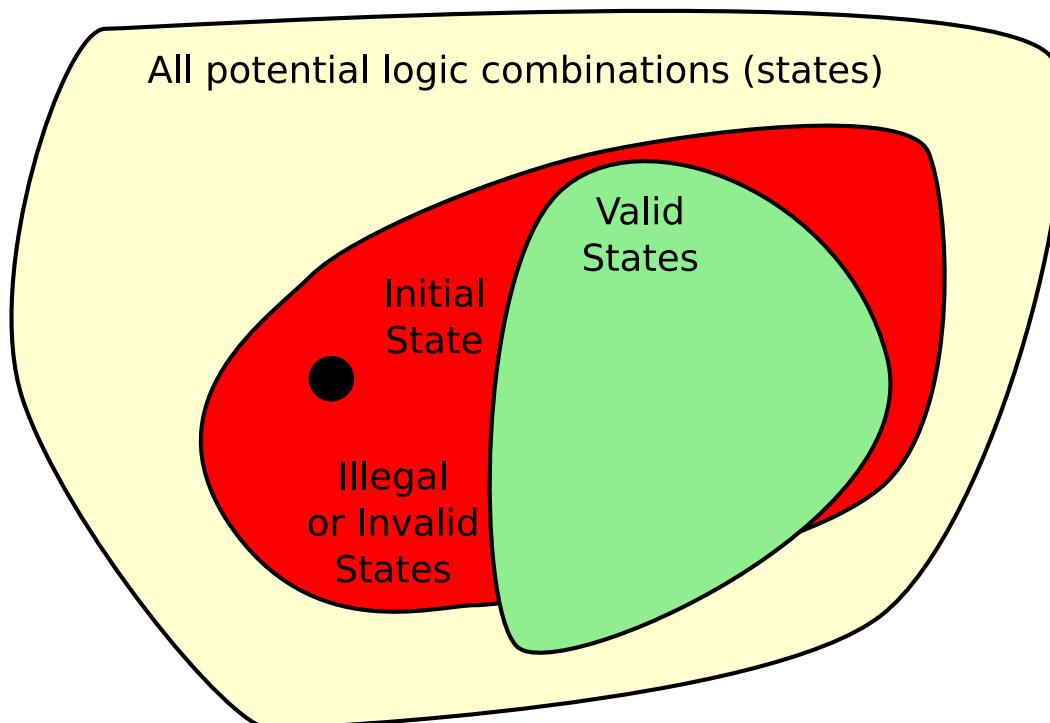
What did we do wrong?

```
File Edit Tools Syntax Buffers Window Help
39 // 
40 `default_nettype none
41 //
42 module counter(i_clk, i_start_signal, o_busy);
43   parameter [15:0] MAX_AMOUNT = 22;
44   //
45   input wire i_clk;
46   //
47   input wire i_start_signal;
48   output reg o_busy;
49   reg [15:0] counter;
50
51   always @(posedge i_clk)
52     if ((i_start_signal)&&(counter == 0))
53       counter <= MAX_AMOUNT-1'b1;
54     else if (counter != 0)
55       counter <= counter - 1'b1;
56
57   always @(*)
58     o_busy <= (counter != 0);
59
60 `ifdef FORMAL
61   always @(*)
62     assert(counter < MAX_AMOUNT);
63 `endif
64 `endif
65 endmodule
```

Line 63, Here's the assertion that failed

53,37-51 Bot

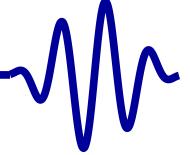
Did you notice the missing initial statement?

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- Problem: No initial statement
- Solver finds an invalid initial state
- Model fails



Exercise



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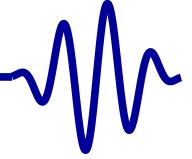
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Try adding in the initial statement, will it work?



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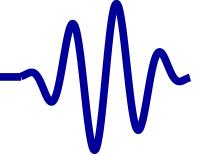
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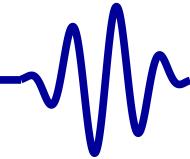
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Our Objective:

- To learn how to make assertions crossing time intervals
 - **\$past()**
- Before the beginning of time
 - Assumptions always hold
 - Assertions rarely hold
- How to get around this with f_past_valid

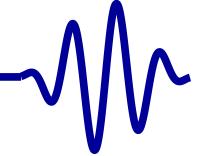
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- **\$past(X)** Returns the value of X one clock ago.
- **\$past(X,N)** Returns the value of X N clocks ago.
- Depends upon a clock
 - This is illegal

```
always @(*)  
if (x)  
    assert(y == $past(y));
```

- No clock is associated with the **\$past** operator.
- But you can do this

```
always @(posedge clk)  
if (x)  
    assert(y == $past(y));
```

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\$past FV Rule

Only use \$past as a precondition

```
always @(posedge clk)
if ((f_past_valid)&&($past(value)))
    assert(something);
```

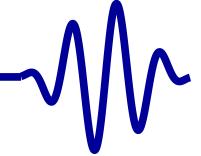
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Let's modify our counter, by creating some additional properties:

```
always @(*)  
    assume (! i_start_signal);  
  
always @(posedge clk)  
    assert ($past(counter == 0));
```

- `i_start_signal` is now never true, so the counter should always be zero.
- `assert(counter == 0);`
This should always be true, since counter starts at zero, and is never changed from zero.
- Will `assert($past(counter == 0));` succeed?

You can find this file in `exercise-02/pastassert.v`

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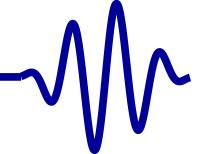
- This fails

```
always @(*)
```

```
    assume (!i_start_signal);
```

```
always @ (posedge clk)
```

```
    assert ($past(counter == 0));
```

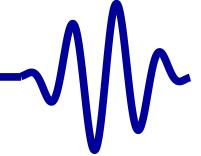
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- This fails

```
always @(*)  
    assume (!i_start_signal);
```

```
always @(posedge clk)  
    assert ($past(counter == 0));
```

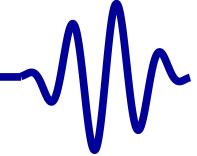
- Before time, counter is unconstrained.
- The solver can make it take on any value it wants in order to make things fail
- This will not show in the VCD file

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- This succeeds

```
always @(*)  
    assume (!i_start_signal);
```

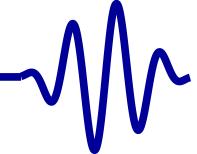
```
always @(*)  
    assert (counter == 0);
```

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Let's try again:

```
always @(posedge clk)
if ($past(i_start_signal))
    assert(counter == MAX_AMOUNT-1'b1);
```

This should work, right?

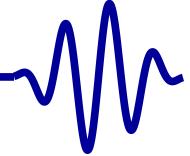
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Let's try again:

```
always @(posedge clk)
if ($past(i_start_signal))
    assert(counter == MAX_AMOUNT - 1'b1);
```

This should work, right? No, it fails.

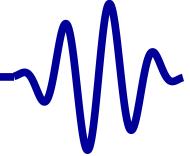
- `i_start_signal` is unconstrained before time
- `counter` is initially constrained to zero
- If `i_start_signal` is one before time,
`counter` will still be zero when time begins

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We can fix this with a register I call, f_past_valid:

```
reg f_past_valid;  
  
initial f_past_valid = 1'b0;  
always @(posedge clk)  
    f_past_valid <= 1'b1;  
  
always @(posedge clk)  
if ((f_past_valid)&&($past(i_start_signal)))  
    assert(counter == MAX_AMOUNT-1'b1);
```

Will this work?

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We can fix this with a register I call, f_past_valid:

```
reg f_past_valid;  
  
initial f_past_valid = 1'b0;  
always @(posedge clk)  
    f_past_valid <= 1'b1;  
  
always @(posedge clk)  
if ((f_past_valid)&&($past(i_start_signal)))  
    assert(counter == MAX_AMOUNT-1'b1);
```

Will this work? Almost, but not yet.

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- What about the case where `i_start_signal` is raised while the counter isn't zero?

```
reg f_past_valid;  
  
initial f_past_valid = 1'b0;  
always @ (posedge clk)  
    f_past_valid <= 1'b1;  
  
always @ (posedge clk)  
if ((f_past_valid)&&($past(i_start_signal))  
    &&($past(counter == 0)))  
    assert(counter == MAX_AMOUNT - 1'b1);
```

- Will this work?

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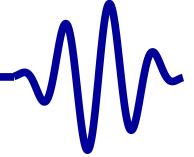
- What about the case where `i_start_signal` is raised while the counter isn't zero?

```
reg f_past_valid;  
  
initial f_past_valid = 1'b0;  
always @ (posedge clk)  
    f_past_valid <= 1'b1;  
  
always @ (posedge clk)  
if ((f_past_valid)&&($past(i_start_signal))  
    &&($past(counter == 0)))  
    assert(counter == MAX_AMOUNT - 1'b1);
```

- Will this work? Yes, now it will work
- You'll find lots of references to `f_past_valid` in my own designs



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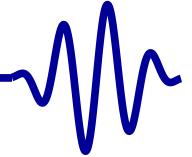
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Let's look at some practical examples

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The rule: Every design should start in the reset state.

```
initial assume(i_RESET);
```

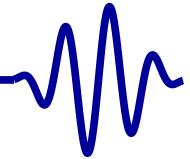
```
always @(*)
  if (!f_past_valid)
    assume(i_RESET);
```

What would be the difference between these two properties?

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The rule: On the clock following a reset, there should be no outstanding bus requests.

```
always @(posedge clk)
  if ((f_past_valid)&&($past(i_RESET)))
    assert (!o_CYC);
```

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Two times registers must have their reset value

- Initially
- Following a reset

```
always @(posedge clk)
if ((!f_past_valid)||($past(i_reset)))
begin
    assert (!o_CYC);
    assert (!o_STB);
    // etc.
end
```

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The rule: while a request is being made, the request cannot change until it is accepted.

```
always @(posedge clk)
  if ((f_past_valid)
      &&($past(o_STB))&&($past(i_STALL)))
    begin
      assert(o_STB);
      assert(o_REQ == $past(o_REQ));
    end
```

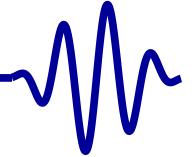
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Many of my projects include some type of “busy counter”

- Serial port logic must wait for a baud clock
Transmit characters must wait for the port to be idle
- I2C logic needs to slow the clock down
- SPI logic may also need to slow the clock down

Objectives:

- Gain some confidence using formal methods to prove that alternative designs are equivalent

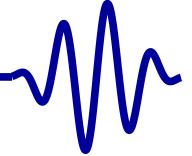
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Ex: Busy
▷ Counter

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Here's the basic design. It should look familiar.

```
parameter [15:0] MAX_AMOUNT = 22;  
  
reg [15:0] counter;  
  
initial counter = 0;  
always @(posedge i_clk)  
if (i_reset)  
    counter <= 0;  
else if ((i_start_signal)&&(counter == 0))  
    counter <= MAX_AMOUNT-1'b1;  
else if (counter != 0)  
    counter <= counter - 1;  
  
always @(*)  
o_busy = (counter != 0);
```

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You can find the design in `exercise-03/busyctr.v`.

Exercise: Create the following properties:

1. `i_start_signal` may be raised at any time

No property needed here

2. Once raised, *assume* `i_start_signal` will remain high until it is high and the counter is no longer busy.

3. `o_busy` will always be true while the counter is non-zero

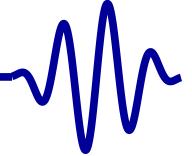
Make sure you check `o_busy` both when `counter == 0` and `counter != 0`

This requires an assertion

4. If the counter is non-zero, it should always be counting down

Beware of the reset!

This requires another assertion

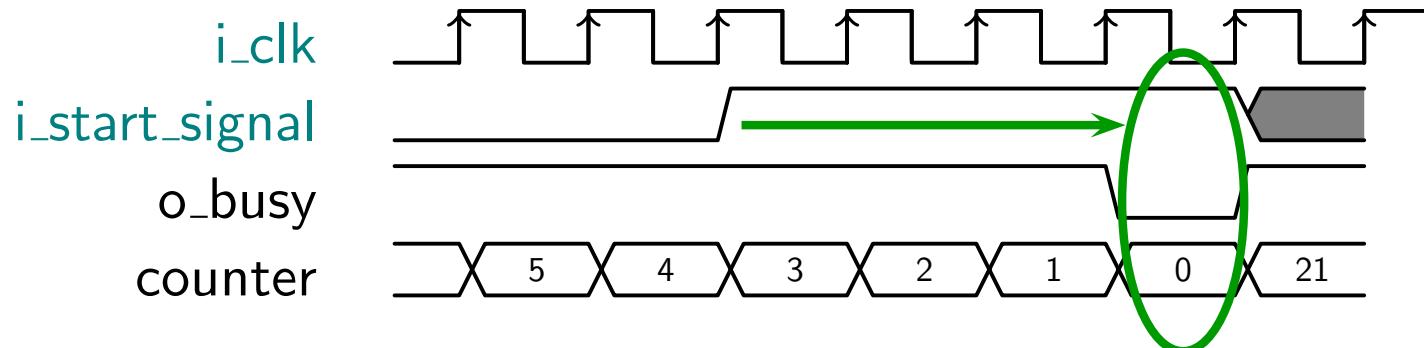
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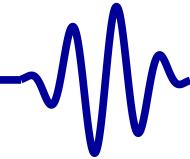
Ex: Busy
Counter

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Let's draw this requirement out

- Once raised, *assume i_start_signal will remain high until it is high and the counter is no longer busy.*



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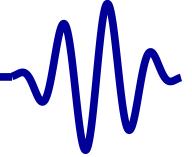
Exercise:

1. Make o_busy a clocked register

```
always @(posedge i_clk)
    o_busy <= /* your logic goes here */;
```

2. Prove that o_busy is true if and only if the counter is non-zero

- You can use this approach to adjust your design to meet timing
 - Shuffle logic from one clock to another, then
 - Prove the new design remains valid



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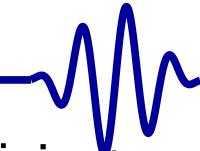
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If you want to formally verify your design, BMC is insufficient

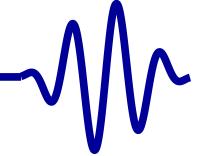
- Bounded Model Checking (BMC) will only prove that your design is correct for the first N clocks.
- It cannot prove that the design won't fail on the next clock, clock $N + 1$
- This is the purpose of the *induction* step: proving correctness for all time

Our Goals

- Be able to explain what induction is
- Be able to explain why induction is valuable
- Know how to run induction
- What are the unique problems associated with induction



From Pre-Calc



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Proof by induction has two steps:

1. **Base case:** Prove for $N = 0$ (or one)
2. **Inductive step:** Assume true for N , prove true for $N + 1$.

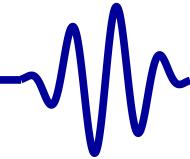
Example: Prove $\sum_{n=0}^{N-1} x^n = \frac{1-x^N}{1-x}$

- For $N = 1$, the sum is x^0 or one

$$\sum_{n=0}^{N-1} x^n = x^0 = \frac{1-x}{1-x}$$

So this is true (for $x \neq 1$).

- For the inductive step, we'll
 - Assume true for N , then prove for $N + 1$



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Prove $\sum_{n=0}^{N-1} x^n = \frac{1-x^N}{1-x}$ for all N

- Assume true for N , prove for $N + 1$

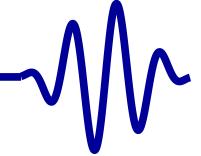
$$\sum_{n=0}^N x^n = x^N + \sum_{n=0}^{N-1} x^n = x^N + \frac{1-x^N}{1-x}$$

- Prove for $N + 1$

$$\begin{aligned} \sum_{n=0}^N x^n &= \frac{1-x}{1-x} x^N + \frac{1-x^N}{1-x} \\ &= \frac{x^N - x^{N+1} + 1 - x^N}{1-x} = \frac{1-x^{N+1}}{1-x} \end{aligned}$$

This proves the inductive case.

- Hence this is true for all N (where $N > 0$ and $x \neq 1$)

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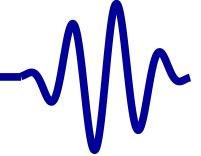
Suppose $\forall n : P[n]$ is what we wish to prove

- Traditional induction

- Base case: show $P[0]$
 - Inductive case: show $P[n] \rightarrow P[n + 1]$

- k induction

- Base case: show $\bigwedge_{k=0}^{N-1} P[k]$
 - k -induction step: $\left(\bigwedge_{k=n-N+1}^n P[k] \right) \rightarrow P[n + 1]$

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Suppose $\forall n : P[n]$ is what we wish to prove

- Traditional induction

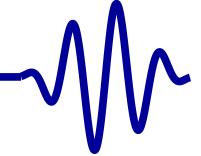
- Base case: show $P[0]$
 - Inductive case: show $P[n] \rightarrow P[n + 1]$

- k induction

- Base case: show $\bigwedge_{k=0}^{N-1} P[k]$

This is what we did with BMC

- k -induction step: $\left(\bigwedge_{k=n-N+1}^n P[k] \right) \rightarrow P[n + 1]$

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Suppose $\forall n : P[n]$ is what we wish to prove

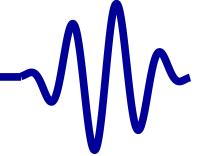
- Traditional induction

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 - Inductive case: show $P[n] \rightarrow P[n + 1]$

- k induction

- Base case: show $\bigwedge_{k=0}^{N-1} P[k]$
 - k -induction step: $\left(\bigwedge_{k=n-N+1}^n P[k] \right) \rightarrow P[n + 1]$

This is our next step

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Suppose $\forall n : P[n]$ is what we wish to prove

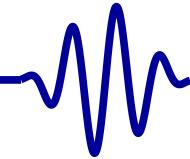
- Traditional induction

- Base case: show $P[0]$
 - Inductive case: show $P[n] \rightarrow P[n + 1]$

- k induction

- Base case: show $\bigwedge_{k=0}^{N-1} P[k]$
 - k -induction step: $\left(\bigwedge_{k=n-N+1}^n P[k] \right) \rightarrow P[n + 1]$

Why use k induction?

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Formal verification uses k induction

- **Base case:**

Assume the first N steps do not violate any assumptions, . . .

Prove that the first N steps do not violate any assertions.

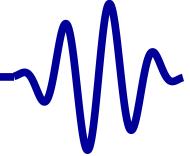
This is the BMC pass we've already done.

- **Inductive Step:**

Assume N steps exist that neither violate any assumptions nor any assertions, and

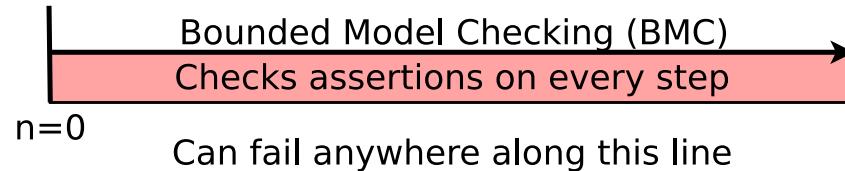
Assume the $N + 1$ step violates no assumptions, . . .

Prove that the $N + 1$ step does not violate any assertions.

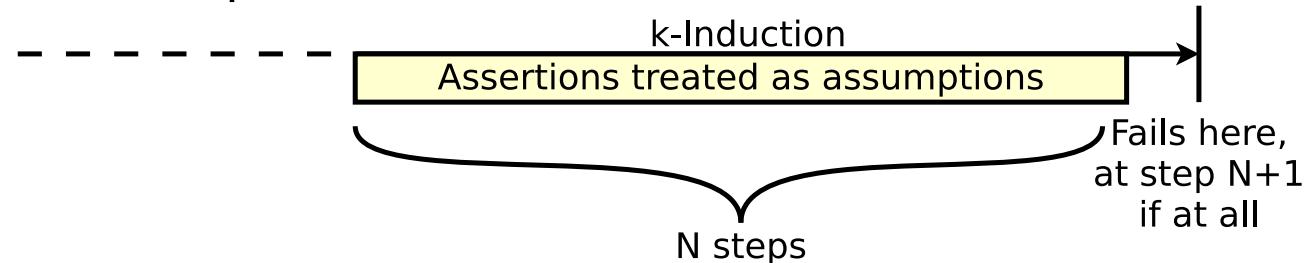
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BMC and induction are very different.

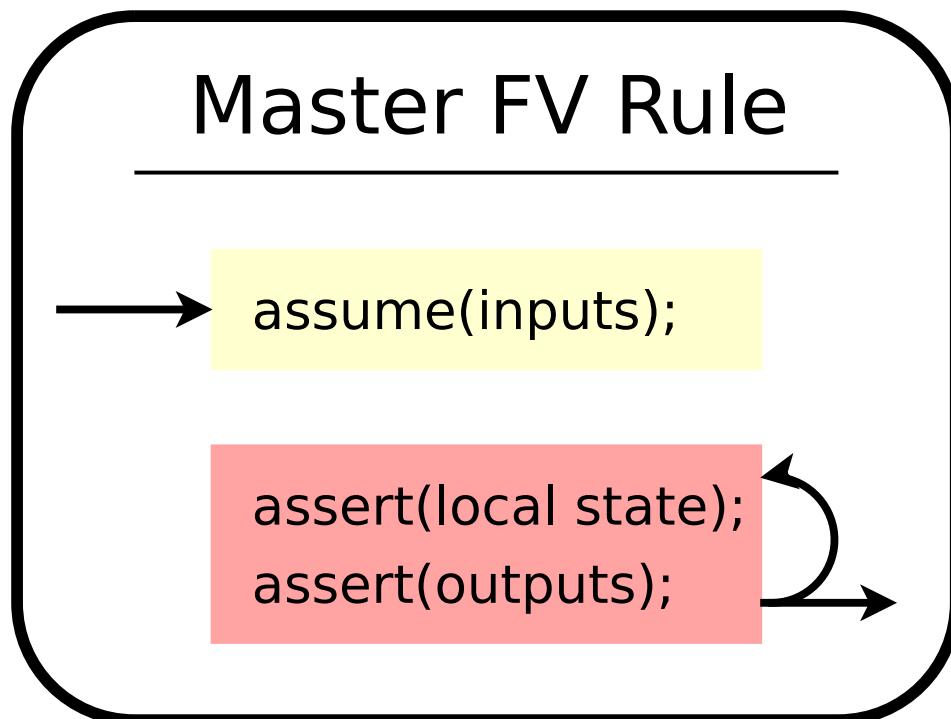
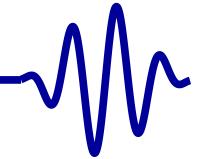
- BMC, the base case



- Induction step



- The number of BMC time-steps must be more than the number of inductive time-steps
- Register values at the beginning of the inductive step can be *anything* allowed by your assertions and assumptions
- This is where the work takes place.



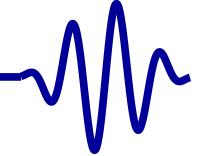
The general rule hasn't changed:

- assume inputs,
- assert internal states and any outputs.

If you assume too much, your design will pass formal verification and still not work.



Checkers



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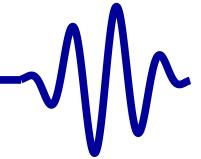
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Some assertions:

- Games are played on black squares
- Players will never have more than 12 pieces
- Only legal moves are possible
- Game is over when one side can no longer move

Where might the induction engine start?



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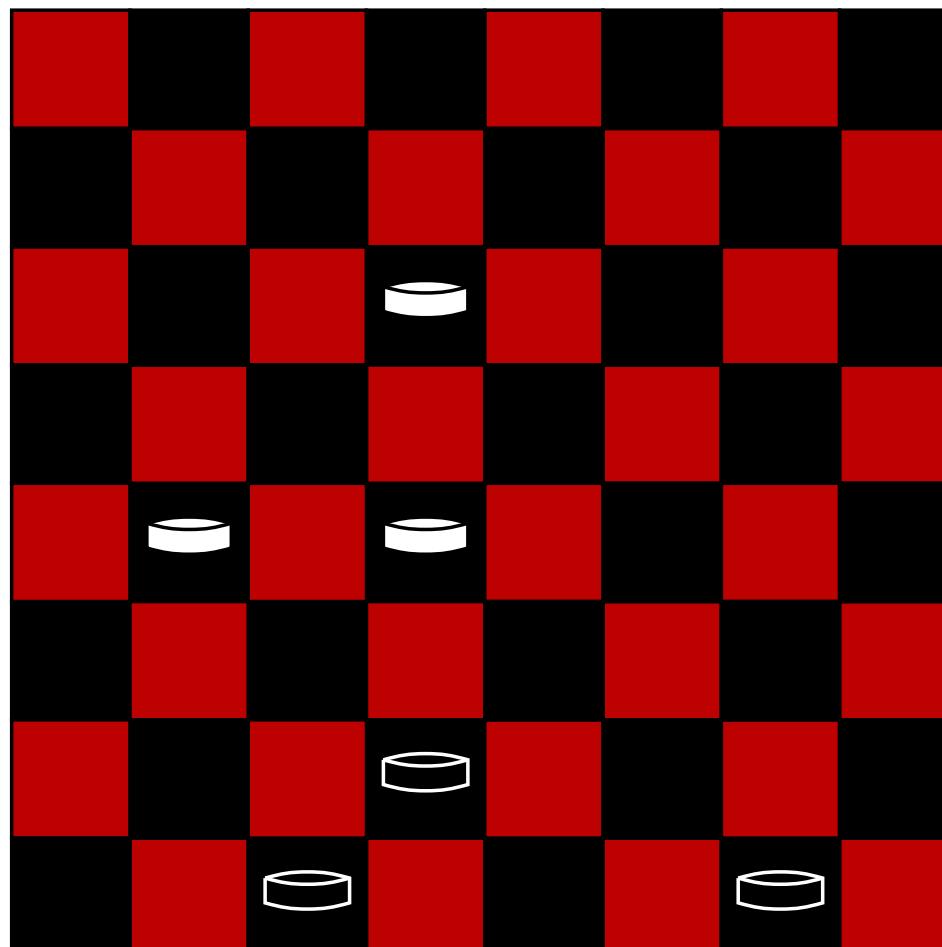
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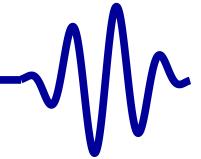
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Black's going to move and win



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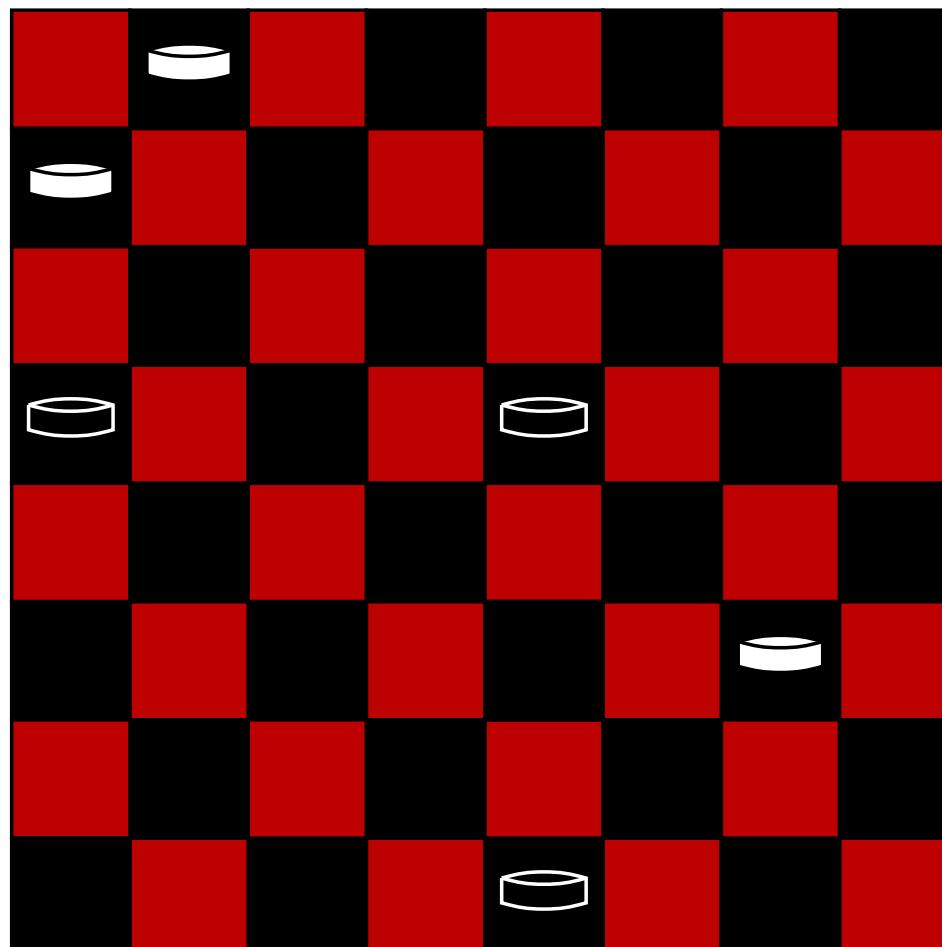
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Multiple-Clocks

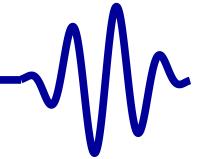
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White's going to move and win



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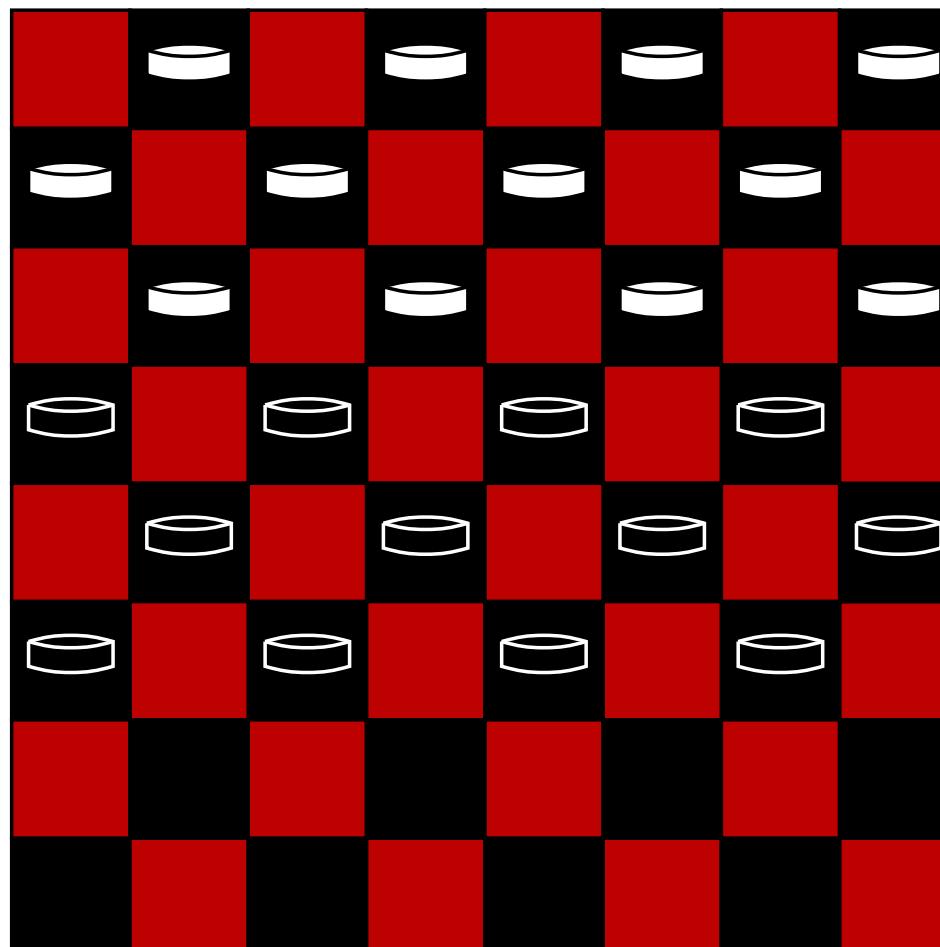
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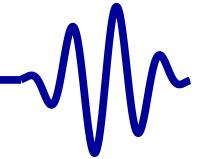
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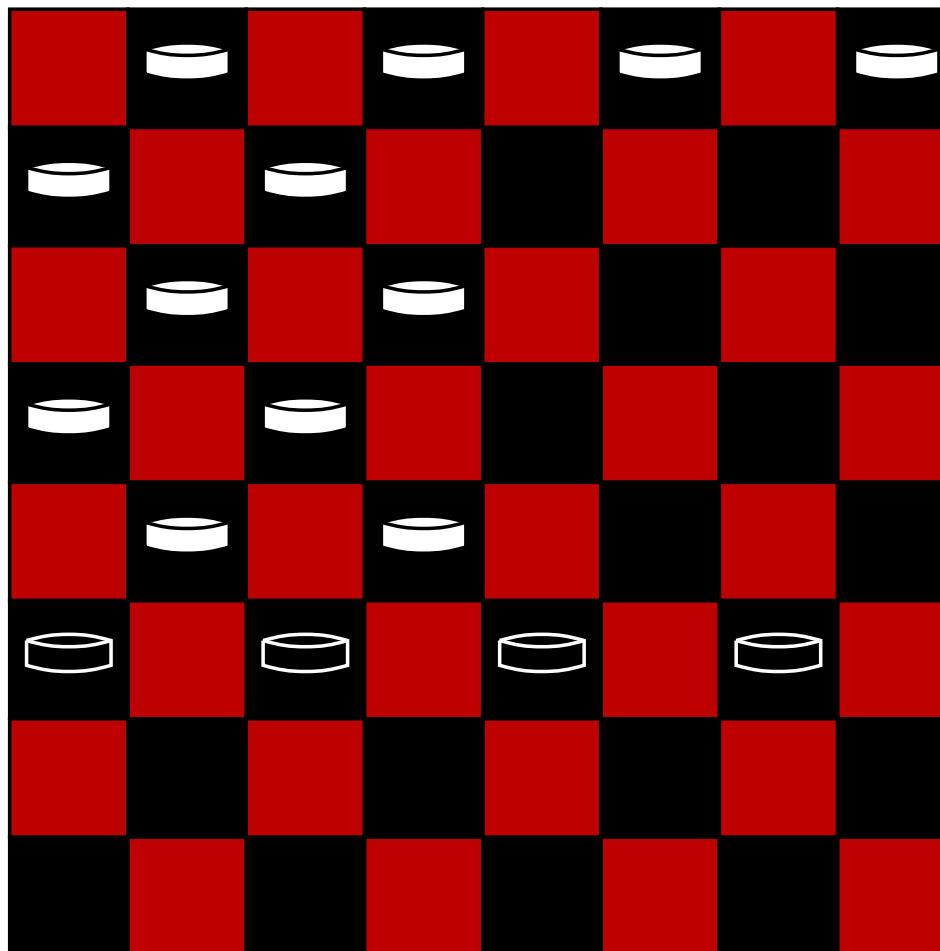
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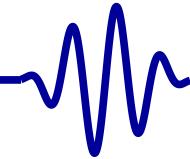
Black's going to . . . , huh?



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Would this pass our criteria?



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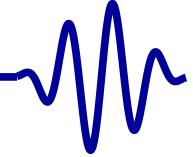
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What can we learn from Checkers?

- Inductive step starts in the *middle of the game*
Only the assumptions and asserts are used to validate the game
- All of the FF's (variables) start in arbitrary states
These states are *only* constrained by your assumptions and assertions.
- Your formal constraints are required to limit the allowable states



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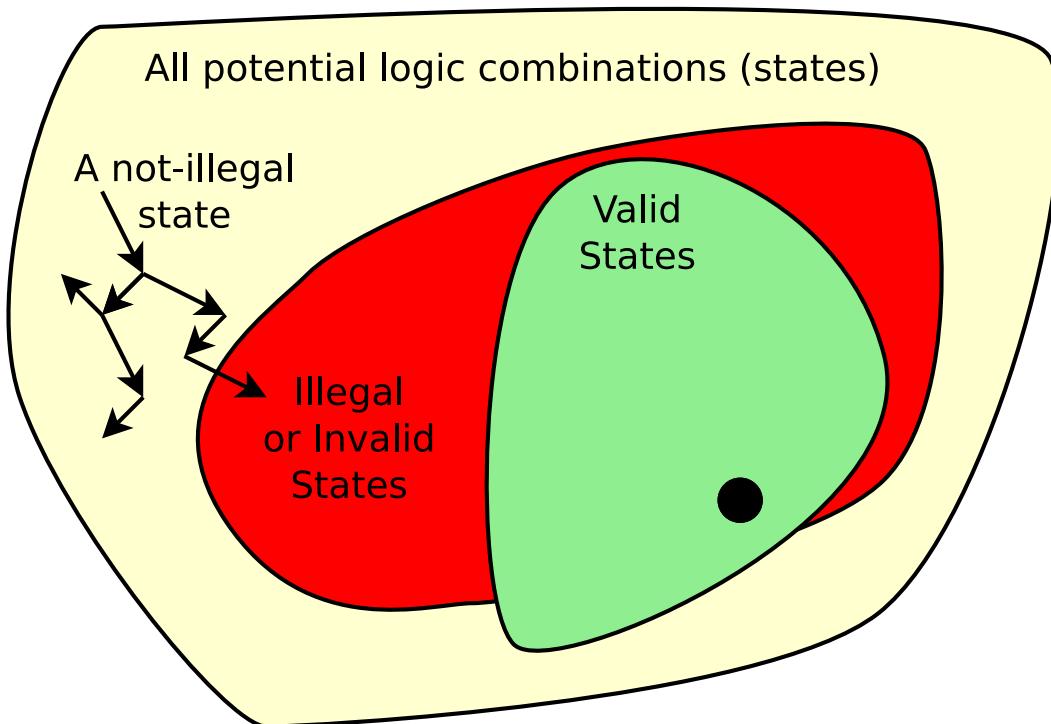
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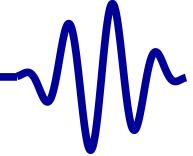
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- If your formal properties are not strict enough,
Induction may start in an unreachable state
- *This is a common problem!*



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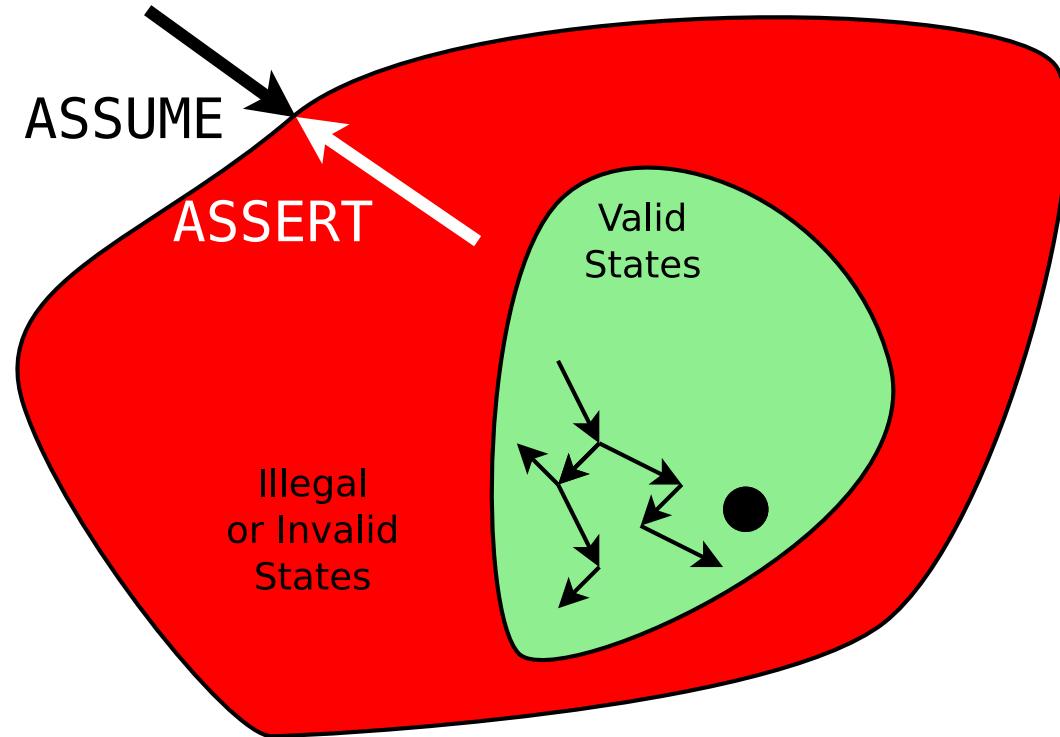
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To make induction work, you must . . .

- **assume** unrealistic inputs will never happen
- **assert** any remaining unreachable states are illegal
- Induction often requires more properties than BMC alone

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Unlike BMC, the results of induction might be inconclusive

		Basecase (BMC)	
		FAIL	PASS
k Induction	FAIL	Design	UNKNOWN
	PASS	Fails	SUCCESS!

The k induction pass will fail if your design doesn't have enough assertions.

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There's also a difference in when BMC and induction finish

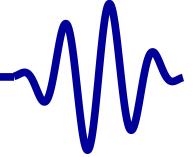
- BMC will finish early if the design FAILs
- Induction will finish early if the design PASSes
- In all other cases, they will take a full depth steps

You can use this fact to trim the depth of your proof

- Once induction succeeds, trim your proof depth to that length
- This will immediately make your proof run that much faster



Examples



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- Let's look at some examples

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This design would pass *many* steps of BMC

```
reg [15:0] counter;  
  
initial counter = 0;  
always @ (posedge clk)  
    counter <= counter + 1'b1;  
  
always @ (*)  
    assert(counter < 16'd65000);
```

It will not pass induction.

Can you explain why not?

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Here's another counter that will pass BMC, but not induction

```
reg [15:0] counter;  
  
initial counter = 0;  
always @(posedge clk)  
if (counter == 16'd22)  
    counter <= 0;  
else  
    counter <= counter + 1'b1;  
  
always @(*)  
    assert(counter != 16'd500);
```

Can you explain why not?

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With one simple change, this design will now pass induction

```
reg [15:0] counter;  
  
initial counter = 0;  
always @(posedge clk)  
if (counter == 16'd22)  
    counter <= 0;  
else  
    counter <= counter + 1'b1;  
  
always @(*)  
    assert(counter <= 16'd22);
```

See the difference?

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These shift registers will be equal during BMC, but require at least sixteen steps to pass induction

```
reg      [15:0]  sa , sb ;
initial sa = 0;
initial sb = 0;
always @ (posedge clk)
    sa <= { sa[14:0] , i_bit } ;
always @ (posedge clk)
    sb <= { sb[14:0] , i_bit } ;
always @ (*)
    assert (sa[15] == sb[15]);
```

Can you explain why it would take so long?

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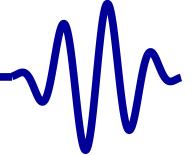
This design is almost identical to the last one, yet fails induction. The key difference is the **if** (`i_ce`).

```
reg      [15:0]  sa, sb;
initial sa = 0;
initial sb = 0;
always @ (posedge clk)
if (i_ce)
    sa <= { sa[14:0], i_bit };
always @ (posedge clk)
if (i_ce)
    sb <= { sb[14:0], i_bit };
always @ (*)
    assert (sa[15] == sb[15]);
```

Can you explain why this wouldn't pass?



Fixing Shift Reg



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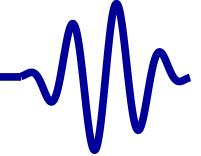
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Several approaches to fixing this:

1. **assume(i_ce);**



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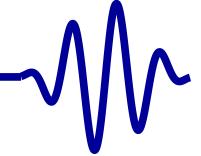
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Several approaches to fixing this:

1. **assume(i_ce);**
Doesn't really test the design
2. opt_merge –share_all, yosys option



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Several approaches to fixing this:

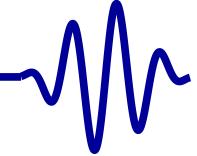
1. **assume(i_ce);**
Doesn't really test the design
2. opt_merge –share_all, yosys option
Works for some designs
3. **assert(sa == sb);**

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Several approaches to fixing this:

1. **assume(i_ce);**
Doesn't really test the design
2. opt_merge –share_all, yosys option
Works for some designs
3. **assert(sa == sb);**
Best, but only works when sa and sb are visible
4. Insist on no more than M clocks between i_ce's

Fixing Shift Reg



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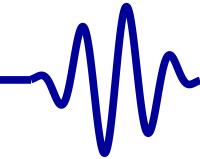
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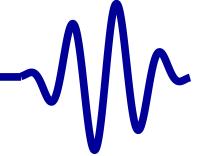
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Several approaches to fixing this:

1. **assume(i_ce);**
Doesn't really test the design
2. opt_merge –share_all, yosys option
Works for some designs
3. **assert(sa == sb);**
Best, but only works when sa and sb are visible
4. Insist on no more than M clocks between i_ce's
5. Use a different prover, under the [**engines**] option
 - smtbmc
 - abc pdr
 - aiger suprove



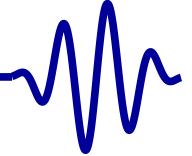
Several approaches to fixing this:

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Several approaches to fixing this:

1. **assume(i_ce);**
Doesn't really test the design
2. opt_merge –share_all, yosys option
Works for some designs
3. **assert(sa == sb);**
Best, but only works when sa and sb are visible
4. Insist on no more than M clocks between i_ce's
5. Use a different prover, under the [**engines**] option
 - smtbmc **Inconclusive Proof (Induction fails)**
 - abc pdr **Pass**
 - aiger suprove **Pass**

Most of these options work for *some* designs only



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[**options**]

mode prove

[**engines**]

smtbmc

[**script**]

read –formal module.v

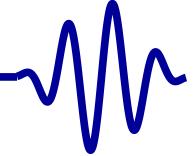
... *other files would go here*

prep –top module

opt_merge –share_all

[**files**]

.. / path-to/module.v

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Here's how we'll change our sby file:

[**options**]

mode prove ← Use BMC and *k*-induction

[**engines**]

smtbmc

[**script**]

read –formal module.v

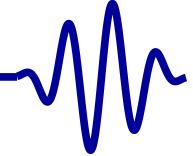
... other files would go here

prep –top module

opt_merge –share_all

[**files**]

.. / path-to/module.v

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Here's how we'll change our sby file:

```
[ options ]
```

```
mode prove
```

```
[ engines ]
```

```
smtbmc ← Other potential engines would go here
```

```
[ script ]
```

```
read -formal module.v
```

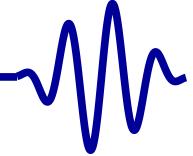
```
# ... other files would go here
```

```
prep -top module
```

```
opt_merge -share_all
```

```
[ files ]
```

```
../ path-to/module.v
```

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Here's how we'll change our sby file:

```
[ options ]
```

```
mode prove
```

```
[ engines ]
```

```
smtbmc
```

```
[ script ]
```

```
read -formal module.v
```

```
# ... other files would go here
```

```
prep -top module
```

```
opt_merge -share_all ← Here's where opt_merge would go
```

```
[ files ]
```

```
../ path-to/module.v
```

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Exercise #4: dblpipe.v

```
module dblpipe(i_clk,
               i_ce, i_data, o_data);
  // ...
  wire a_data, b_data;
  lfsr_fib one(i_clk, 1'b0, i_ce,
                i_data, a_data);
  lfsr_fib two(i_clk, 1'b0, i_ce,
                i_data, b_data);
  initial o_data = 1'b0;
  always @ (posedge i_clk)
    o_data <= a_data ^ b_data;
endmodule
```



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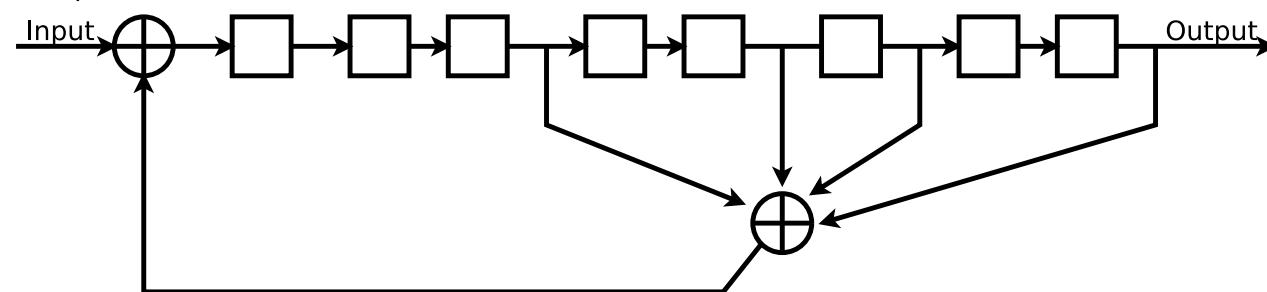
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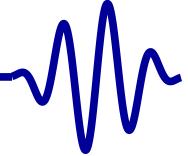
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Exercise #4: dblpipe.v

- lfsr_fib just implements a Fibonacci linear feedback shift register,



```
sreg [(LN-2):0] <= sreg [(LN-1):1];
sreg [(LN-1)] <= (^ (sreg & TAPS)) ^ i_in;
```

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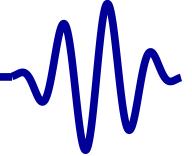
Exercise #4: dblpipe.v, lfsr_fib.v

```
reg      [(LN-1):0]      sreg;  
  
initial sreg = INITIAL_FILL;  
always @(posedge i_clk)  
if (i_reset)  
    sreg <= INITIAL_FILL;  
else if (i_ce)  
begin // Basic shift register update operation  
    sreg[(LN-2):0] <= sreg[(LN-1):1];  
    sreg[(LN-1)] <= (^ (sreg & TAPS)) ^ i_in;  
end  
  
assign o_bit = sreg[0];
```

- Both registers one and two use *the exact same logic*



Ex: DblPipe



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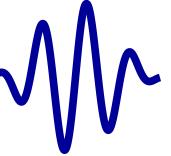
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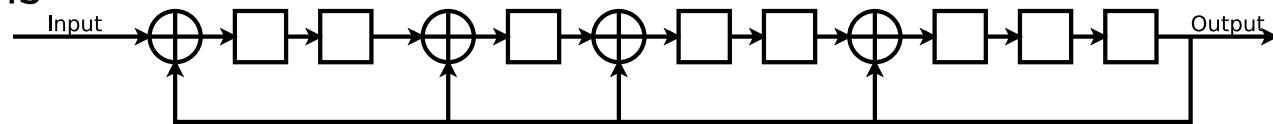
Exercise #4:

- Using dblpipe.v
 - Prove that the output, o_data, is zero

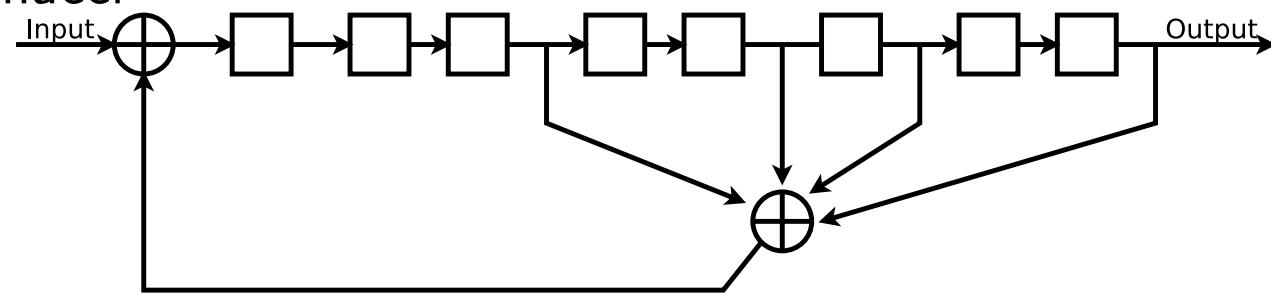
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Galois and Fibonacci are supposedly identical

- Galois



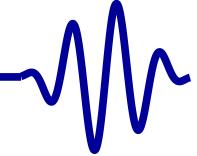
- Fibonacci



- Exercise #5 will be to prove these two implementations are identical



Ex: LFSRs



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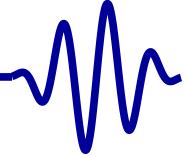
Quizzes

Exercise #5:

- exercise-05/ contains files `lfsr_equiv.v`, `lfsr_gal.v`, and `lfsr_fib.v`.
- `lfsr_gal.v` contains a Galois version of an LFSR
- `lfsr_fib.v` contains a Fibonacci version of the same LFSR
- `lfsr_equiv.v` contains an assertion that these are equivalent

Prove that these are truly equivalent shift registers.

Where is the bug?



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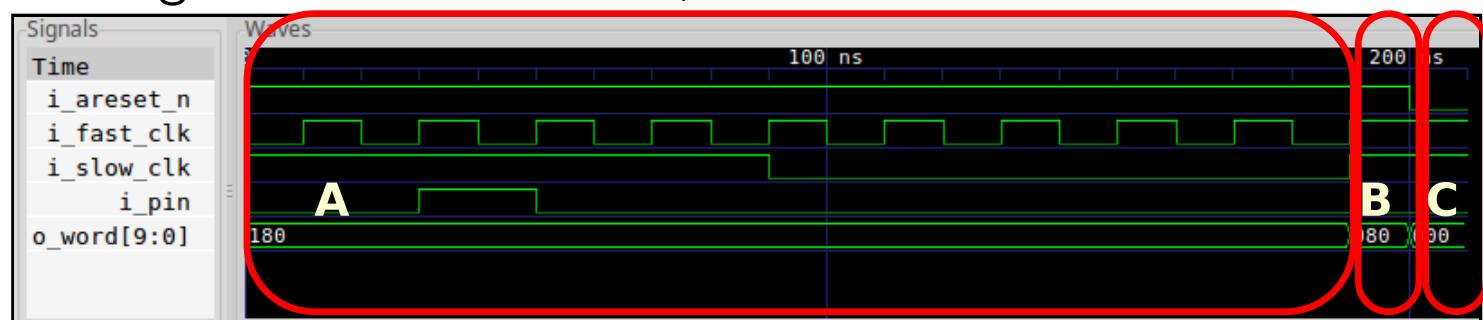
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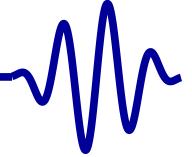
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Following an induction failure, look over the trace



If you see a problem in section ...

- A You have a missing one or more assertions
You'll only have this problem with induction.
- B You have a failing **assert @(posedge clk)**
- C You have a failing **assert @(*)**
These latter two indicate a potential logic failure, but they could still be caused by property failures.



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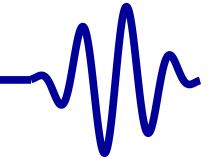
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We have everything we need now to write formal properties for a bus

- This lesson walks through an example the Wishbone Bus

Our Objectives:

- Learn to apply formal methods to something imminently practical
- Learn to build the formal description of a bus component
- Help lead up to a bus arbiter component

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Ex: WB Bus

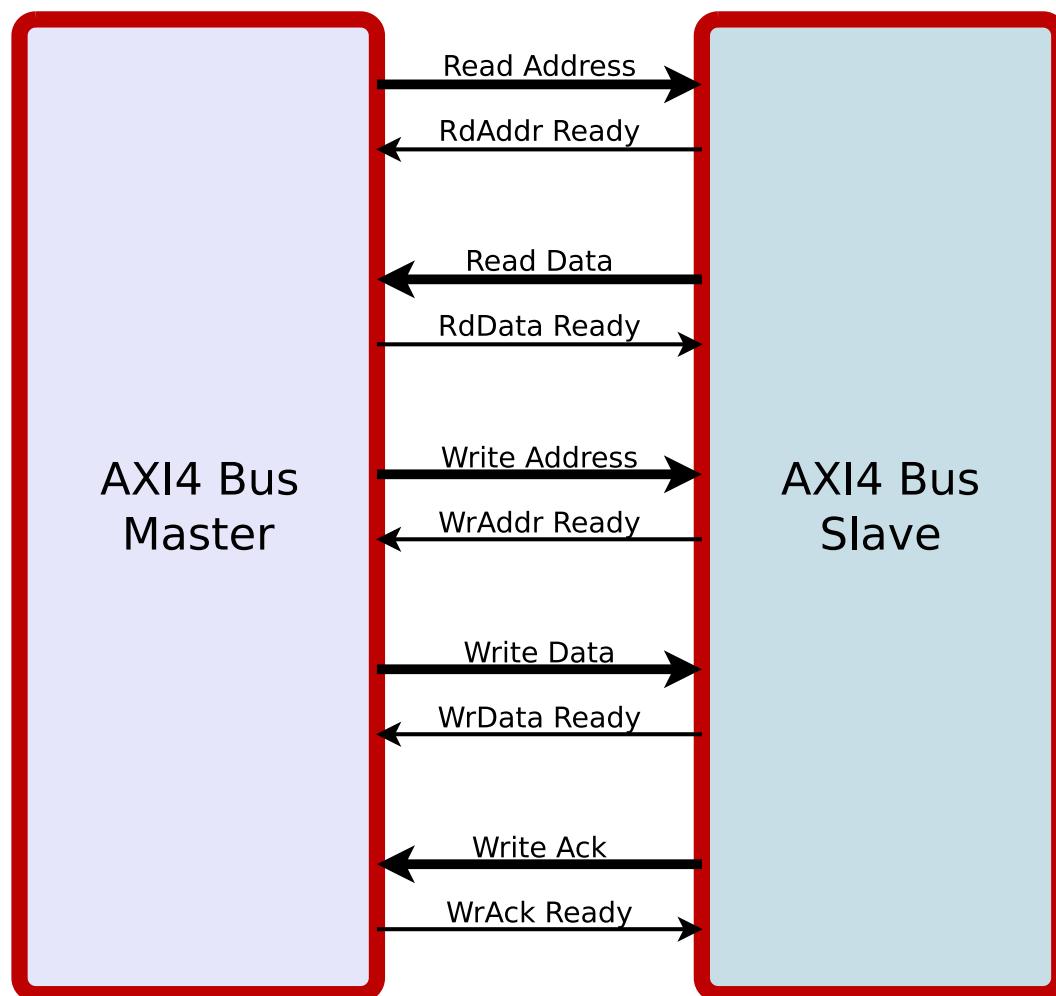
▷ AXI

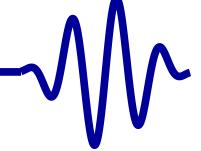
Avalon

Wishbone

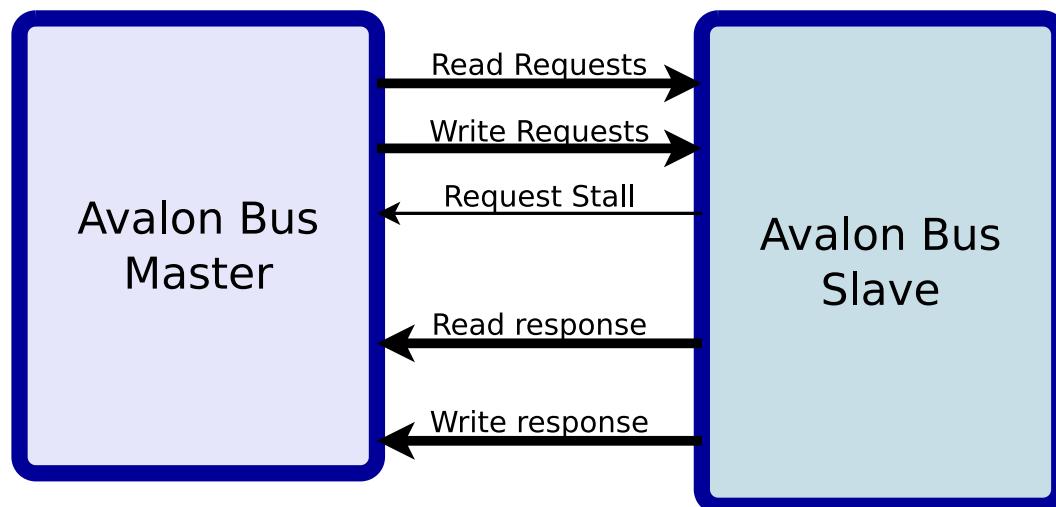
WB Basics

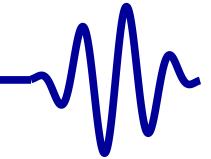
WB Basics

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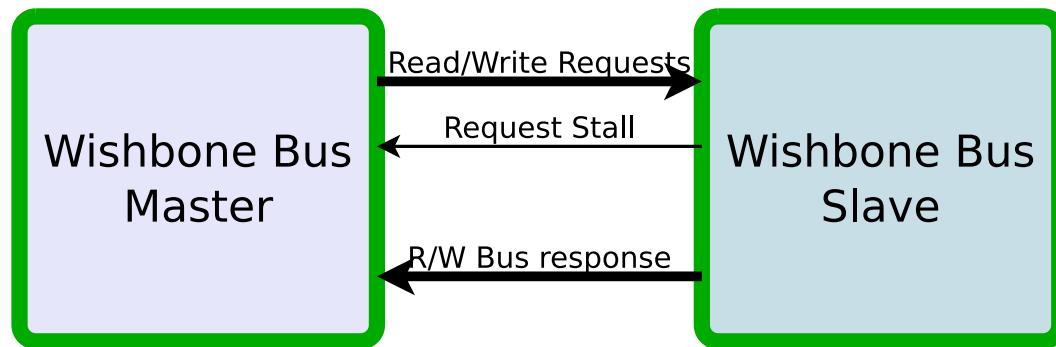


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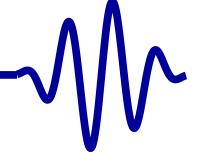
- Why use the Wishbone? *It's simpler!*

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From the master's perspective:

Specification name	My name
CYC_O	o_wb_cyc
STB_O	o_wb_stb
WE_O	o_wb_we
ADDR_O	o_wb_addr
DATA_O	o_wb_data
SEL_O	o_wb_sel
STALL_I	i_wb_stall
ACK_I	i_wb_ack
DATA_I	i_wb_data
ERR_I	i_wb_err

WB Signals



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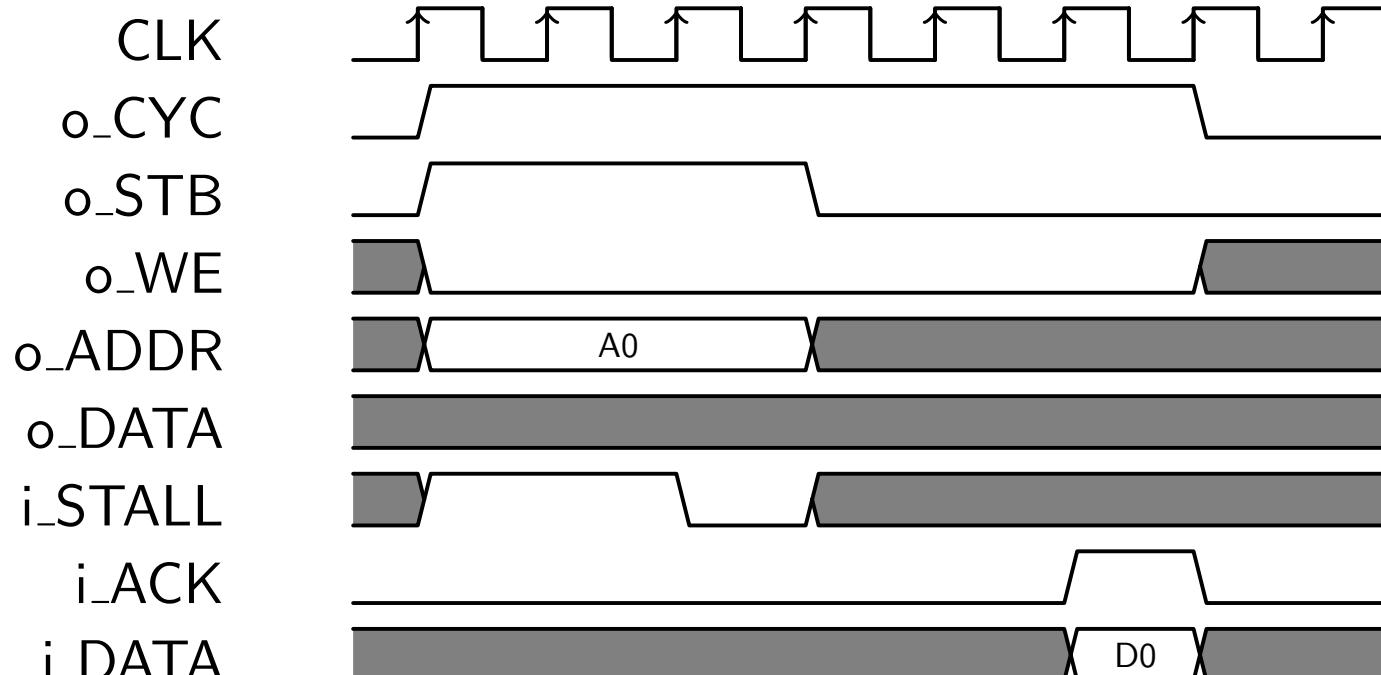
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From the slave's perspective:

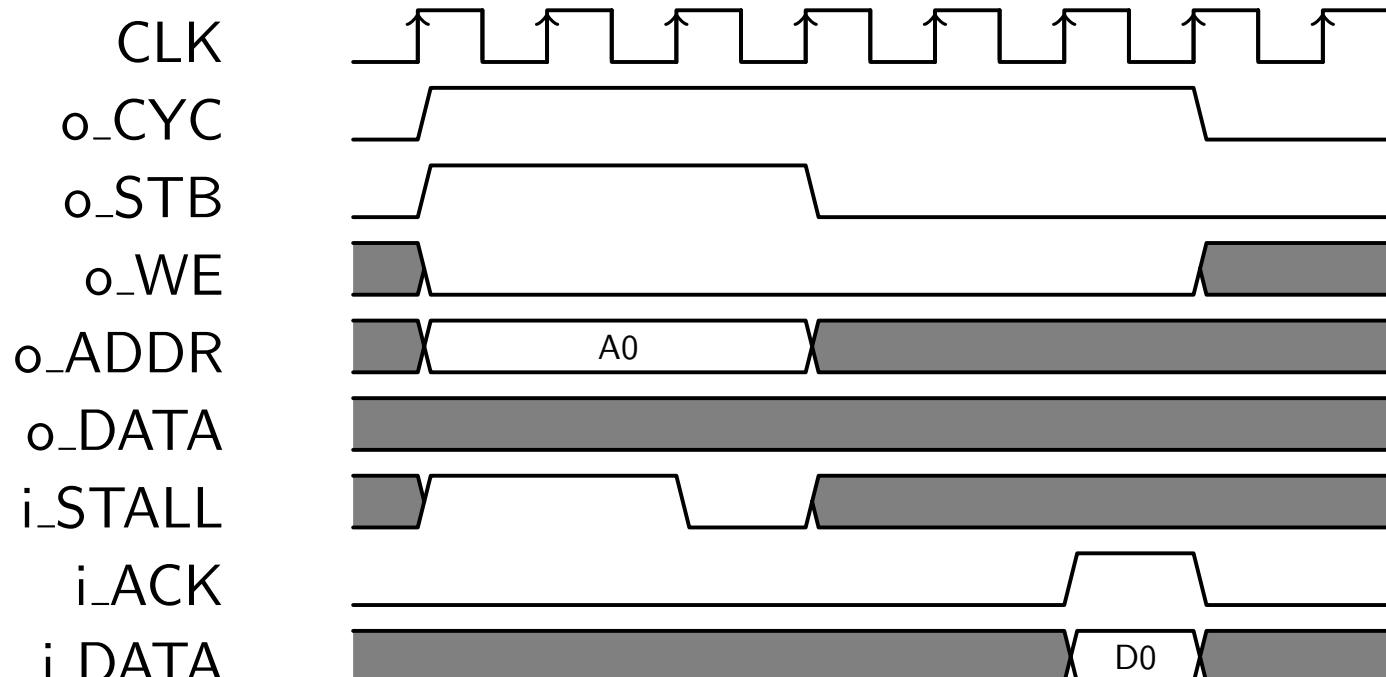
Specification name	My name
CYC_I	i_wb_cyc
STB_I	i_wb_stb
WE_I	i_wb_we
ADDR_I	i_wb_addr
DATA_I	i_wb_data
SEL_I	i_wb_sel
STALL_O	o_wb_stall
ACK_O	o_wb_ack
DATA_O	o_wb_data
ERR_O	o_wb_err

To swap perspectives from master to slave ...

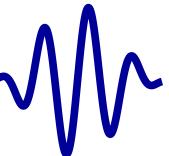
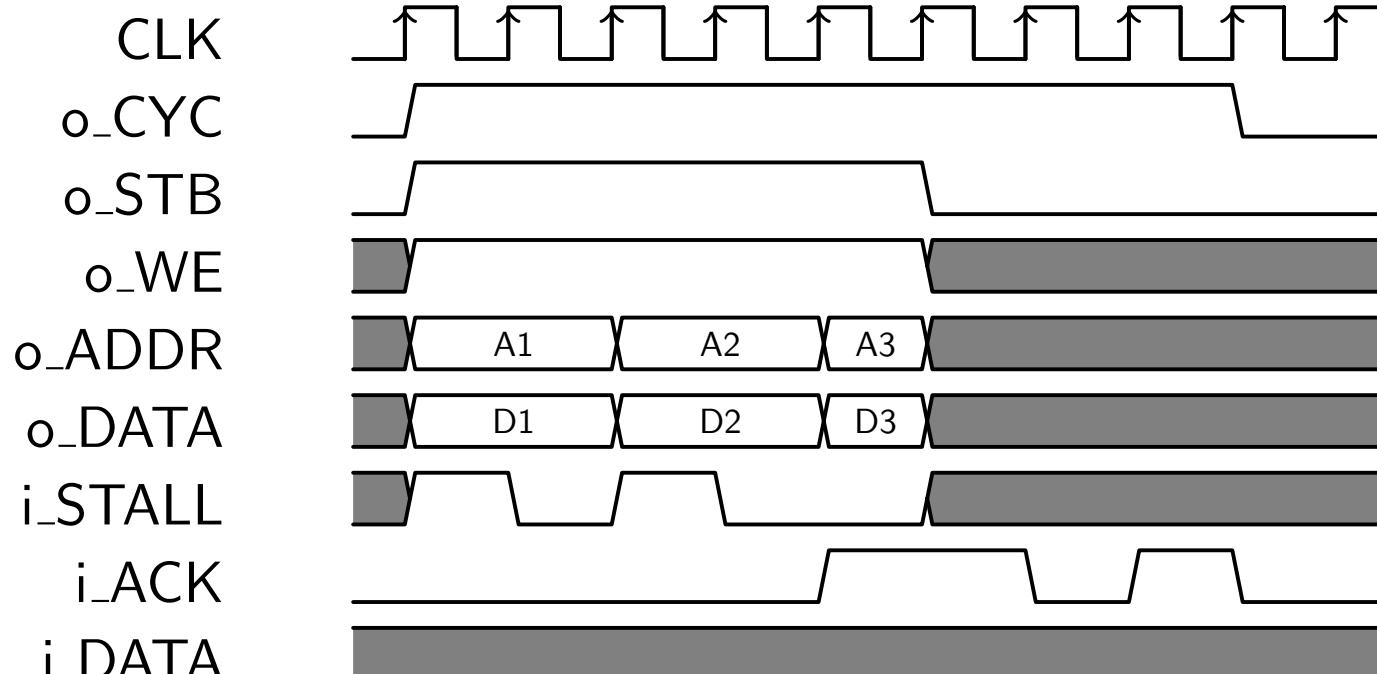
- Swap the port direction
- Swap the **assume()** statements for **assert()**s

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- STB must be low when CYC is low
- If CYC goes low mid-transaction, the transaction is aborted
- While STB and STALL are active, the request cannot change
- One request is made for every clock with STB and !STALL

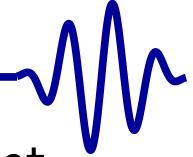
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- One ACK response per request
- No ACKs allowed when the bus is idle
- No way to stall the ACK line
- The bus result is in i_DATA when i_ACK is true

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Let's start building some formal properties

GT CYC and STB



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- The bus starts out idle, and returns to idle after a reset

```
always @(posedge i_clk)
  if ((!f_past_valid)||($past(i_reset)))
    begin
      assume (!i_wb_ack);
      assume (!i_wb_err);
      //
      assert (!o_wb_cyc);
      assert (!o_wb_stb);
    end
```

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- The bus starts out idle, and returns to idle after a reset

```
always @(posedge i_clk)
  if ((!f_past_valid)||($past(i_reset)))
    begin
      assume (!i_wb_ack);
      assume (!i_wb_err);
      //
      assert (!o_wb_cyc);
      assert (!o_wb_stb);
    end
```

- STB is low whenever CYC is low

```
always @(*)
  if (!o_wb_cyc)
    assert (!o_wb_stb);
```

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- While STB and STALL are active, the request doesn't change

```
assign f_request = { o_stb, o_we, o_addr,
                     o_data };
always @(posedge clk)
if ($past(o_wb_stb)&&($past(i_wb_stall)))
    assert(f_request == $past(f_request));
```

- Did we get it?

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- While STB and STALL are active, the request doesn't change

```
assign f_request = { o_stb, o_we, o_addr,  
                     o_data };  
always @(posedge clk)  
if ($past(o_wb_stb)&&($past(i_wb_stall)))  
    assert(f_request == $past(f_request));
```

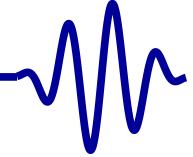
- Did we get it? Well, not quite
o_data is a don't care for any read request

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- While STB and STALL are active, the request doesn't change

```
assign f_rd_request = { o_stb, o_we, o_addr };
assign f_wr_request = { f_rd_request, o_data };

always @(posedge clk)
if ((f_past_valid)
  &&($past(o_wb_stb))&&($past(i_wb_stall)))
begin
  // First, for reads—o_data is a don't care
  if ($past(!i_wb_we))
    assert(f_rd_request == $past(f_rd_request));
  // Second, for writes—o_data must not change
  if ($past(i_wb_we))
    assert(f_wr_request == $past(f_wr_request));
end
```



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- No acknowledgements without a request
- No errors without a request
- Following any error, the bus cycle ends
- A bus cycle can be terminated early

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The rule: the slave (external) cannot stall the master more than F_OPT_MAXSTALL counts:

```
initial f_stall_count = 0;
always @(posedge i_clk)
if ((i_reset)||(!o_CYC)|| ((o_STB)&&(!i_STALL)))
    f_stall_count <= 0;
else if (o_STB)
    f_stall_count <= f_stall_count + 1'b1;

always @(posedge i_clk)
if (o_CYC)
    assume(f_stall_count < F_OPT_MAXSTALL);
```

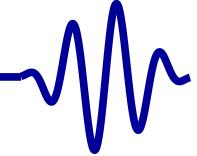
This solves the i_ce problem, this time with the i_STALL signal

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The rule: the slave can only respond to requests

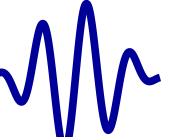
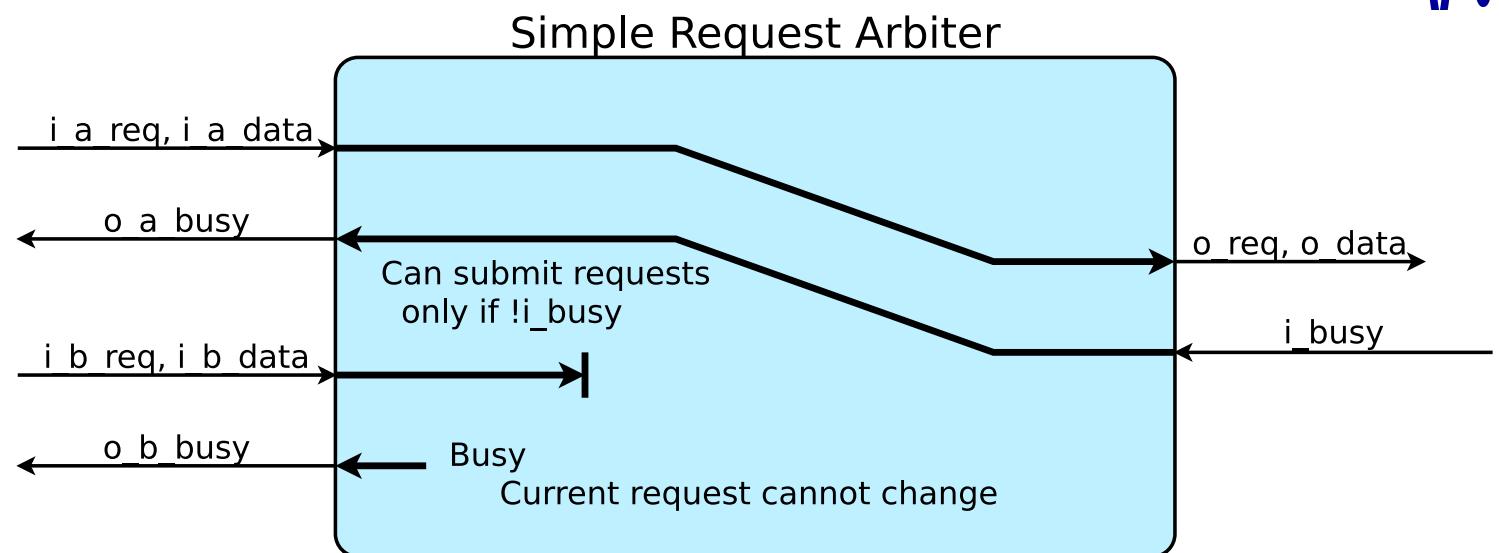
```
initial f_nreqs = 0;
always @(posedge clk)
if ((i_reset)||(!i_CYC))
    f_nreqs <= 1'b0;
else if ((i_STB)&&(!o_STALL))
    f_nreqs <= f_nreqs + 1'b1;
// Similar counter for acknowledgements
always @(*)
if (f_nreqs == f_nacks)
    assert (!o_ACK);
```

The logic above *almost* works. Can any one spot the problems?

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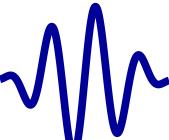
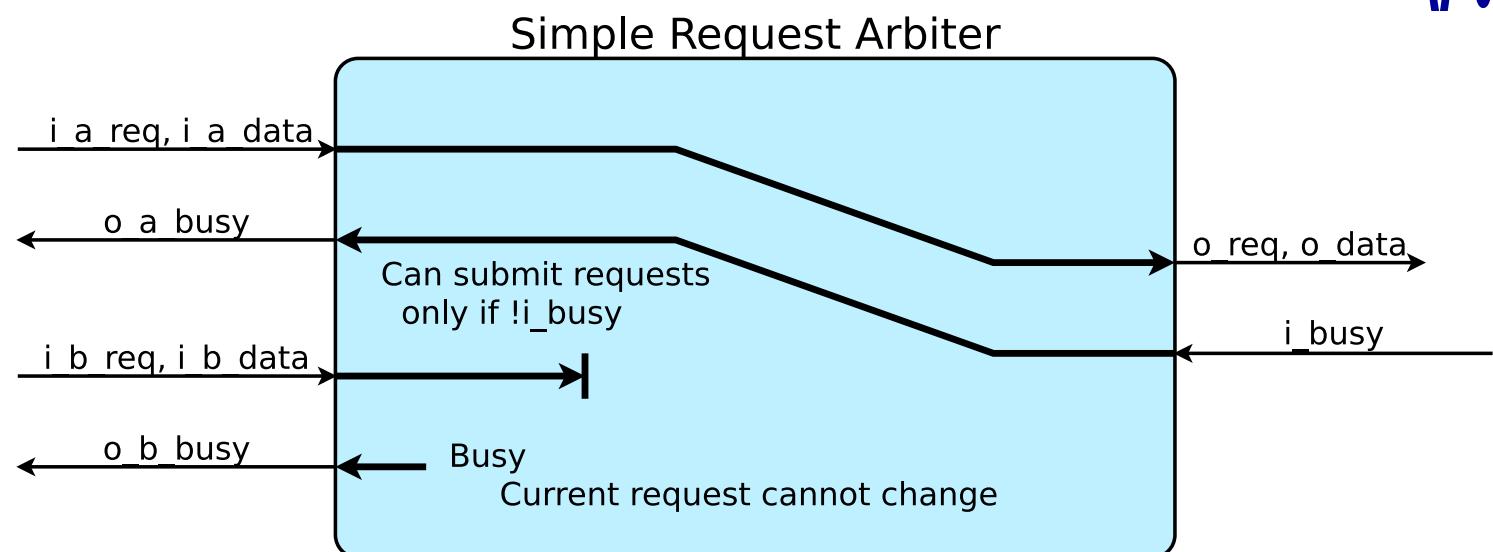
Let's build up to proving a WB arbiter

- Let's prove (BMC + k -Induction) . . .
 1. Exercise #6: A simple arbiter
`exercise-06/reqlarb.v`
 2. Exercise #7: Then a Wishbone bus arbiter
`exercise-07/wbpriarbiter.v`
- Given a set of bus properties: `fwb_slave.v`

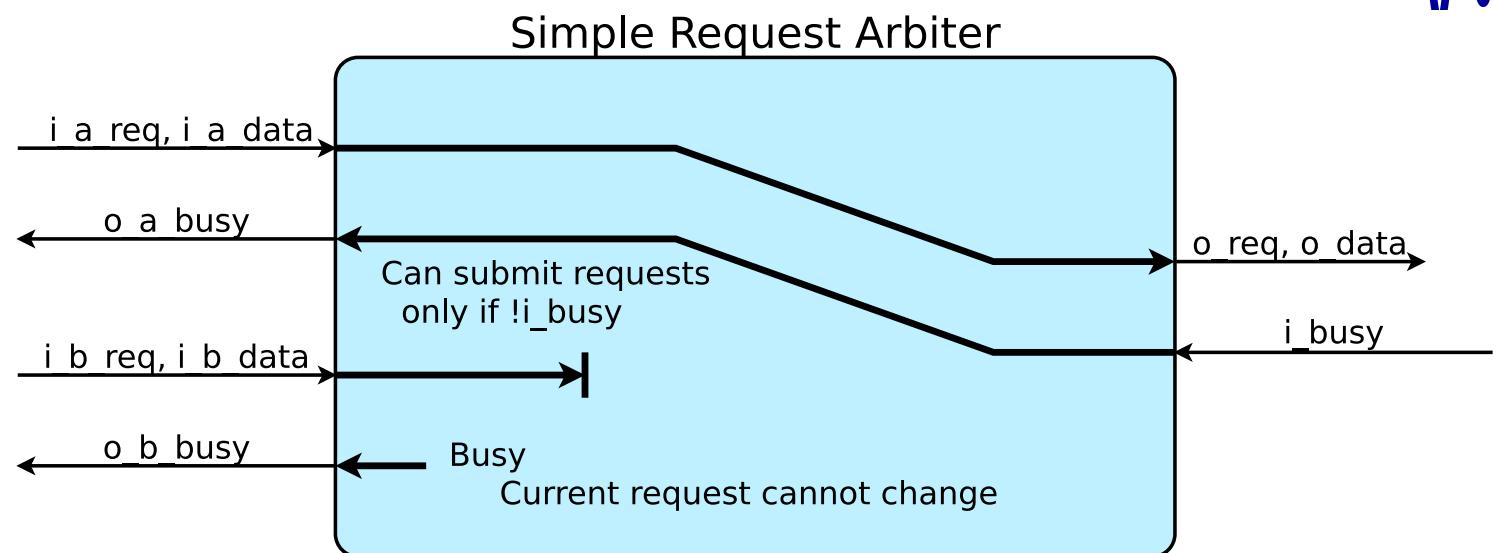
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The basics

- *_req requests a transaction
- *_data, the contents of the transaction
- *_busy, true if the source must wait

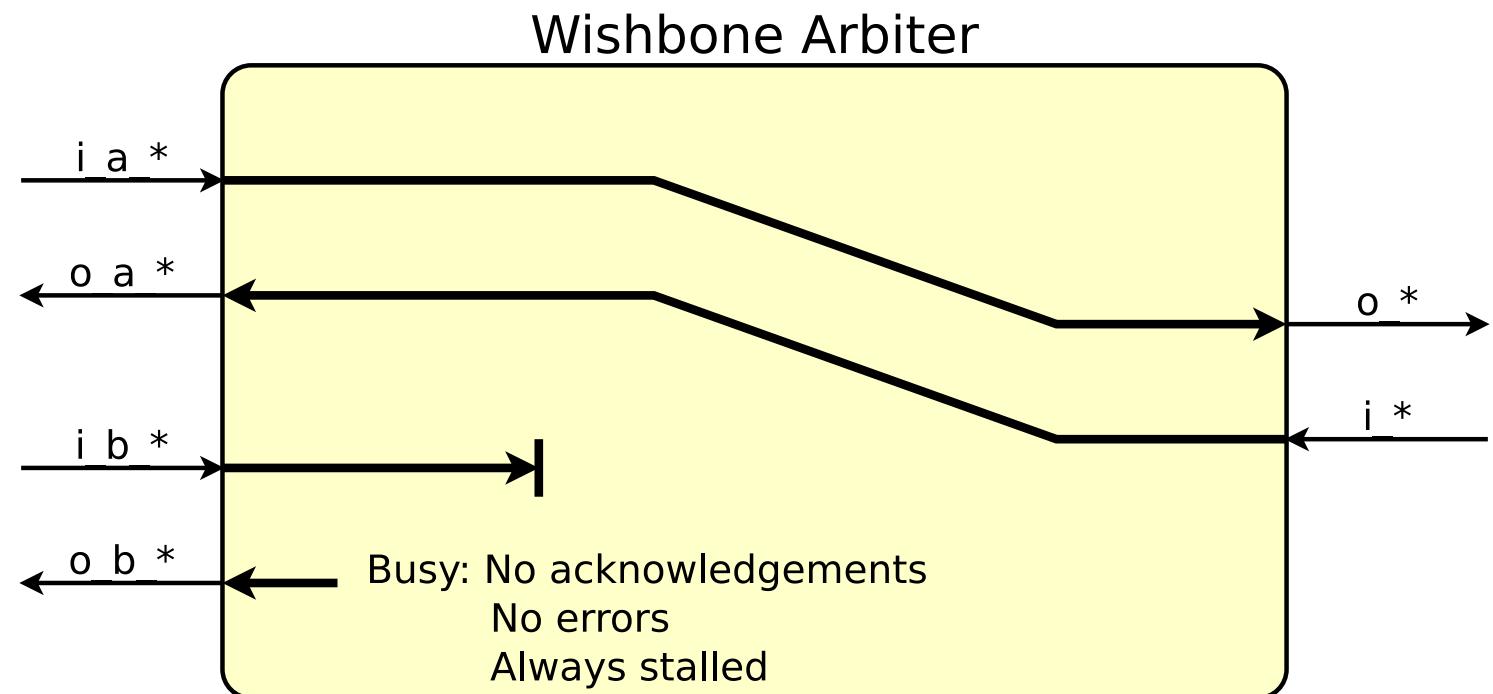
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- If $(*_\text{req}) \& \& (\text{!}_\text{*_busy})$,
the request is accepted
- If $(*_\text{req}) \& \& (\text{*_busy})$,
the request may not change, except on reset

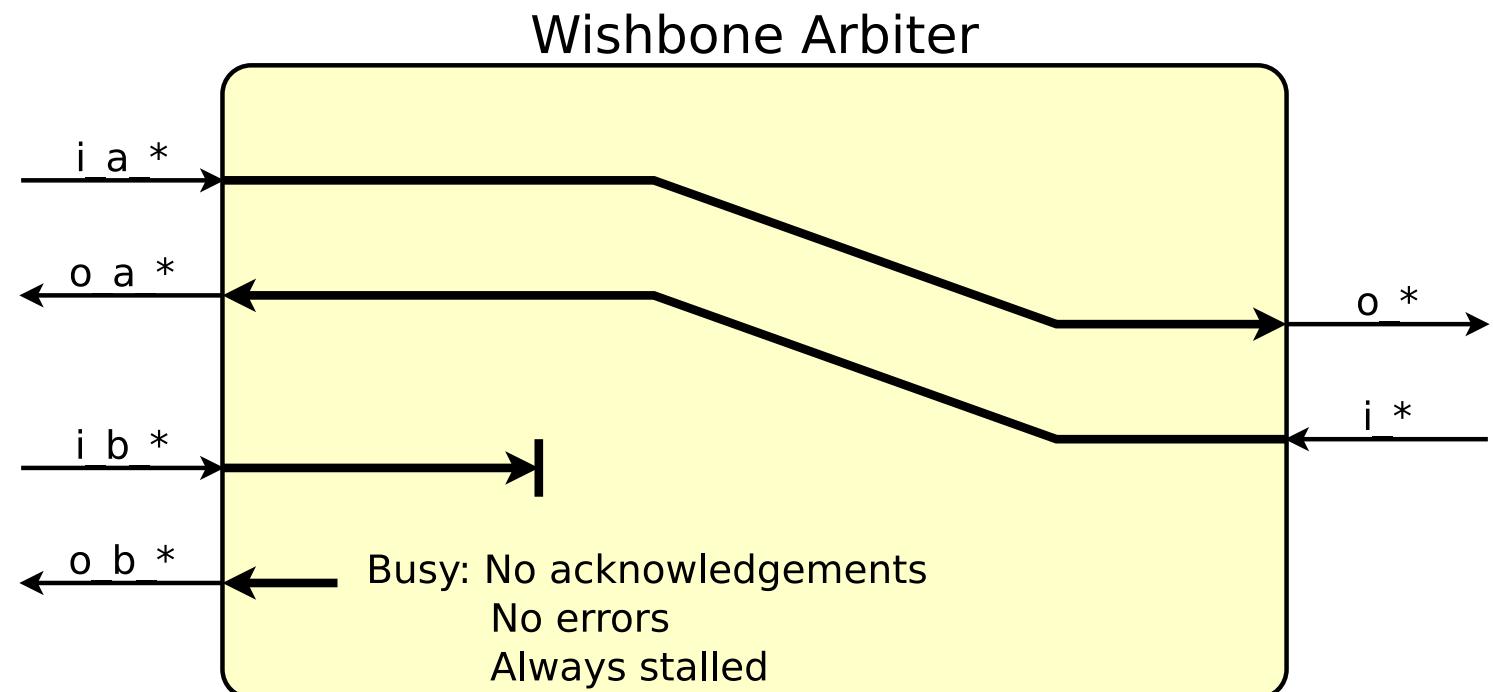
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To prove:

- No data will be lost, no requests will be dropped
 - Assume all requests remain stable until accepted
- Only one source ever gets access at a time
 - Assert one busy line is always high
- Therefore, all requests go through ... eventually
 - This is a natural consequence of the above. Don't worry about starvation here.

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Shall we try this with Wishbone?

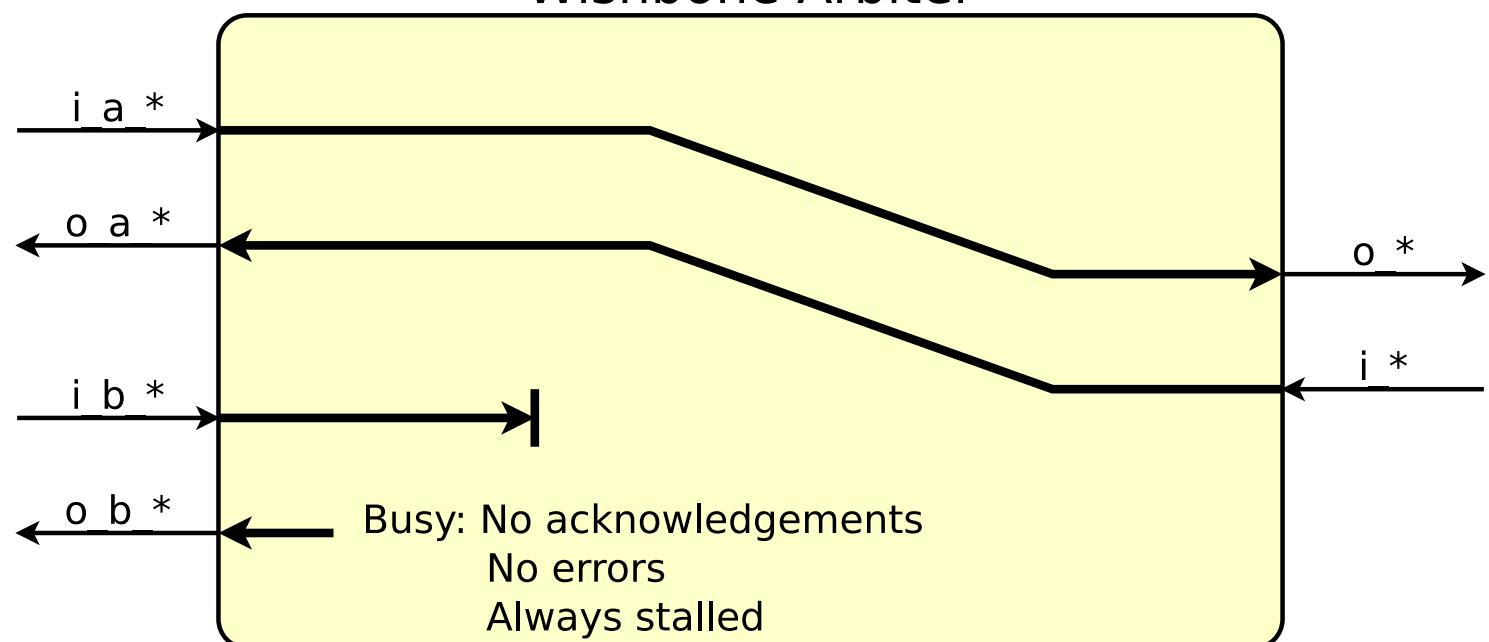
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This request side is almost identical

- If (STB)&&(!STALL)
the request is accepted
- If (STB)&&(STALL)
the request must not change

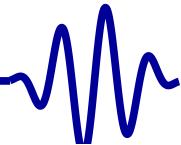
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Wishbone Arbiter

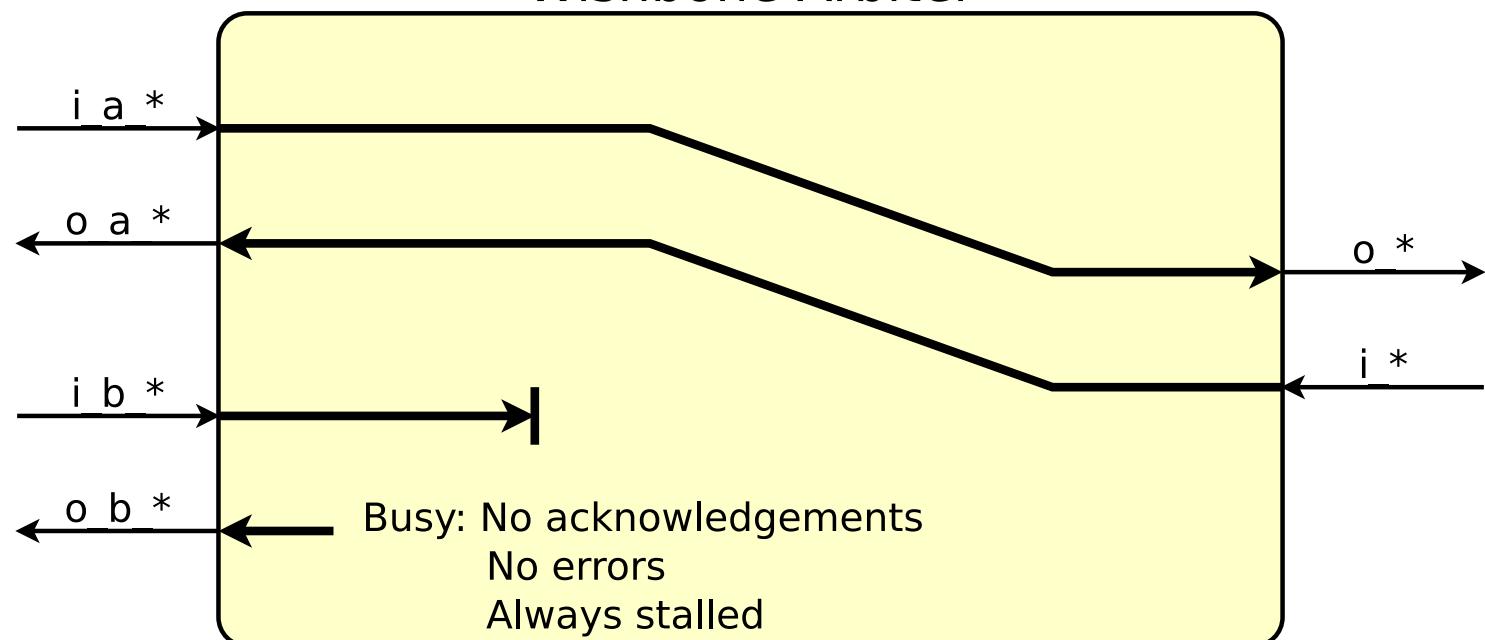


The difference is the acknowledgements

- The arbiter cannot change during an active transaction
- All requests get responses
- No response can be returned without a request

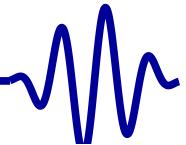
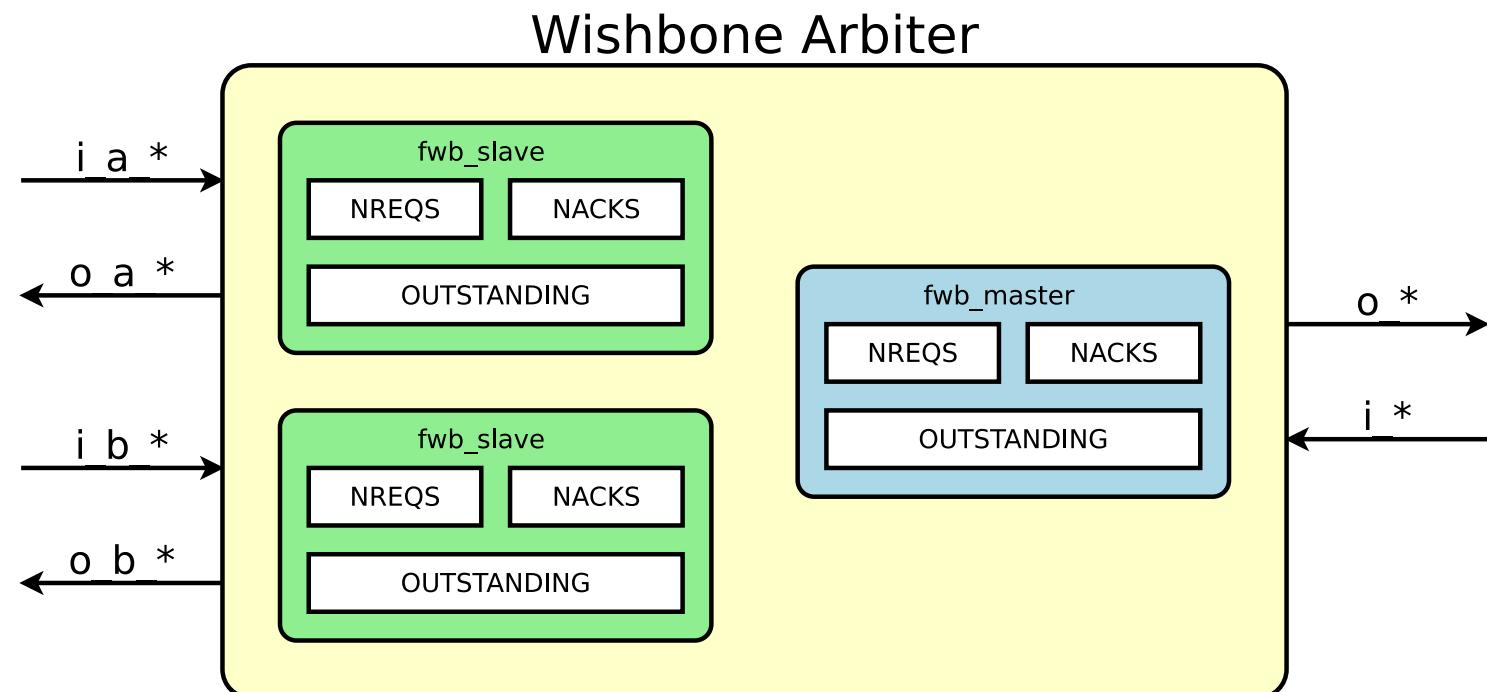
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Wishbone Arbiter



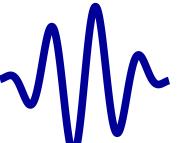
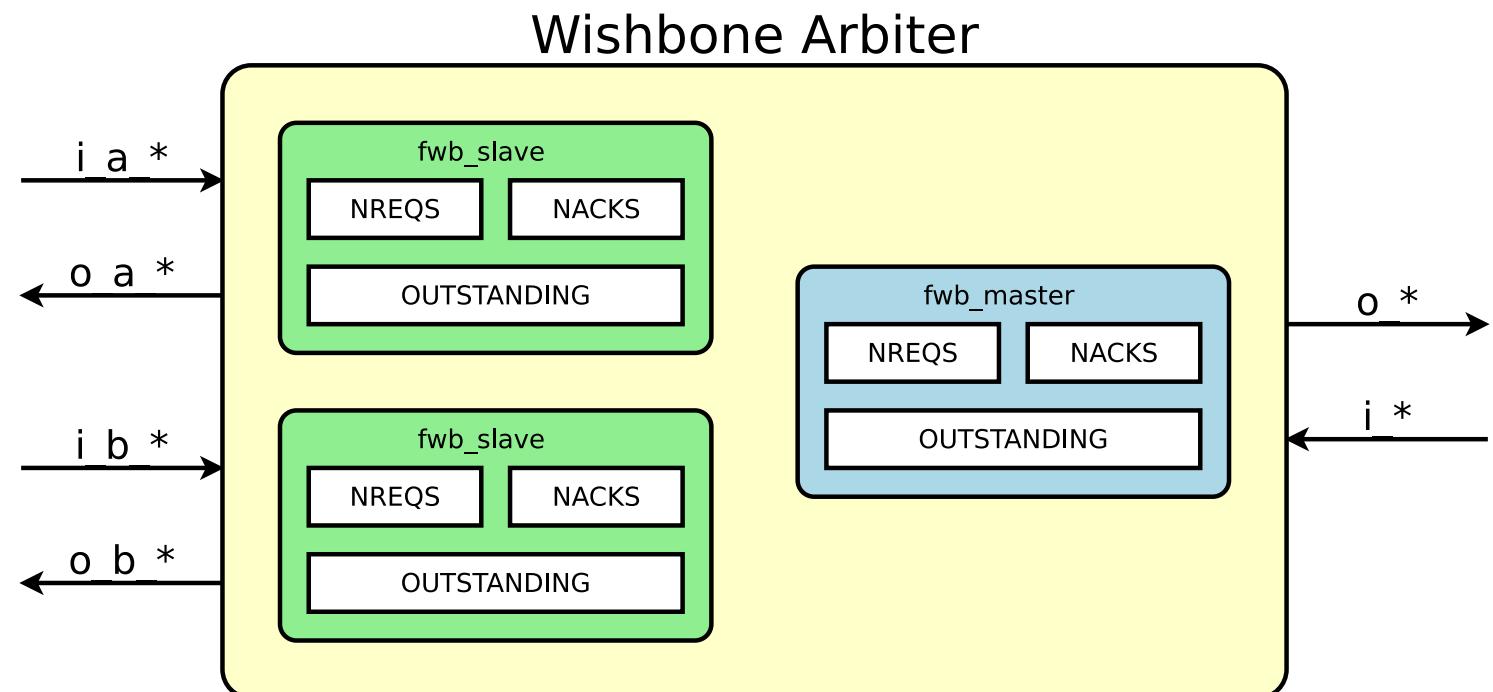
Now, prove that `exercise-07/wbpriarbiter.v` works.

- Use both BMC and k -induction (mode prove)
- You'll need to build `fwb_master.v` properties

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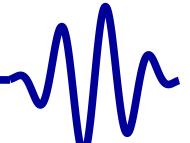
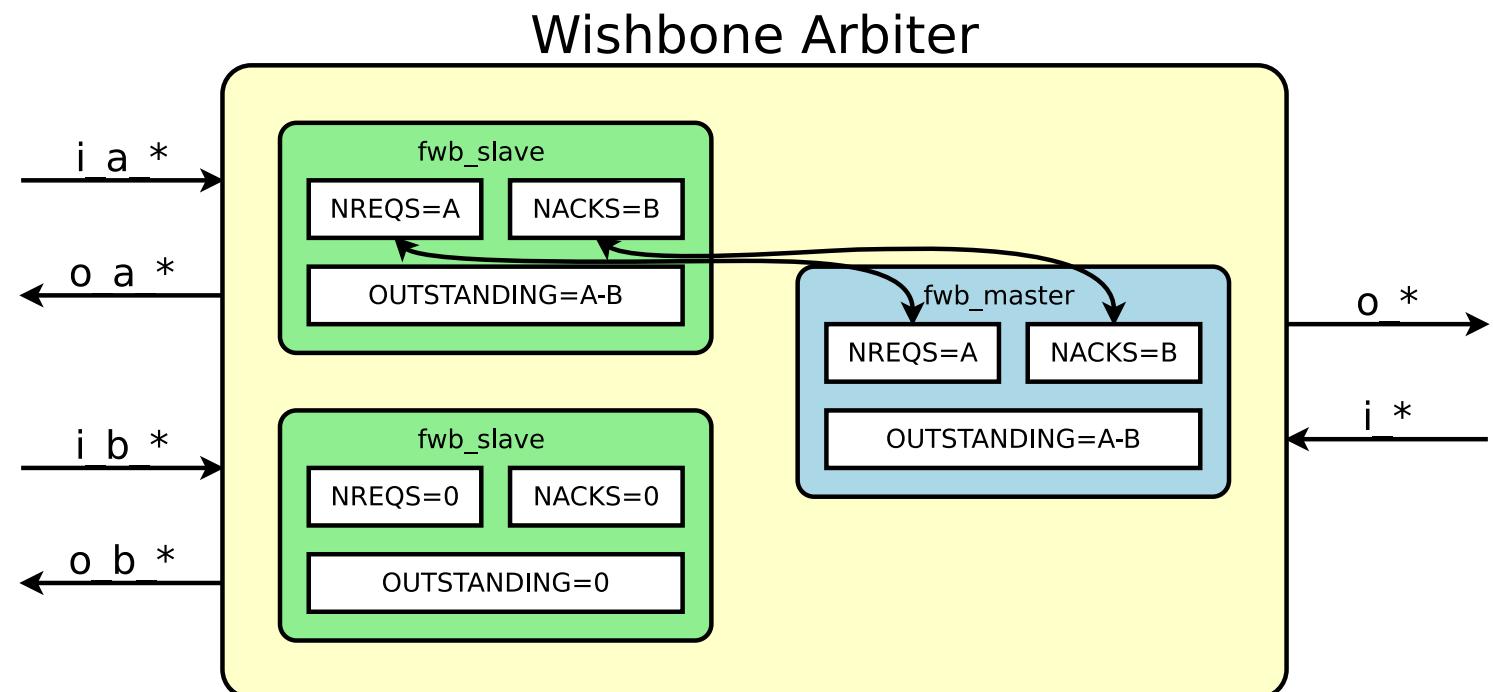
The `fwb_slave.v` properties will

- Assume a behaving master
- Assert a behaving slave

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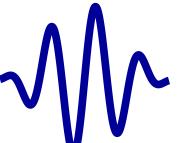
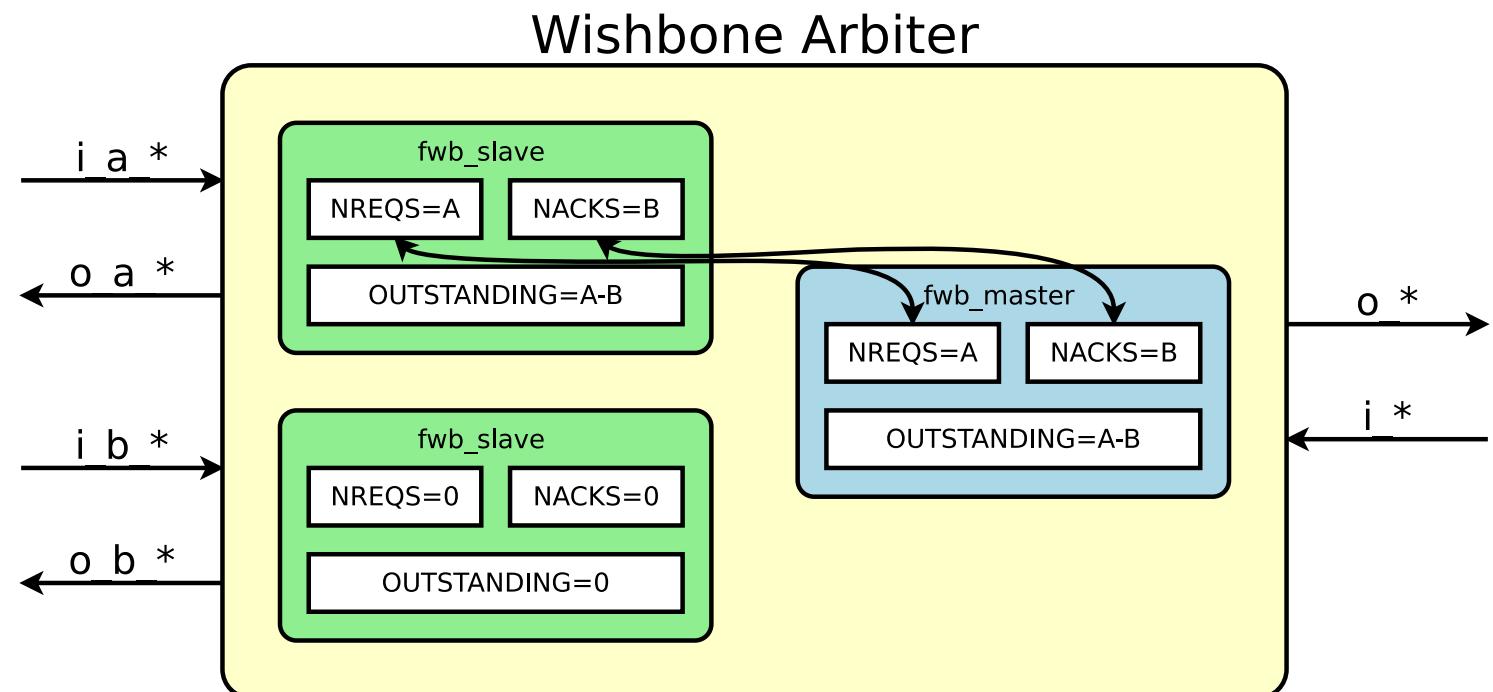
You'll write the `fwb_master.v` properties

- Swapping inputs with outputs
 - Port names need not change
- Swapping assumptions with assertions

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The magic is in how the files are connected

- If one interface is connected, both master and slave...
 - Should see the same number of requests
 - Should see the same number of acknowledgements

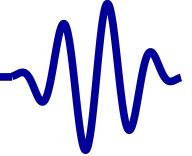
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The magic is in how the files are connected

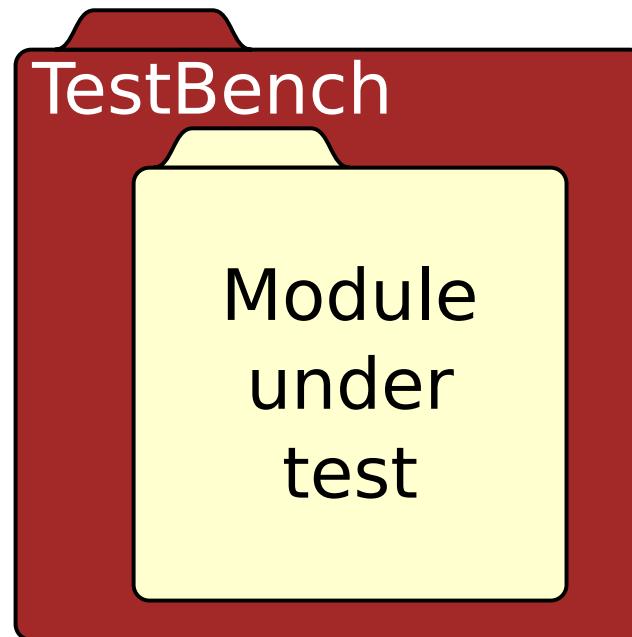
- If one interface is connected, the other ...
 - Should not have made any successful requests
 - Should not have received any acknowledgements



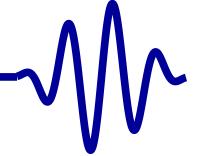
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- Traditional test-bench file structure
- Doesn't work with yosys formal
- Why not?



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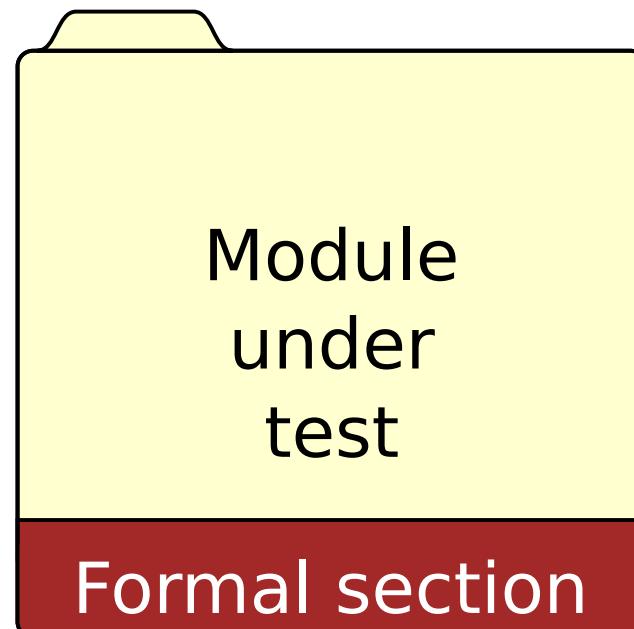
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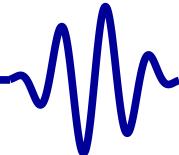
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- Formal Properties can be placed at the bottom
- This works well for testing some modules
- What's the limitation?



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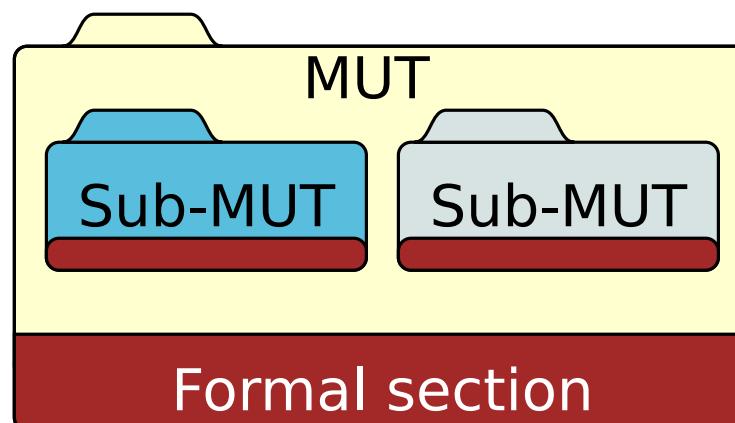
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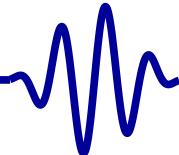
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- Design with multiple files
- They were each formally correct
- Problems?



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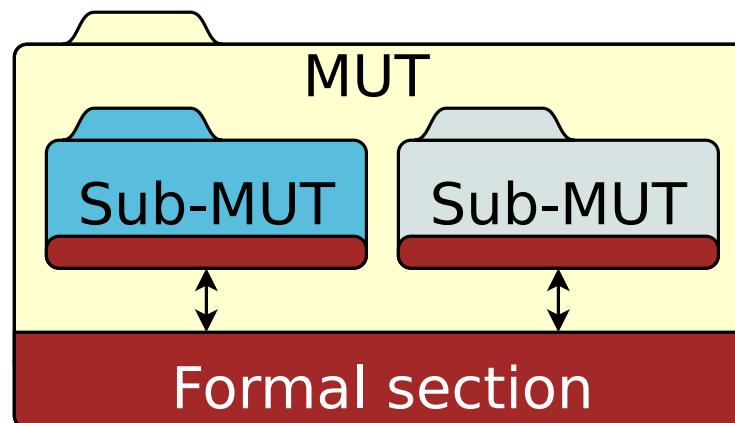
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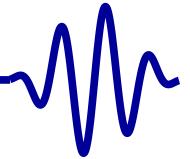
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- Design with multiple files
- They were each formally correct
- Problems? Yes! In induction
- State variables needed to be formally synchronized (**assert()**)

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Ex: WB Bus

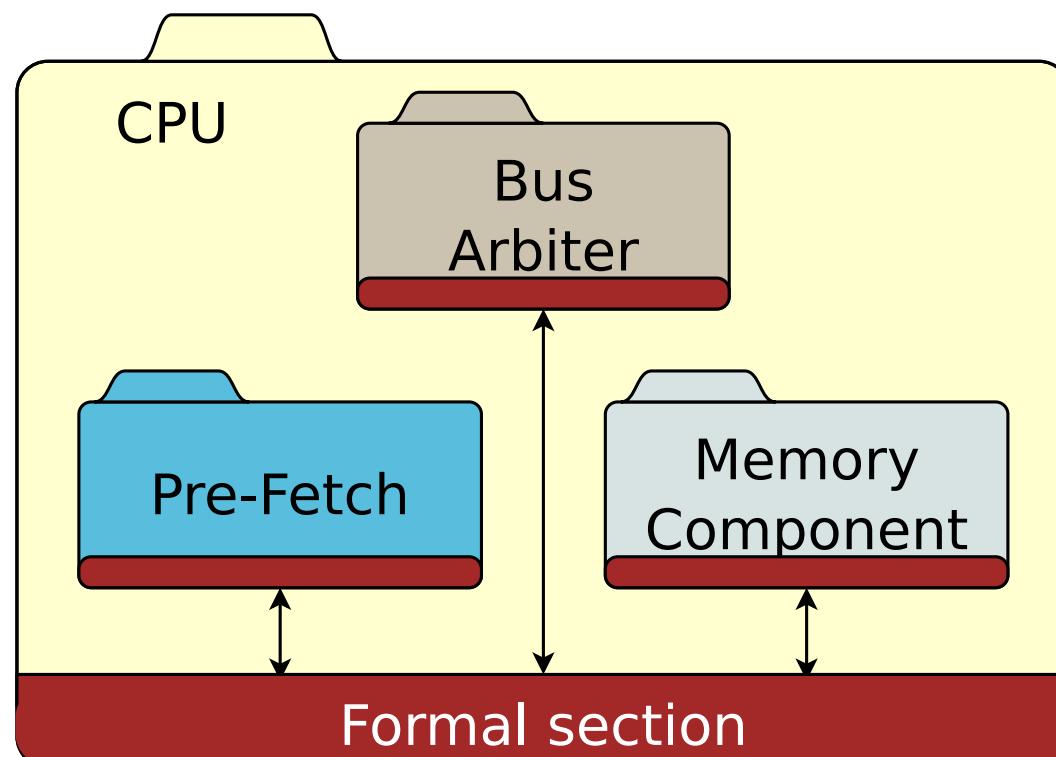
AXI

Avalon

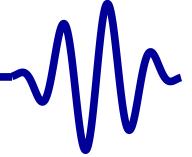
Wishbone

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Proving properties for many components together can quickly get out of hand!



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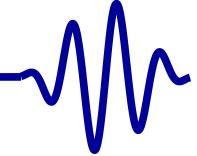
When dealing with memory, ...

- Testing the entire memory is not required
- Testing an arbitrary value is

It's time to discuss (* `anyconst` *) and (* `anyseq` *)
Objectives

- Understand what a free variable is
- Understand how (* `anyconst` *) and (* `anyseq` *) can be used to create free variables
- Learn how you can use free variables to validate memory and memory interfaces

any*



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- (* anyconst *)

```
(* anyconst *) wire [N-1:0] cval;
```

- Can be anything
- Defined at the beginning of time
- Never changed

- (* anyseq *)

```
(* anyseq *) wire [N-1:0] sval;
```

- Can change from one timestep to the next

Both can still be constrained via **assume()** statements



Memory



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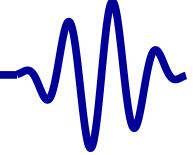
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How might you verify a memory with this?

```
(* anyconst *) wire [AW-1:0] f_const_addr;  
                    reg [DW-1:0] f_mem_value;
```

```
// Handle writes  
always @(posedge i_clk)  
if ((i_stb)&&(i_we)&&(i_addr == f_const_addr))  
    f_mem_value <= i_data;  
  
// Handle reads  
always @(posedge i_clk)  
if ((f_past_valid)&&($past(i_stb))&&(!$past(i_we))  
    &&($past(i_addr == f_const_addr)))  
    assert(o_data == f_mem_value);
```

GT So what?



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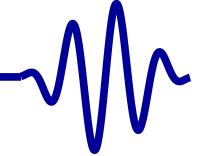
Consider the specification of a prefetch

- The contract

```
(* anyconst *) wire [31:0] f_const_data;  
  
always @ (posedge i_clk)  
if ((o_valid)&&(o_pc == f_const_addr))  
    assert(o_insn == f_const_data);
```

- You'll also need to assume a bus input

```
always @ (posedge i_clk)  
if ((i_ack)&&(ackd_address == f_const_addr))  
    assume(i_data == f_const_data);
```

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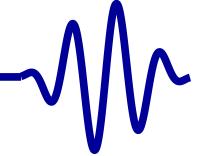
How would our general rule apply here?

- Assume inputs, assert internal state and outputs
- Both (* `anyconst` *) and (* `anyseq` *) act like inputs
- You could have written

```
input      wire  i_value;  
  
always @(posedge i_clk)  
    assume(i_value == $past(i_value));
```

for the same effect as (* `anyconst` *)

- **assume()** them therefore, and not **assert()**

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This works for a flash (or other ROM) controller too:

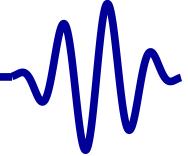
```
(* anyconst *) wire [AW-1:0] f_addr;
(* anyconst *) wire [DW-1:0] f_data;

always @(*)
if ((o_wb_ack)&&(f_request_addr == f_addr))
    assert(o_wb_data == f_data);
```

Don't forget the corollary assumptions!

```
always @(*)
if (f_request_addr == f_addr)
    assume(i_spi_miso
          == f_data[controller_state]);
```

... or something similar

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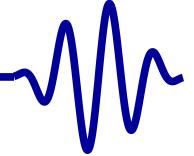
You can use this to build a serial port transmitter

```
(* anyseq *) wire f_tx_start;
(* anyseq *) wire [7:0] f_tx_data;
always @(*)
if (f_tx_busy)
    assume (!f_tx_start);

always @(posedge f_txclk)
if (f_tx_busy)
    assume(f_tx_data == $past(f_tx_data));
```

You can then

- Tie assertions to partially received data
- ... and pass induction



How would you use free variables to verify a cache implementation?

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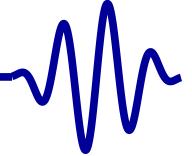
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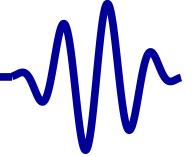
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How would you use free variables to verify a cache implementation?

Hint: you only need *three properties* for the cache contract



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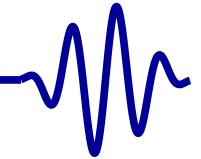
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- Proving simple modules is easy.
- What about large and complex ones?

It's time to discuss *abstraction*.

Objectives

- Understand what abstraction is
- Gain confidence in the idea of abstraction
- Understand how to reduce a design via abstraction

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Formally, if

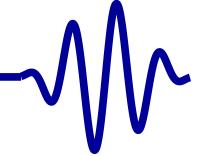
$$A \rightarrow C$$

then we can also say that

$$(AB) \rightarrow C$$



Formal Proof



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Shall we go over the proof?

$$A \rightarrow C \Rightarrow \neg A \vee C = \text{True}$$

True or anything is still true, so

$$(\neg A \vee C) \vee \neg B$$

Rearranging terms

$$\neg A \vee \neg B \vee C$$

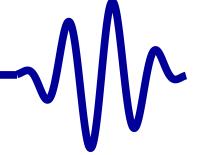
$$\neg (AB) \vee C$$

Expressing as an implication

$$(AB) \rightarrow C$$

Q.E.D.!

GT So what?



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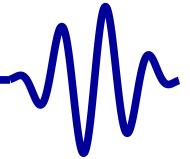
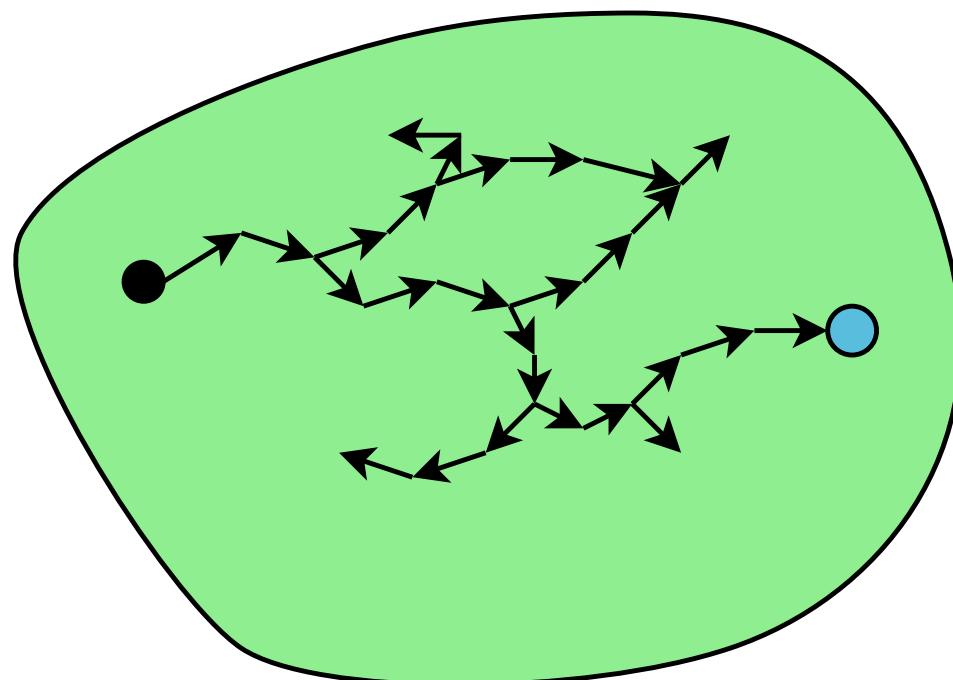
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With every additional module,

- Formal verification becomes more difficult
- Complexity increases exponentially
- You only have so many hours and dollars

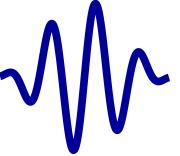
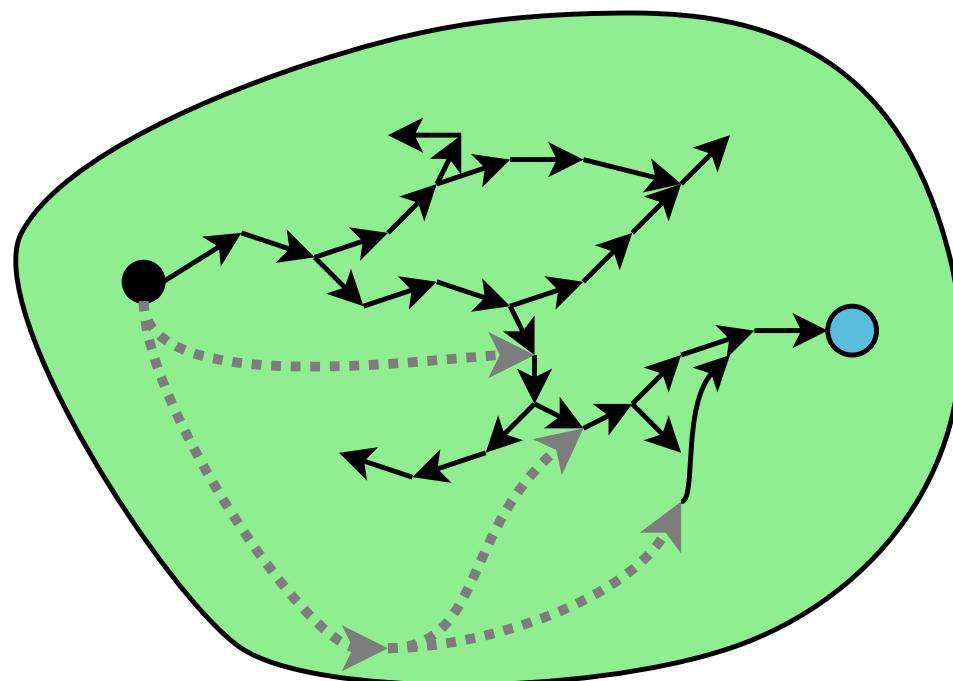
On the other hand,

- Anything you can simplify by abstraction . . .
- is one less thing you need to prove

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Suppose your state space looked like this

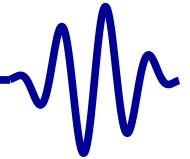
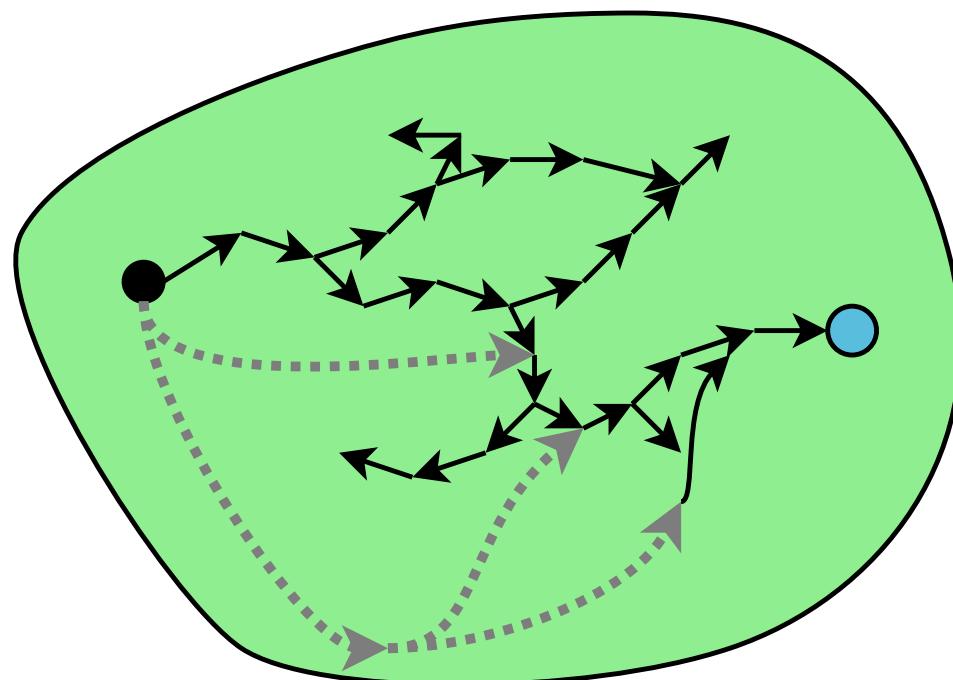
- It takes many transitions required to get to interesting states

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Suppose we added to this design ...

- Some additional states, and
- Additional transitions

The *real* states and transitions must still remain

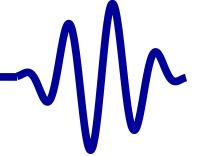
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If this new design still passes, then ...

- Since the original design is a subset ...
- The original design must also still pass

If done well, the new design will require less effort to prove

GT A CPU



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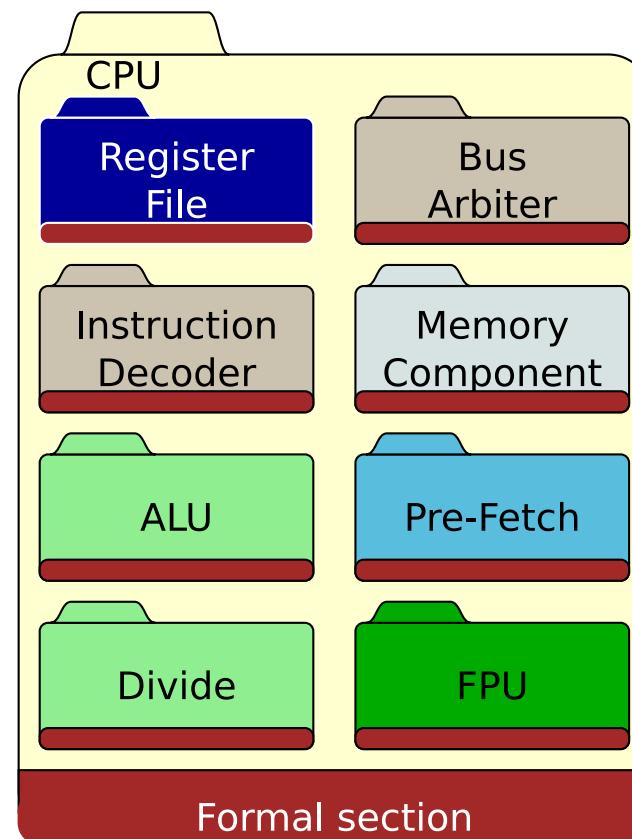
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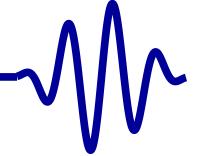
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Where would you start?



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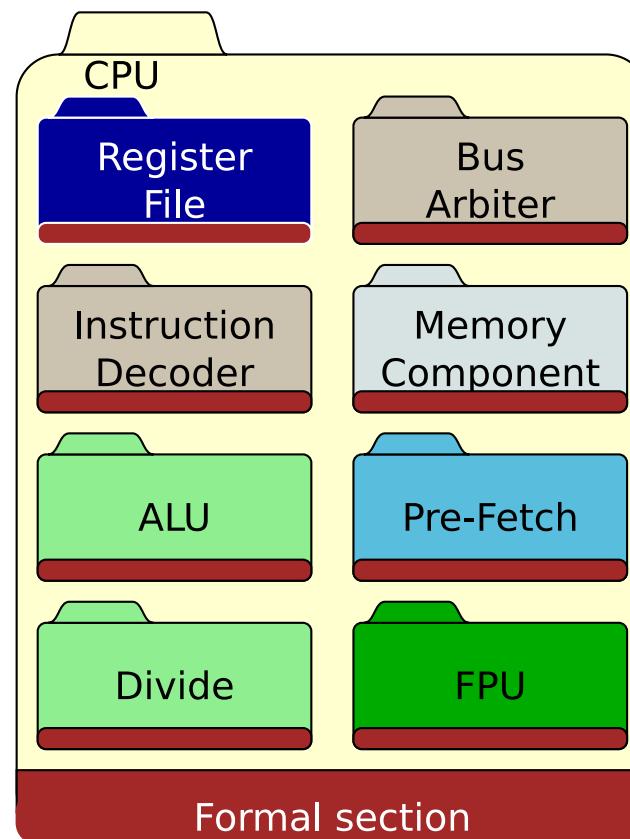
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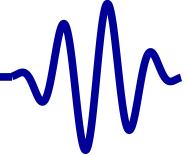
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Where would you start?



At the interfaces!



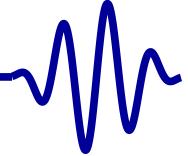
Let's consider a prefetch module as an example.



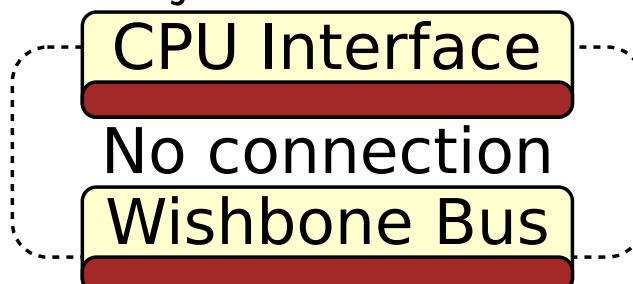
If you do this right,

- Any internally consistent Prefetch,
- that properly responds to the CPU, *and*
- interacts properly with the bus,
- must work!

Care to try a different prefetch approach?

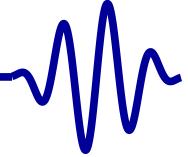
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Suppose the prefetch was just a shell

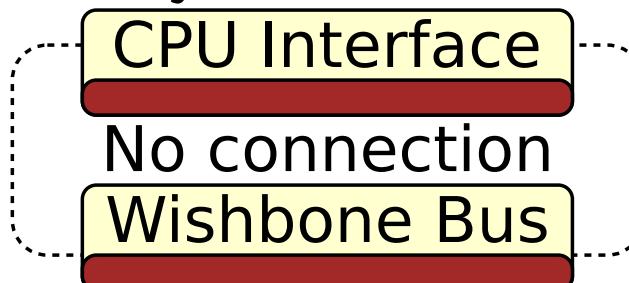


It would still interact properly with

- The bus, and
- The CPU
- It just might not return values from the bus to the CPU

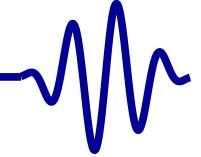
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Suppose the prefetch was just a shell



If the CPU still acted “correctly”

- With either the right, or the wrong instructions, then
- The CPU *must act correctly with the right instructions*



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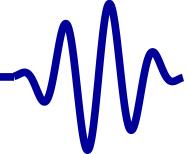
Consider these statements:

□

If
And
Then



Examples



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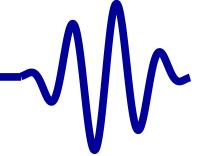
Consider these statements:

- Prefetch is bus master, interfaces w/CPU

If (Prefetch responds to CPU insn requests)

And (Prefetch produces the right instructions)

Then (The prefetch works within the design)

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Consider these statements:

- The CPU is just a wishbone master within a design

If (The CPU is valid bus master)

And (CPU properly executes instructions)

Then (CPU works within a design)

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Consider these statements:

- The ALU must return a calculated number

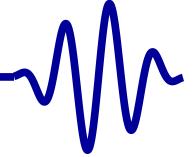
If (ALU returns a value when requested)

And (It is the right value)

Then (The ALU works within the design)



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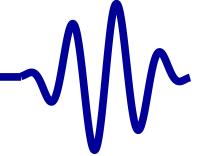
Consider these statements:

- A flash device responds in 8-80 clocks

If (Bus master reads/responds to a request)

And (The response comes back in 8-80 clocks)

Then (The CPU can interact with a flash memory)

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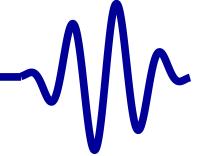
Consider these statements:

- The divide must return a calculated number

If (Divide returns a value when requested)

And (It is the right value)

Then (The divide works within the design)

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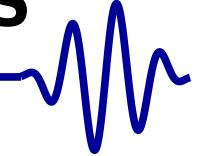
Consider these statements:

- Formal solvers break down when applied to multiplies

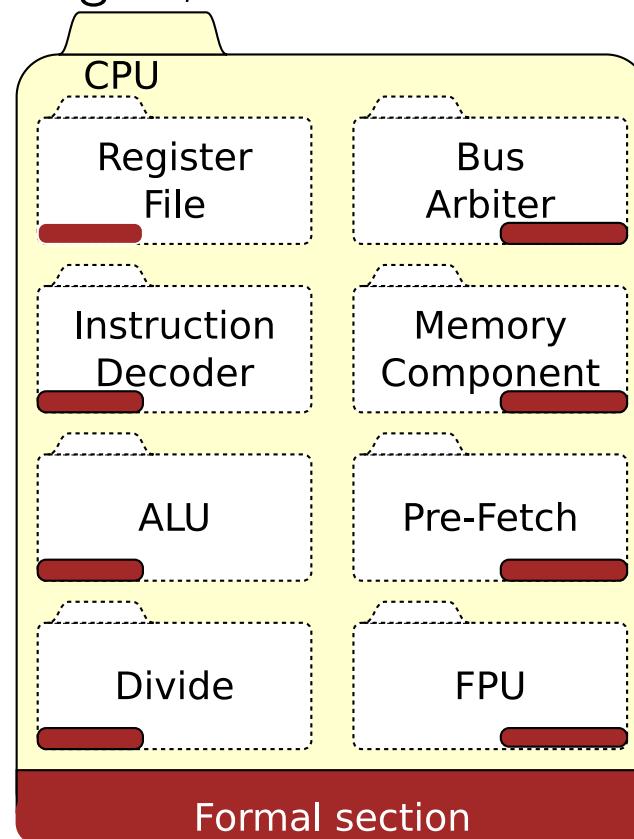
If (Multiply unit returns an answer N clocks later)

And (It is the right value)

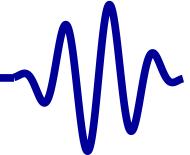
Then (The multiply works within the design)

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Looking at the CPU again,



- Replace all the components with abstract shells
- ... shells that *might* produce the same answers

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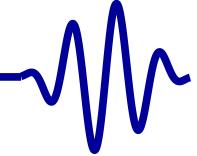
Let's consider a fractional counter:

```
reg      [31:0]  r_count;
initial r_count = 0;
initial o_pps = 0;
always @(posedge i_clk)
    { o_pps, r_count } <= r_count + 32'd43;
```

The problem with this counter

- It will take 100×10^6 clocks to roll over and set o_pps
- Formally checking 100×10^6 clocks is prohibitive

We'll need a better way, or we'll never deal with this

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How might we build an abstract counter?

- First, create an arbitrary counter increment

```
(* anyseq *) wire [31:0]           increment;
assign rollover = - r_count;
always @(*)
begin
    assume(increment > 0);
    assume(increment < { 2'h1, 30'h0 });
    if (rollover < 32'd43)
        assume(increment == 32'd43);
    else
        assume(increment < rollover);
end
```

The correct increment, 32'd43, must be a possibility

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We can now increment our counter by this arbitrary increment

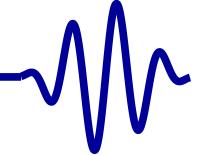
```
always @ (posedge i_clk)
    { o_pps, r_count } <= r_count + increment;
```

Will this work?

- Let's try this to see!

```
always @ (posedge i_clk)
if (f_past_valid)
    assert (r_count != $past(r_count));

always @ (posedge i_clk)
if ((f_past_valid)&&(r_count < $past(r_count)))
    assert (o_pps);
```



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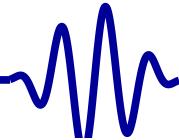
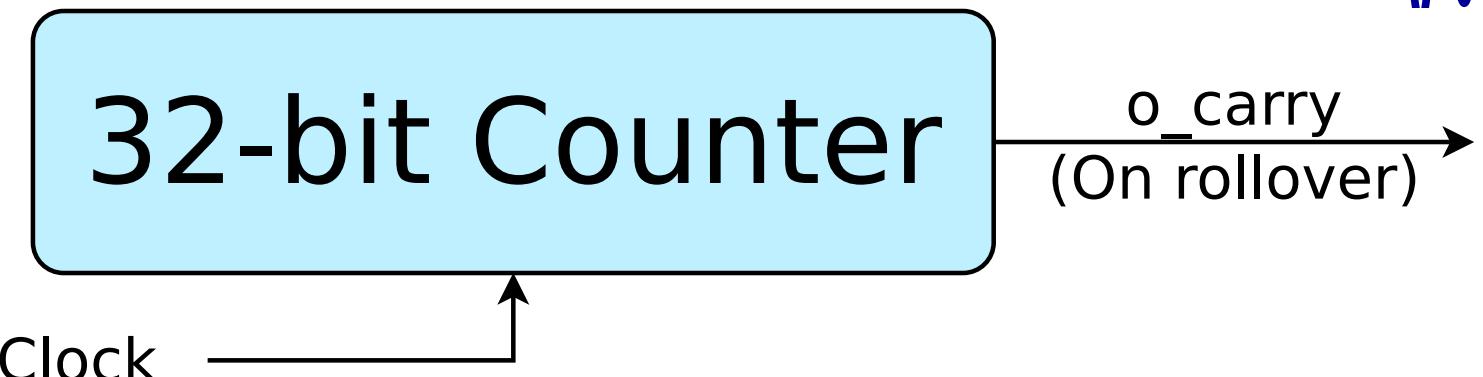
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How else might you use this?

- Bypassing the runup for an external peripheral
- Testing a real-time clock or date

Or . . . how about that CPU?

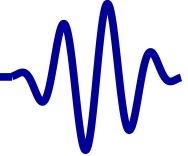
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Let's modify this abstract counter

- Increment by one, rather than fractionally

Exercise Objectives:

- Prove a design works both with and without abstraction
- Gain some confidence using abstraction

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Your task:

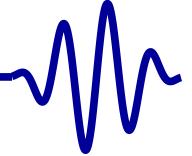
- Rebuild the counter
- Make it increment by one
- Build it so that ...

```
always @(*)  
    assert(o_carry == (r_count == 0));
```

// and

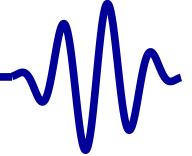
```
always @(posedge i_clk)  
    if ((f_past_valid)&&(!$past(&r_count)))  
        assert(!o_carry);
```

- Prove that this abstracted counter works

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Your task:

- Rebuild the counter
- Make it increment by one
- *Prove that this abstracted counter works*

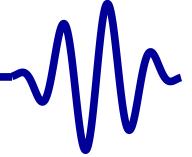
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Your task:

- Rebuild the counter
- Make it increment by one
- *Prove that this abstracted counter works*

Hints:

- `&r_count` must take place before `r_count==0`
- You cannot skip `&r_count`
- Neither can you skip `r_count == 0`



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Lesson Removed



This lesson is currently being revised, and will be released again shortly

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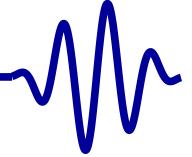
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(* gclk *)

\$rose

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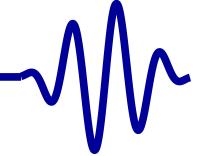
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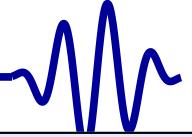
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The SymbiYosys option `multiclock` . . .

- Used to process systems with dissimilar clocks
- Examples
 - A serial port, with a formally generated transmitter coming from a different clock domain
 - A SPI controller that needs both high speed and low speed logic

Our Objective:

- To learn how to handle multiple clocks within a design
 - `(* gclk *)`
 - **\$stable, \$changed**
 - **\$rose, \$fell**

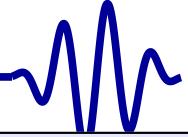
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```
[options]
mode prove
multiclock on

[engines]
smtbmc

[script]
read -formal module.v
prep -top module

[files]
# file list
```



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\$rose
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```
[options]
mode prove
multiclock on ← Multiple clocks require this line

[engines]
smtbmc

[script]
read -formal module.v
prep -top module

[files]
# file list
```

Five Tools



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(* gclk *)

\$rose

\$stable

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- `(* gclk *)`
Provides access to the global formal time-step
- **\$stable**
True if a signal is stable (i.e. doesn't change) with this clock.
Equivalent to $A == \$past(A)$
- **\$changed**
True if a signal has changed since the last clock tick.
Equivalent to $A != \$past(A)$
- **\$rose**
True if the signal rises on this formal time-step
This is very useful for positive edged clocks transitions
 $\$rose(A)$ is equivalent to $(A[0]) \&\& (!\$past(A[0]))$
- **\$fell**
True if a signal falls on this time-step, creating a negative edge
 $\$fell(A)$ is equivalent to $(!A[0]) \&\& (\$past(A[0]))$

(* gclk *)



- A global formal time step

```
(* gclk *) wire gbl_clk;
```

- You can use this to describe clock properties

```
// Assume a single clock signal
//
reg f_last_clk;

initial f_last_clk = 0;
always @ (posedge gbl_clk)
begin
    f_last_clk <= !f_last_clk;
    assume(i_clk == f_last_clk);
end
```

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\$rose

\$stable

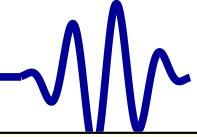
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```
always @(*posedge gbl_clk)
begin
    f_last_clk <= !f_last_clk;
    assume(i_clk == f_last_clk);
end
```



(* gclk *)



- Used to gain access to the formal time-step

```
(* gclk *) wire gbl_clk;
```

- You can use this to describe clock properties

```
// Assume two related clock signals
//
reg [2:0] f_clk_counter;

initial f_clk_counter = 0;
always @ (posedge gbl_clk)
begin
    f_clk_counter <= f_clk_counter + 1'b1;
    assume(i_clk_fast == f_clk_counter[0]);
    assume(i_clk_slow == f_clk_counter[2]);
end
```

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The clock logic on the last slide forces these two clocks to be in sync

f_clk_counter



i_clk_fast



i_clk_slow



(* gclk *)



- Used to gain access to the formal time-step
- You can use this to describe clock properties

```
// Assume two clocks, same speed,  
// unknown constant phase offset  
(* gclk *)      wire      gbl_clk;  
(* anyconst *)   wire [2:0] f_clk_offset;  
  
initial f_clk_counter= 0;  
always @ (posedge gbl_clk)  
begin  
    f_clk_counter <= f_clk_counter + 1'b1;  
    f_clk_two <= f_clk_counter  
                  + f_clk_offset;  
    assume(i_clk_one == f_clk_counter[2]);  
    assume(i_clk_two == f_clk_two[2]);  
end
```

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\$stable

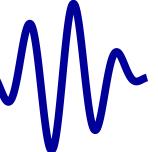
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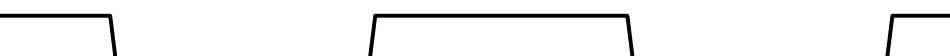
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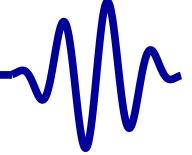
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The formal tool will pick the phase offset between these two generated clock waveforms

f_clk_counter 

i_clk_one 

i_clk_two 



How might you describe two unrelated clocks?

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\triangleright (* gclk *)

\$rose

\$stable

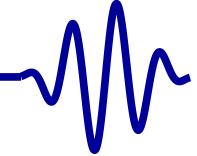
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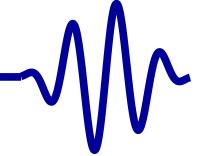
How might you describe two unrelated clocks?

```
(* gclk *)      wire      gbl_clk;
(* anyconst *)  wire  [7:0] f_a_step;
always @(*)
assume((f_a_step > 0) &&(f_a_step[7] == 1'b0));

always @ (posedge gbl_clk)
begin
    f_a_counter <= f_a_counter + f_a_step;

    assume(i_clk_a == f_a_counter[7]);
end
```

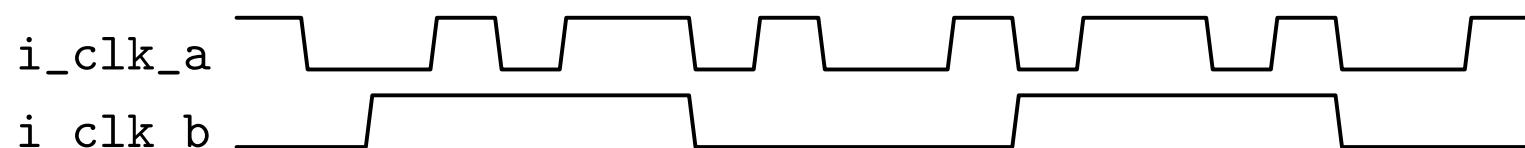
- The (* anyconst *) register may take on any constant value
- You can repeat this logic for the second clock.

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The timing relationship between these two clocks can be anything

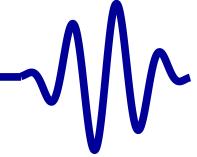
- Each clock can have an arbitrary frequency
- Each clock can have an arbitrary phase

Here's a theoretical example trace



Don't be surprised by the appearance of phase noise

Bonus: The trace above isn't realistic. Why not?



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(* gclk *)

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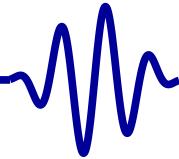
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Synchronous logic has some requirements

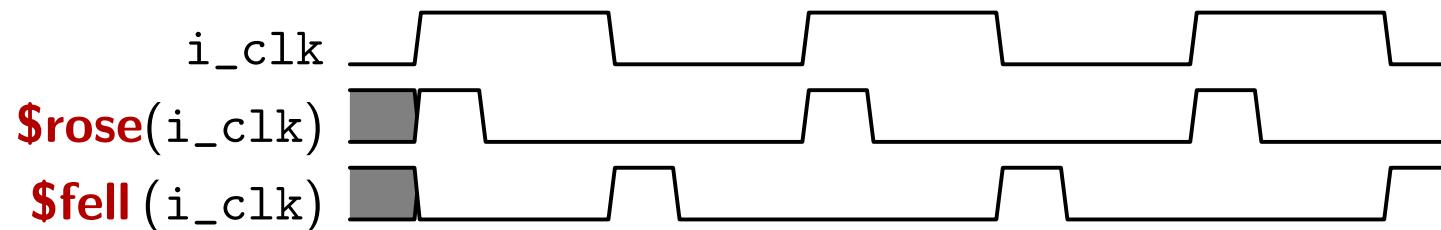
- Inputs should *only* change on a clock edge
They should be stable otherwise
- **\$rose(i_clk)** can be used to express this

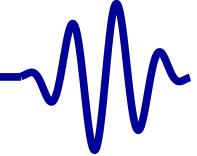
Here's an example using **\$rose(i_clk)** . . .

```
always @(posedge gbl_clk)
if (! $rose(i_clk))
    assume(i_input == $past(i_input));
```

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\$fell is like **\$rose**, only it describes a negative edge





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(* gclk *)

▷ \$rose

\$stable

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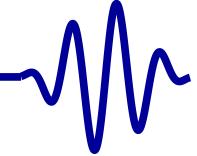
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Let's go back to the synchronous logic requirements

- Inputs only change on clock edges
- **\$rose(i_clk)** and **\$fell(i_clk)** can be used to express this
- Let's try this out

Would this work?

```
always @(posedge gbl_clk)
if (! $rose(i_clk))
    assert(i_input == $past(i_input));
```



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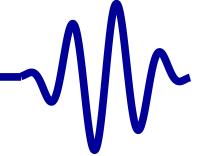
Let's go back to the synchronous logic requirements

- Inputs only change on clock edges
- **\$rose(i_clk)** and **\$fell(i_clk)** can be used to express this
- Let's try this out

Would this work?

```
always @(posedge gbl_clk)
if (! $rose(i_clk))
    assert(i_input == $past(i_input));
```

- **No.** The *general rule* hasn't changed



Could we do it this way?

```
always @(posedge gbl_clk)
if ($fell(i_clk))
    assert(state == $past(state));
```

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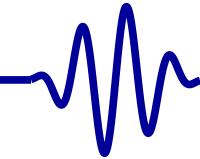
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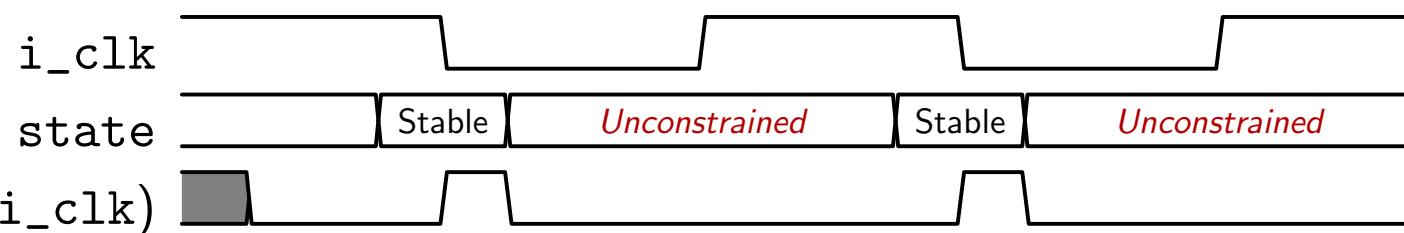
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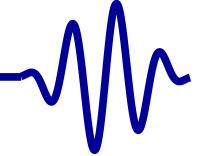
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Could we do it this way?

```
always @(posedge gbl_clk)
if ($fell(i_clk))
    assert(state == $past(state));
```

- No, this doesn't work either





Is this equivalent?

```
always @(posedge gbl_clk)
if (!$past(i_clk))
    assert(state == $past(state));
```

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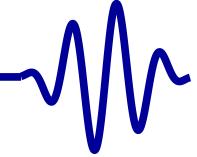
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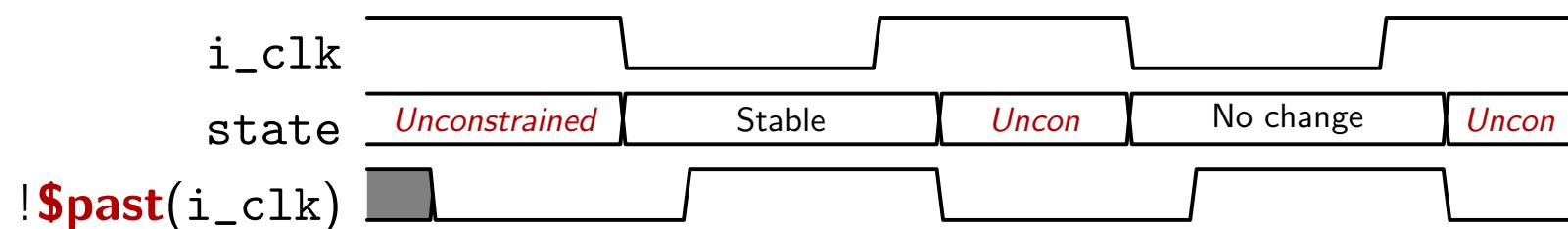
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Is this equivalent?

```
always @(posedge gbl_clk)
if (! $past(i_clk))
    assert(state == $past(state));
```

- Why not?



\$rose



This fixes our problems. Will this work?

```
always @(posedge gbl_clk)
if (!$rose(i_clk))
    assert(state == $past(state));
```

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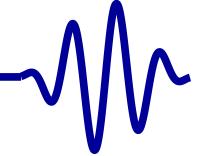
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This fixes our problems. Will this work?

```
always @(posedge gbl_clk)
if (!$rose(i_clk))
    assert(state == $past(state));
```

- Not quite. Can you see the problem?

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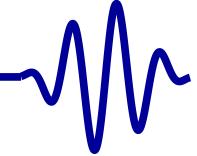
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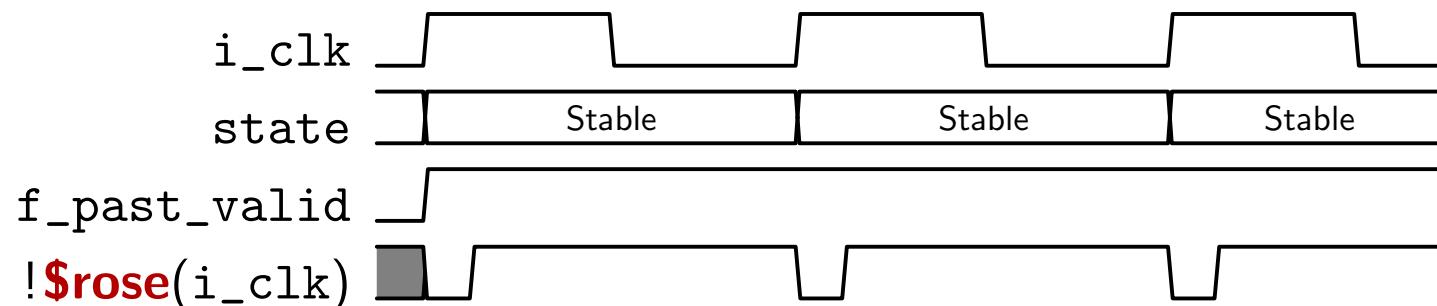
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- State/outputs should be clock synchronous

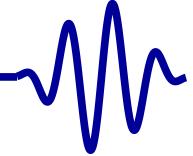
```
always @ (posedge gbl_clk)
  if ((f_past_valid)&&(!$rose(i_clk))
      assert(state == $past(state));
```

- With f_past_valid this works



- **\$rose** requires a clock, such as
always @(posedge gbl_clk)

\$stable



Describes a signal which has not changed

```
always @(posedge gbl_clk)
if ((f_past_valid)&&(!$rose(i_clk)))
    assert($stable(state));
```

- Requires a clock edge
 - always @(**posedge** gbl_clk)**
 - always @(**posedge** i_clk)**
- This is basically the same as state == **\$past(state)**

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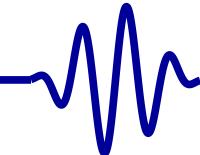
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> \$stable

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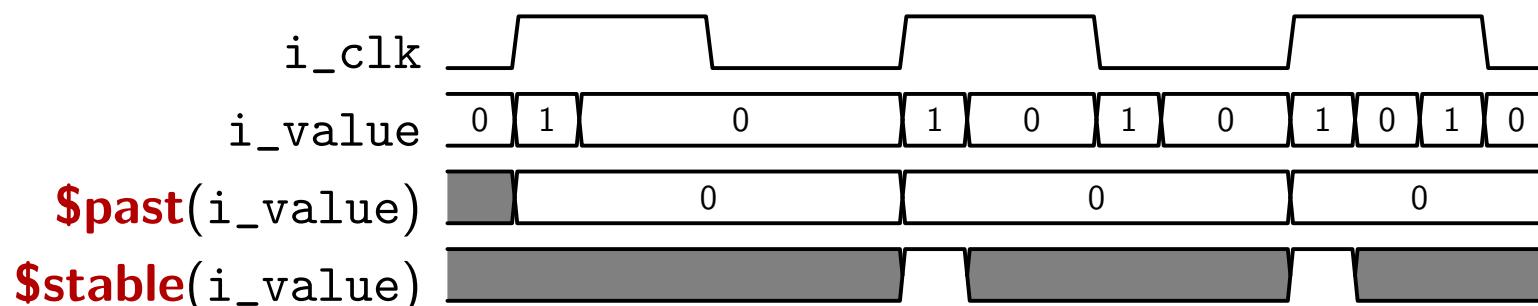
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Caution: **\$stable**(x) might still change between clock edges

```
always @(posedge i_clk)
    assume($stable(i_value));
```

The waveform below would satisfy the assumption above

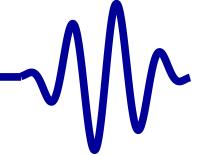


The key to understanding what's going on is to realize . . .

- The assumption is only evaluated on @(**posedge** i_clk)
- **\$past**(i_value) is only sampled @(**posedge** i_clk)
- . . . and not on the formal (* **gclk** *) time step.



Examples



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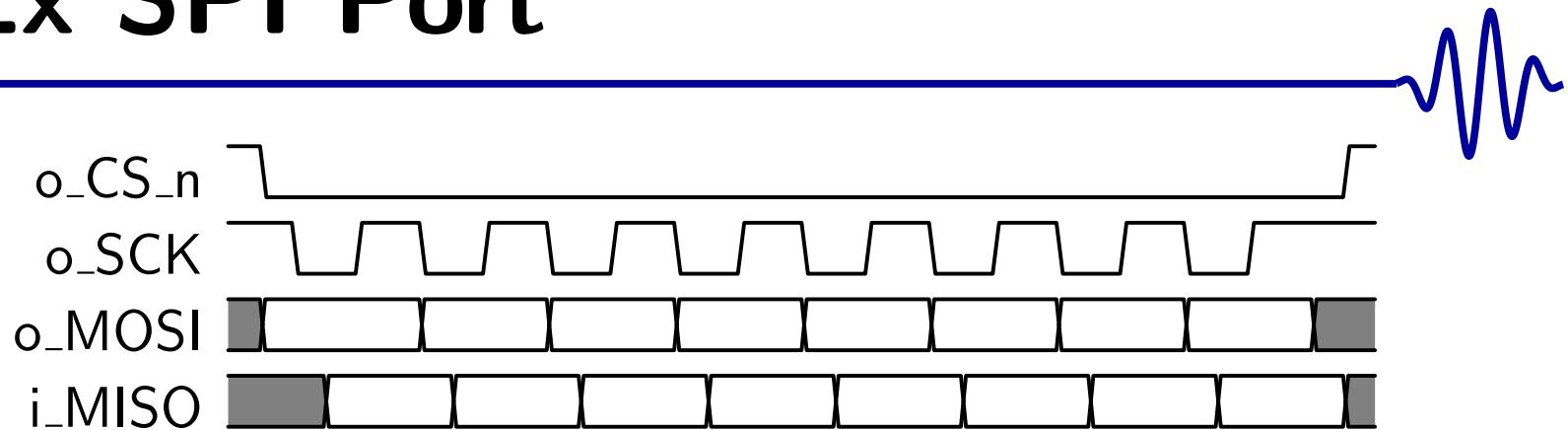
- Most logic doesn't need the multiclock option
- To help with logic that might need it, I use a parameter

```
parameter [0:0] F_OPT_CLK2FFLOGIC = 1'b0;

generate if (F_OPT_CLK2FFLOGIC)
begin
    (* gclk *) wire gbl_clk;

    always @(*(posedge gbl_clk))
        if ((f_past_valid)&&(!$rose(i_clk)))
            begin
                assume($stable(i_axi_awready));
                assume($stable(i_axi_wready));
                // ...
            end
    end
end generate
```

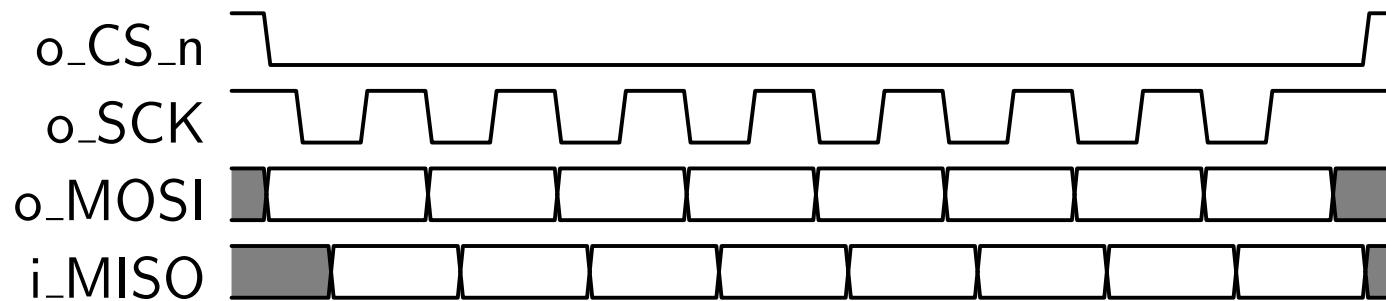
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- How would you formally describe the o_SCK and o_CS_n relationship?



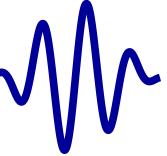
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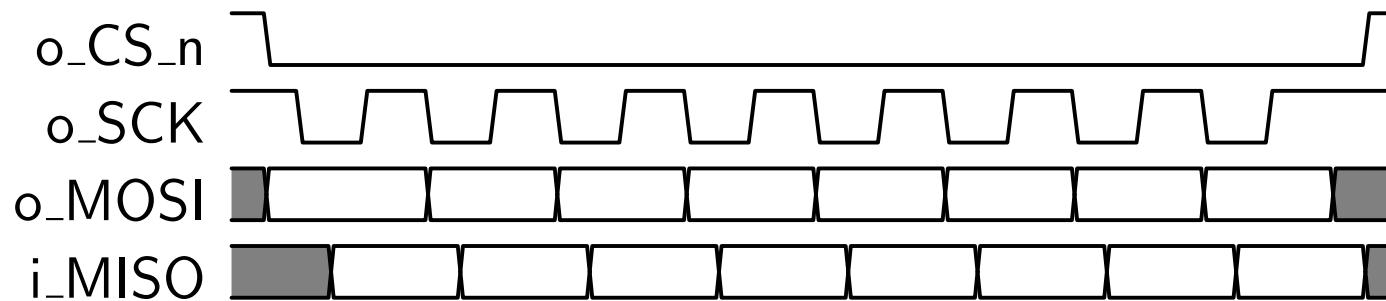
- How would you formally describe the o_SCK and o_CS_n relationship?

```
initial assert(o_CS_n);
initial assert(o_SCK);

always @(*)
if (!o_SCK)
    assert(!o_CS_n);
```



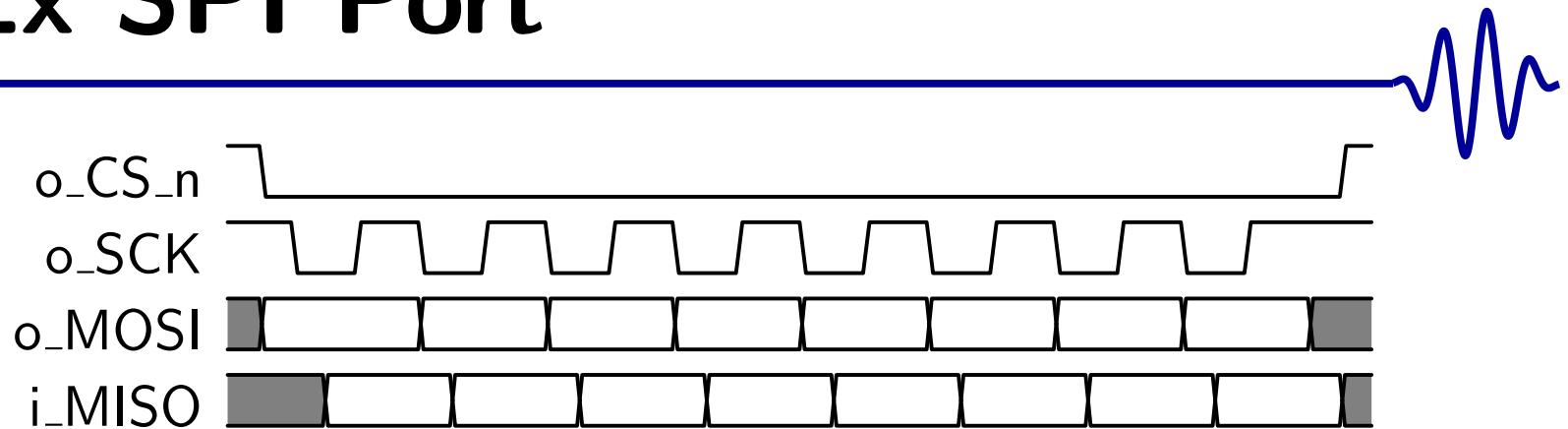
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- How would you formally describe the o_SCK and o_CS_n relationship?

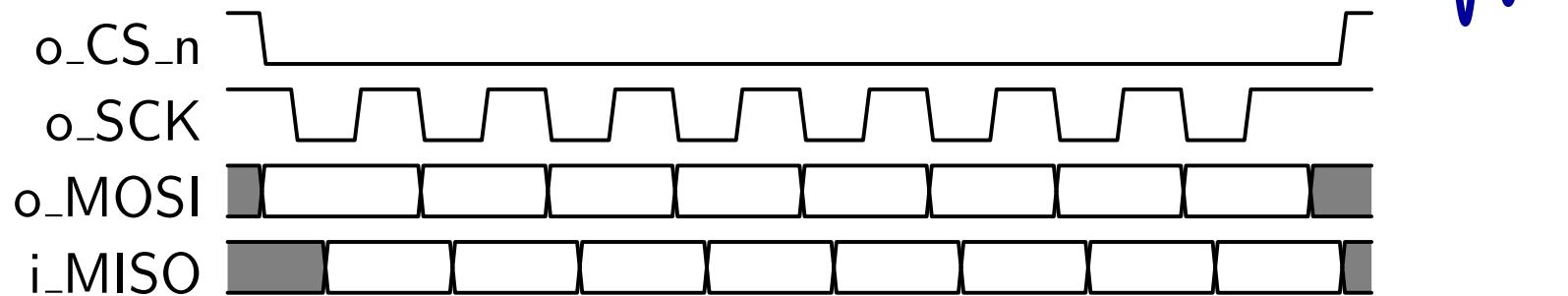
```
always @(`posedge` gbl_clk)
if ((f_past_valid)
    &&(`$rose(o_CS_n)) || (`$fell(o_CS_n)))))
    assert ((o_SCK)&&(`$stable(o_SCK)));
```

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- How would you describe o_MOSI?

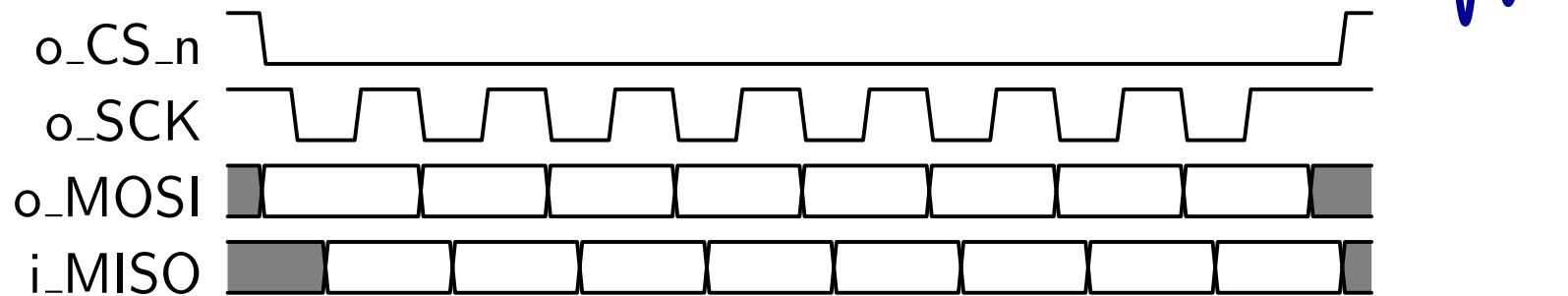
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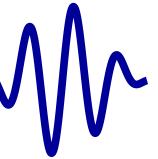
- How would you describe o_MOSI?

```
always @(posedge gbl_clk)
if ((f_past_valid)&&(!o_CS_n)&&(!$fell(o_SCK)))
    assert($stable(o_MOSI));
```

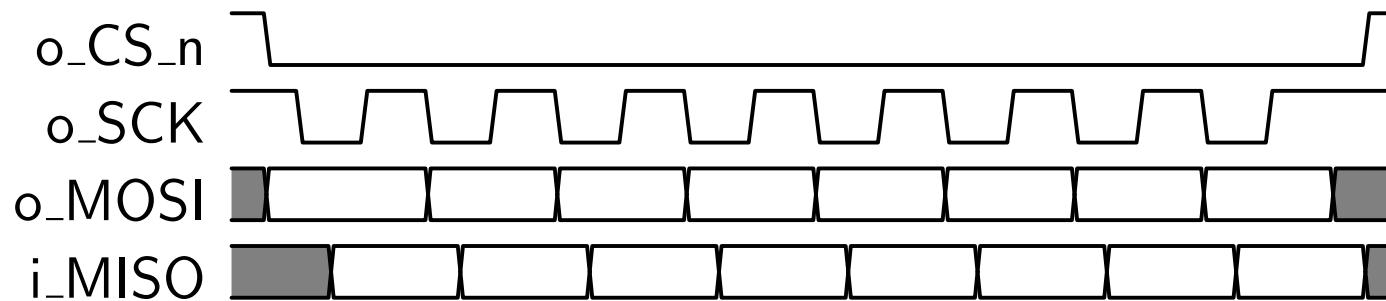
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- How would you describe i_MISO?



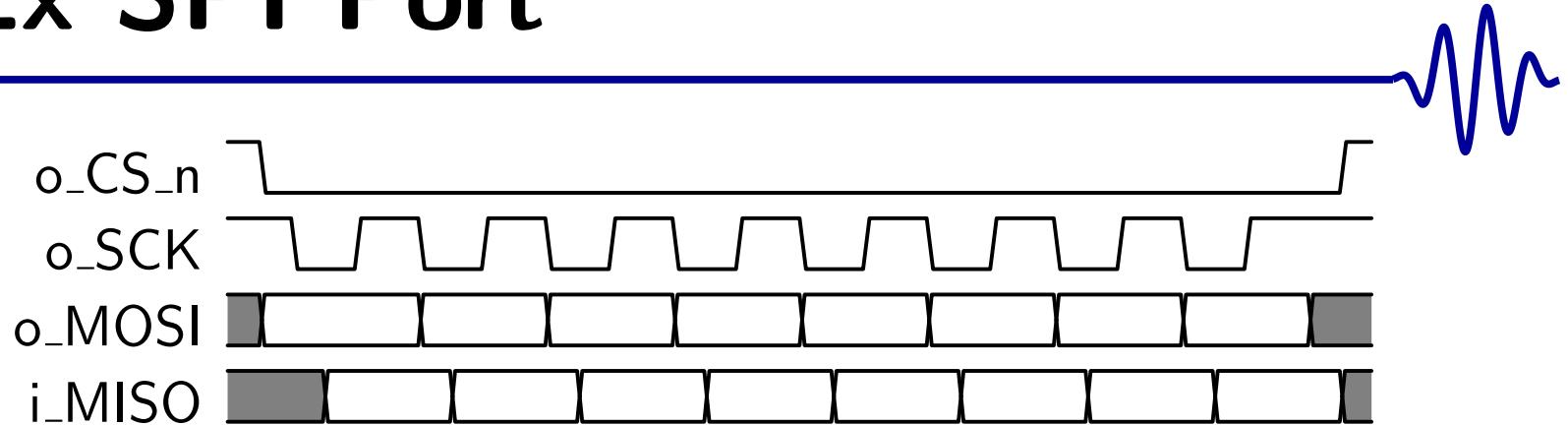
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- How would you describe i_MISO?

```
always @(posedge gbl_clk)
if ((!o_CS_n)&&(o_SCK))
    assume($stable(i_MISO));
```

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- Should the **i_MISO** be able to change more than once per clock?

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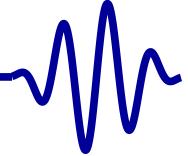
- A little logic will force `i_MISO` to have only one transition per clock

```
always @ (posedge gbl_clk)
  if ((o_CS_n) || (o_SCK))
    f_chgd <= 1'b0;
  else if (i_MISO != $past(i_MISO))
    f_chgd <= 1'b1;
```

```
always @ (posedge gbl_clk)
  if ((f_past_valid)&&(f_chgd))
    assume ($stable(i_MISO));
```

- How would we force exactly 8 `o_SCK` clocks?

Ex SPI Port



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- Forcing exactly 8 clocks

```
always @ (posedge gbl_clk)
  if (o_CS_n)
    f_spi_bits <= 0;
  else if ($rose(o_SCK))
    f_spi_bits <= f_spi_bits + 1'b1;
```

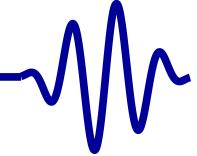
```
always @ (posedge gbl_clk)
  if ((f_past_valid)&&($rose(o_CS_n)))
    assert(f_spi_bits == 8);
```

- Don't forget the induction requirement

```
always @ (*)
  assert(f_spi_bits <= 8);
```



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Three exercises, chose one to verify:

1. Input serdes

`exercises-09/iserdes.v`

2. Clock gate

`exercises-10/clkgate.v`

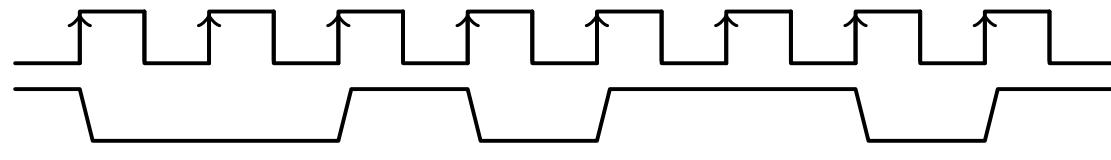
3. Clock Switch

`exercises-11/clkswitch.v`

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Getting a SERDES right is a good example of multiple clocks

i_fast_clk



i_pin

i_slow_clk

o_word

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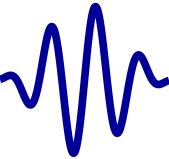
Getting a SERDES right is a good example of multiple clocks

- Two clocks, one fast and one slow

Clocks must be synchronous

\$rose(slow_clk) implies **\$rose**(fast_clk)

- `exercise-09/` Contains the file `iserdes.v`
- Can you formally verify that it works?

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Be aware of the asynchronous reset signal!

i_areset_n



i_fast_clk



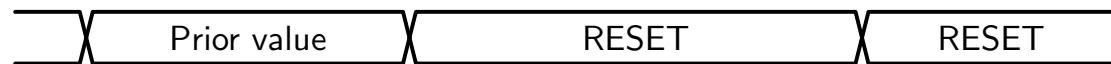
i_pin



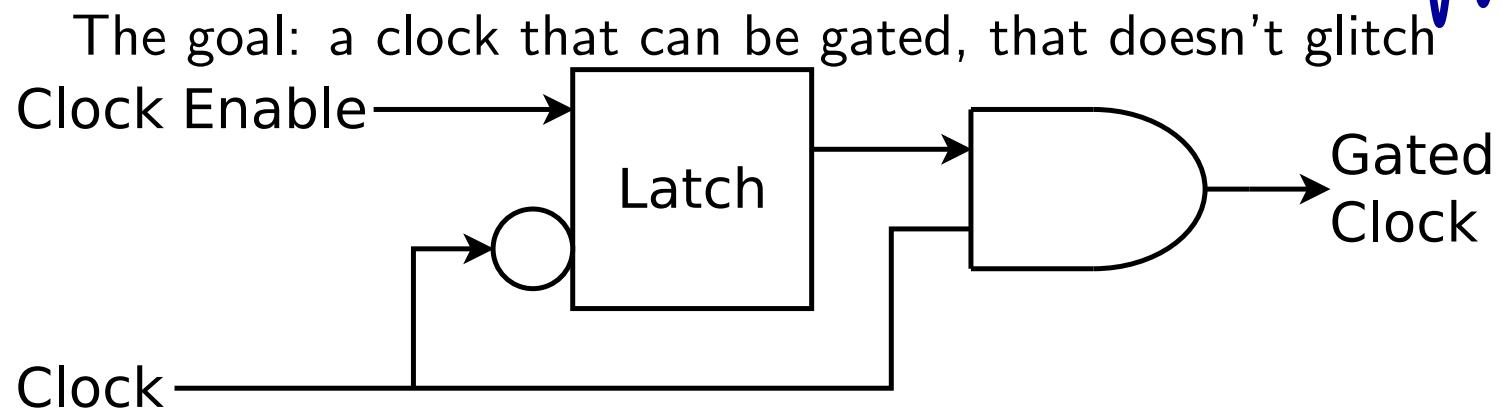
i_slow_clk



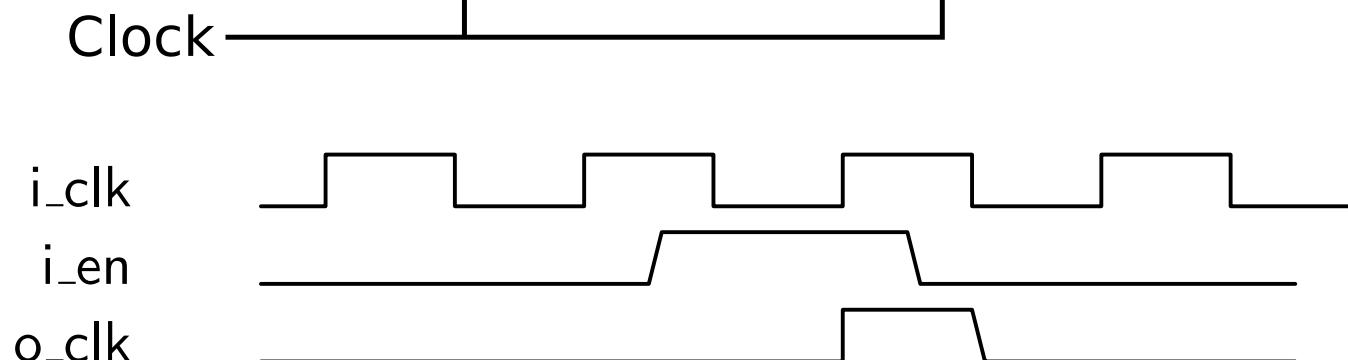
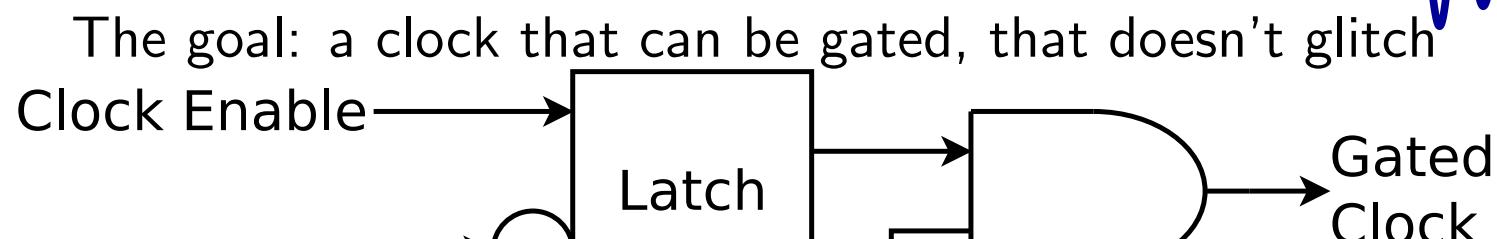
o_word

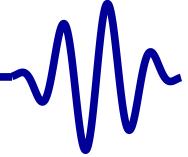


- Can be asserted at any time
- Can only be de-asserted on **\$rose(i_slow_clk)**
- **assume()** these properties, since the reset is an input

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- exercise-10/ Contains the file clkgate.v

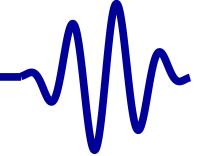
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The goal: a clock that can be gated, that doesn't glitch

- One clock, one unrelated enable
- Prove that the output clock
 - is always high for the full width, but
 - . . . never longer.
 - For any clock rate

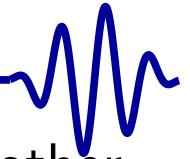
See `exercise-10/clkgate.v`

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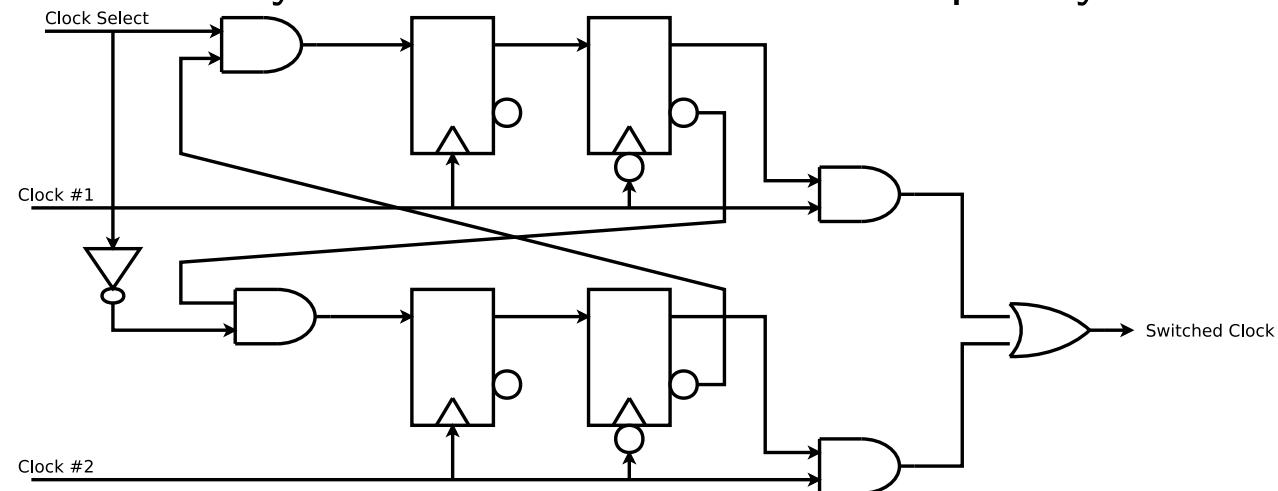
Hints:

- The output clock should only rise if the incoming clock rises
- The output clock should only fall if the incoming clock fall
- If the output clock is ever high, it should always fall with the incoming clock

Be aware of the reset! The output clock might fall mid-clock period due to the asynchronous reset.

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Goal: To safely switch from one clock frequency to another



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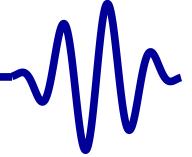
Goal: To safely switch from one clock frequency to another

- Inputs
 - Two arbitrary clocks
 - One select line

Prove that the output clock

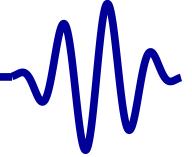
- Is always high (or low) for at least the duration of one of the clocks
- Doesn't stop

You may need to constrain the select line.

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Hints:

- You may assume the reset is only ever initially true
- Only one set of FF's should ever change at any time



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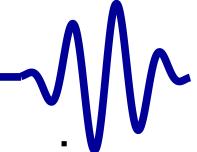
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The cover element is used to make certain something remains possible

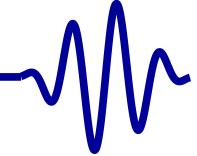
- BMC and induction test *safety* properties
They prove that something *will not* happen
- Cover tests a *liveness* property
It proves that something *may* happen

Objectives

- Understand why cover is important
- Understand how to use cover



Why Cover



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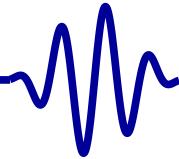
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Personal examples:

- Forgot to set f_past_valid to one
Many assertions were ignored
- Av to WB bridge, passed FV, but couldn't handle writes
- Error analysis
The simulation trace doesn't make sense. Can it be reproduced?
- As an anti-assertion
Can this situation actually happen?

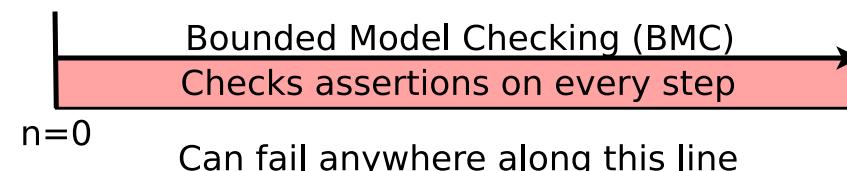
What is cover good for? Catching the *careless assumption!*

What else? Ad hoc simulation traces!

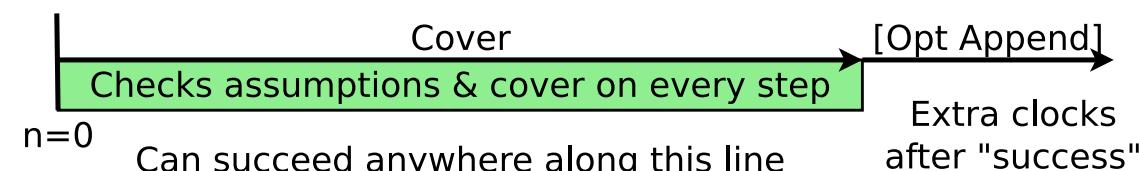
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Cover is more like BMC than Induction is

- BMC



- Cover



- BMC searches for failures
- Cover searches for a success

Formally, we might say . . .

- BMC + k -Induction: proof for all
 $\forall \text{assume}() \Rightarrow \forall \text{assert}()$
- Cover: there exists one
 $\forall \text{assume}() \Rightarrow \exists \text{cover}()$



Cover in Verilog



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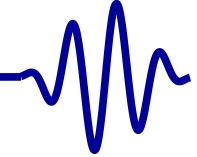
Just like an assumption or an assertion

```
// Make sure a write is possible
always @(posedge i_clk)
cover((o_wb_stb)&&(!i_wb_stall)&&(o_wb_we));

// Or

// What happens when a bus cycle is aborted?
always @(posedge i_clk)
if (i_reset)
    cover((o_wb_cyc)&&(f_wb_outstanding>0));
```

Well, almost but not quite.

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Assert and cover handle surrounding logic differently

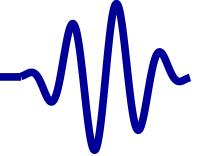
- Assert logic

```
always @(posedge i_clk)
  if (A)
    assert (B);
```

is equivalent to,

```
always @(posedge i_clk)
  assert( (!A) || (B) );
```

This is not true of cover.

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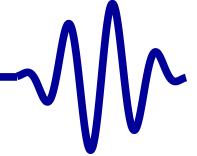
Assert and cover handle surrounding logic differently

- Assert logic
- Cover logic

```
always @(posedge i_clk)
  if (A)
    cover(B);
```

is equivalent to,

```
always @(posedge i_clk)
  cover( (A) && (B) );
// NOT the same as
//      assert( (!A) || (B) );
```



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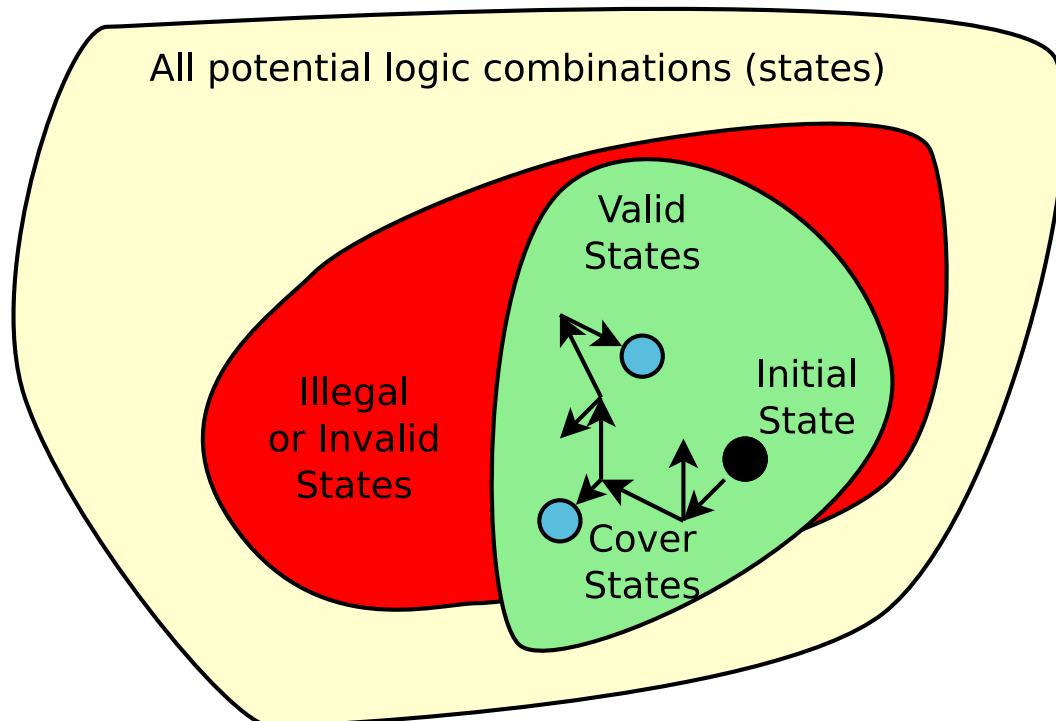
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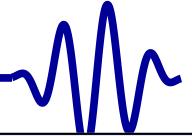


- Goal is to *prove* certain state's are reachable
- Prover solves for example traces

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The SymbiYosys script for cover needs to change as well

- SymbiYosys needs the option: **mode cover**
- Produces one trace per **cover()** statement
... or fail



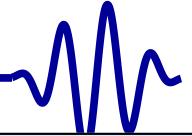
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```
[options]
mode cover
depth 40
append 20

[engines]
smtbmc

[script]
read -formal module.v
prep -top module

[files]
# file list
```



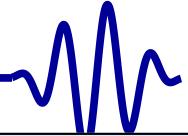
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```
[options]
mode cover ← Run a coverage analysis
depth 40
append 20

[engines]
smtbmc

[script]
read -formal module.v
prep -top module

[files]
# file list
```



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```
[options]
mode cover
depth 40 ← How far to look for a covered state
append 20

[engines]
smtbmc

[script]
read -formal module.v
prep -top module

[files]
# file list
```



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```
[options]
mode cover
depth 40
append 20 ← Follow each trace with 20 extra clocks

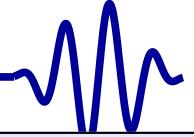
[engines]
smtbmc

[script]
read -formal module.v
prep -top module

[files]
# file list
```



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prf

cvr

[**options**]

prf : **mode** prove

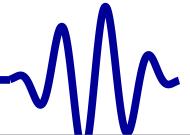
cvr : **mode** cover

depth 40

. . .



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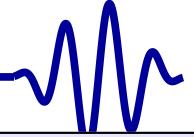


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```
[ tasks ]
prf ←———— Run two tasks: prf and cvr
cvr

[ options ]
prf: mode prove
cvr: mode cover
depth 40

# . . .
```



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[tasks]

prf

cvr

[options]

prf : mode prove ← The prf tasks runs induction

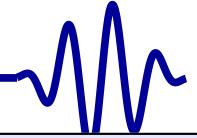
cvr : mode cover

depth 40

. . .



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prf : **mode** prove

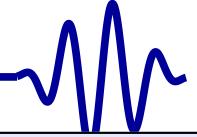
cvr : **mode** cover ← The cvr tasks runs in cover mode

depth 40

. . .



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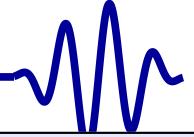
[**options**]

prf : **mode** prove

cvr : **mode** cover

depth 40 ← The same depth can apply to both

. . .



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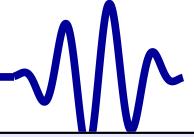
[tasks]**prf****cvr****[options]****prf**: **mode** prove**cvr**: **mode** cover**depth** 40

...

% sby -f sbyfil.sby now runs both modes



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prf

cvr

[**options**]

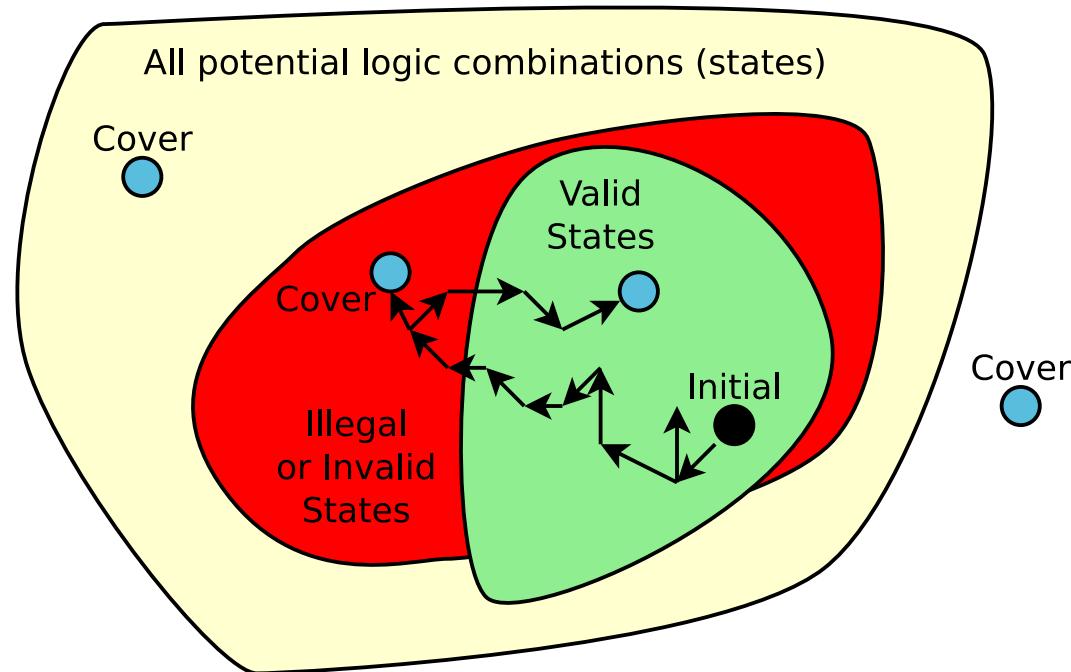
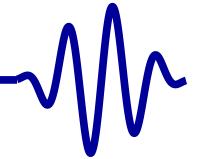
prf : **mode** prove

cvr : **mode** cover

depth 40

...

% sby -f sbyfil.sby cvr will run the cover mode alone

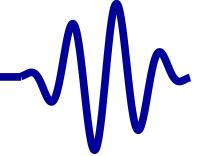


Two basic types of cover failures

1. Covered state is unreachable
No VCD file will be generated upon failure
2. Covered state is reachable, but only by breaking assertions
VCD file will be generated



Ex: I-Cache



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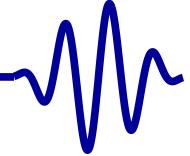
Consider a CPU I-cache:

```
always @(posedge i_clk)
    cover(o_valid);
```

With no other formal logic, what will this trace look like?

- CPU must provide a PC address
- Design must fill the appropriate cache line
- Design returns an item from that cache line

That's a lot of trace for two lines of HDL!

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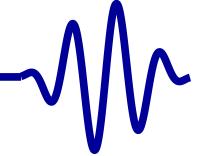
Consider a Flash controller:

```
always @(posedge i_clk)
    cover(o_wb_ack);
```

With no other formal logic, what will this trace look like?

The controller must,

- Initialize the flash device
- Accept a bus request
- Request a read from the flash
- Accumulate the result to return on the bus

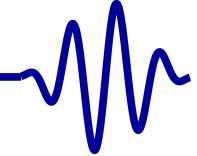
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Consider a Memory Management Unit (MMU):

```
always @(posedge i_clk)
    cover(o_wb_ack);
```

The MMU must,

- Be told a TLB entry
- Accept a bus request
- Look the request up in the TLB
- Forward the modified request downstream
- Wait for a return
- Forward the value returned upstream

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How about an SDRAM controller?

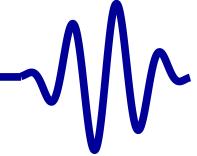
```
always @(posedge i_clk)
    cover(o_wb_ack);
```

The controller must,

- Initialize the SDRAM
- Accept a bus request
- Activate a row on a bank
- Issue a read (or write) command from that row
- Wait for a return value
- Return the result



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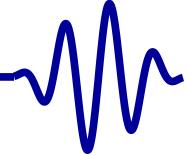
Remember our counter?

```
initial counter = 0;
always @(posedge i_clk)
if ((i_start_signal)&&(counter == 0))
    counter <= MAX_AMOUNT-1'b1;
else if (counter != 0)
    counter <= counter - 1'b1;

always @(*)
    o_busy = (counter != 0);
```



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Let's add some cover statements...

```
// Transition to busy
always @(posedge i_clk)
if ((f_past_valid)&&(!$past(o_busy)))
    cover(o_busy);
```

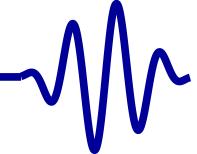
```
// Transition back to idle
always @(posedge i_clk)
if ((f_past_valid)&&($past(o_busy)))
    cover(!o_busy);
```

```
// Mid-cycle
always @(posedge i_clk)
    cover(counter == 3);
```

Will SymbiYosys find traces?



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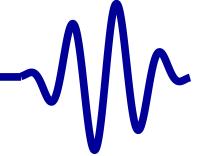
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How about now?

```
always @(posedge i_clk)
    cover((o_busy)&&(counter == 0));
```



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How about now?

```
always @(posedge i_clk)
    cover((o_busy)&&(counter == 0));
```

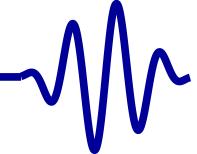
Or this one,

```
always @(posedge i_clk)
    cover(counter == MAX_AMOUNT);
```

Will these succeed?



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How about now?

```
always @(posedge i_clk)
    cover((o_busy)&&(counter == 0));
```

Or this one,

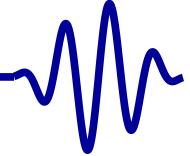
```
always @(posedge i_clk)
    cover(counter == MAX_AMOUNT);
```

Will these succeed? No. Both will fail

- These are outside the reachable state space



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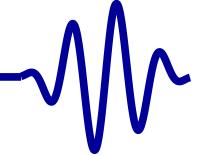
What if the state is unreachable?

```
// Keep the counter from ever starting
always @(*)  
    assume (!i_start_signal);  
  
always @(posedge i_clk)  
    cover(counter != 0);
```

Will this succeed?



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What if the state is unreachable?

```
// Keep the counter from ever starting
always @(*)
    assume (!i_start_signal);

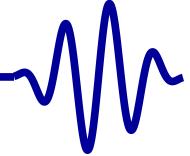
always @(posedge i_clk)
    cover(counter != 0);
```

Will this succeed? No. This will fail with no trace.

- If `i_start_signal` is never true, the cover cannot be reached



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What if an assertion needs to be violated?

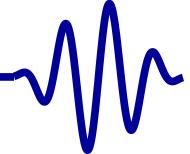
```
always @(*)  
    assert(counter != 10);
```

```
always @(posedge i_clk)  
    cover(counter == 4);
```

What will happen here?



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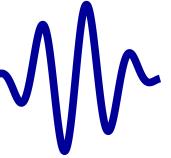
What if an assertion needs to be violated?

```
always @(*)  
    assert(counter != 10);
```

```
always @(posedge i_clk)  
    cover(counter == 4);
```

What will happen here?

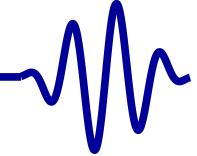
- Cover statement is reachable
- But requires an assertion failure, so a trace is generated

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Covering the clock switch



- Shows the clock switching from fast to slow,
- and again from slow to fast

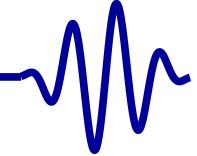
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Return to your Wishbone arbiter. Let's cover four cases:

1. Cover both A and B receiving the bus
2. Cover how B will get the bus after A gets an acknowledgement
3. Cover how A will get the bus after B gets an acknowledgement
4. Add to the last cover
 - B must request while A still holds the bus

Plot and examine traces for each cases. Do they look right?

- If everything works, the first case showing both A and B receiving the bus will FAIL
- No trace is needed from that case
- After getting this failure, you may want to remove it from your cover checks

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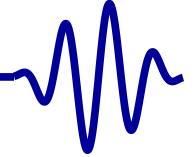
Notice what we just proved:

1. The arbiter will allow both sources to master the bus
2. The arbiter will transition from one source to another
3. The arbiter won't starve A or B

This wasn't possible with just the safety properties (assert statements)



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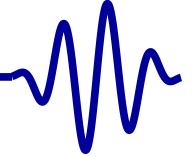
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When should you use cover?



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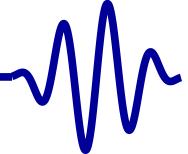
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SystemVerilog has some amazing formal properties

- **property** can be assumed or asserted
By rewriting our assert's and assume's as properties, we can then control when they are asserted or assumed better.
- **bind** formal properties to a subset of your design
Allows us to (finally) separate the properties from the module they support
- **sequence** – A standard property description language

Objectives

- Learn the basics of SystemVerilog Assertions
- Gain confidence with yosys+verific

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Much of what we've written can easily be rewritten in SVA

```
always @(*)  
if (A)  
    assert(B);
```

can be rewritten as,

```
assert property (@(posedge i_clk)  
                  A |-> B);
```

Note that this is now a *clocked* assertion, but otherwise it's equivalent

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Much of what we've written can easily be rewritten in SVA

```
always @(posedge i_clk)
  if ((f_past_valid)&&($past(A)))
    assert(B);
```

Can be rewritten as,

```
assert property (@(posedge i_clk)
  A |=> B);
```

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Much of what we've written can easily be rewritten in SVA

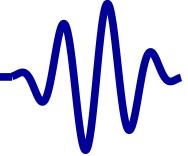
```
always @(posedge i_clk)
if ((f_past_valid)&&($past(A)))
    assert(B);
```

Can be rewritten as,

```
assert property (@(posedge i_clk)
                  A |=> B);
```

- Read this as A implies B on the next clock tick.
- No f_past_valid required anymore. This is a statement about the next clock tick, not the last one.

These equivalencies apply to **assume()** as well

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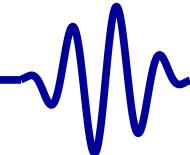
You can also declare properties:

```
property SIMPLE_PROPERTY;  
    @(posedge i_clk) a |=> b;  
endproperty
```

```
assert property(SIMPLE_PROPERTY);
```

This would be the same as

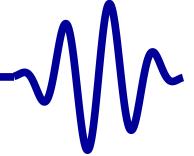
```
always @(posedge i_clk)  
if ((f_past_valid)&&($past(a)))  
    assert(b);
```

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You could also do something like:

```
parameter [0:0] F_SUBMODULE = 1'b0;  
  
generate if (F_SUBMODULE)  
begin  
    assume property(INPUT_PROP);  
end else begin  
    assert property(INPUT_PROP);  
end endgenerate  
  
assert property(LOCAL_PROP);  
assert property(OUTPUT_PROP);
```

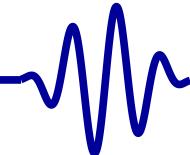
This would work quite nicely for a bus property file

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Properties can also accept parameters

```
property IMPLIES(a,b);
  @(posedge i_clk)
  a |-> b;
endproperty

assert property( IMPLIES(x, y));
```

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Properties can also accept parameters

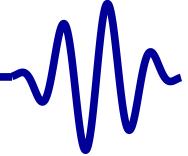
```
property IMPLIES_NEXT(a, b);  
    @ (posedge i_clk) a |=> b;  
endproperty
```

```
assert property (IMPLIES_NEXT(x, y));
```

Remember, if you want to use $|=>$, **\$past**, etc., you need to define a clock.



Clocking



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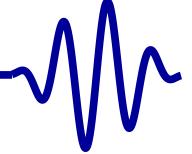
Getting tired of writing @(**posedge i_clk**)?

- You can set a default clock

```
default clocking @(posedge i_clk);  
endclocking
```

Assumes `i_clk` if no clock is given.

Clocking



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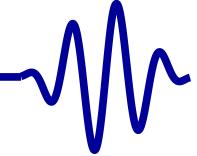
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Getting tired of writing @(**posedge** i_clk)?

- You can set a default clock
- You can set a default clock within a given block

```
clocking @(posedge i_clk);  
    // Your properties can go here  
    // As with assert, assume,  
    // sequence, etc.  
endclocking
```

Assumes i_clk for all of the properties within the clocking block.

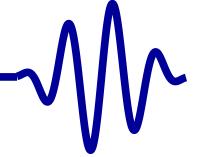
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When using verific, **\$global_clock** must first be defined

```
(* gclk *) wire gbl_clk;  
global clocking @(posedge gbl_clk); endclocking
```

This defines the **\$global_clock** ...

- as a positive edge transition of gbl_clk.
- The (* gclk *) attribute turns it into a formal timestep



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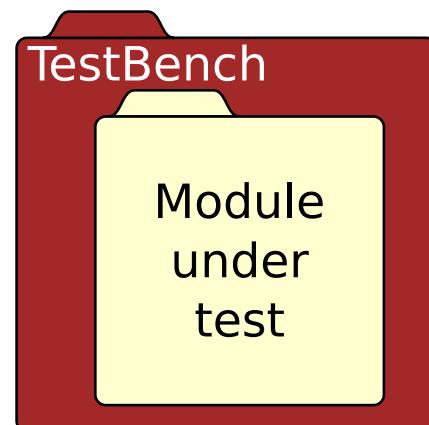
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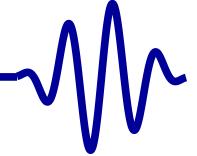
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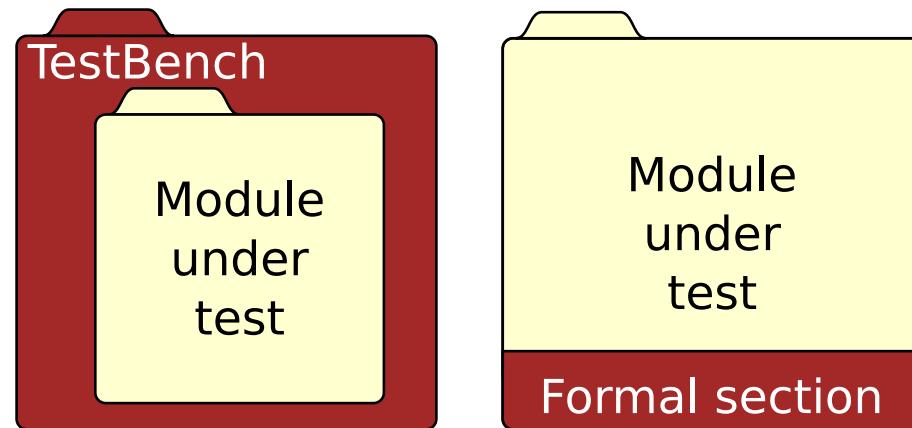
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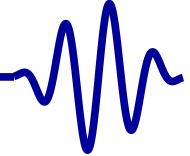
- Common bench testing works on black boxes
- This doesn't work well with formal methods



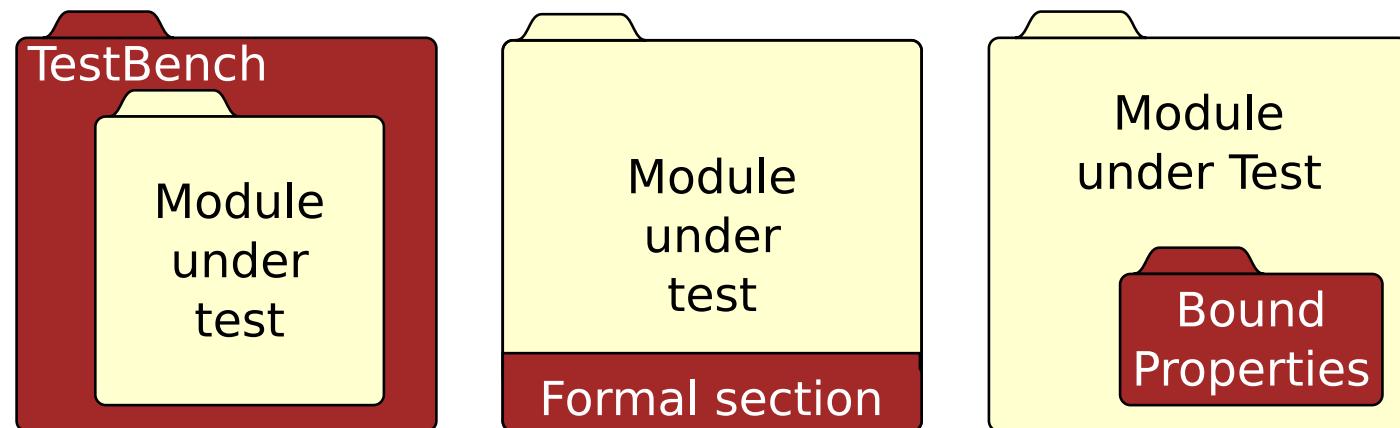
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- Common bench testing works on black boxes
- This doesn't work well with formal methods
- Placing properties within a module doesn't separate the two



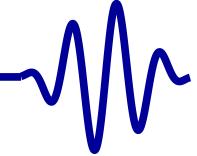
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- Common bench testing works on black boxes
- This doesn't work well with formal methods
- Placing properties within a module doesn't separate the two

Using the SVA *bind* command, we can

- Separate properties from a design
- Maintains the necessary “white box” perspective

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- Can bind to specific named variables

```
module mut(input i, output o);
    reg r;
    // Your logic here
endmodule
```

```
module mut_formal(input a, input b, input r);
    // Your formal properties go here
endmodule
```

```
bind mut mut_formal mut_instance (
    // Bind inputs together
    .a(i), .b(o), .r(r)
    // The general format is
    .mut_formal_name(mut_name));
```

- Note all mut_formal ports must be inputs



Bind



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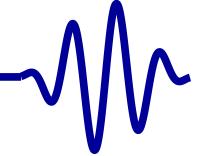
- Can bind to specific named variables
- Can also make *all* variables available to your properties

```
module mut(input i, output o);
    reg      r;
    // Your logic here
endmodule

module mut_formal(input i, input o, input r);
    // Your formal properties go here
endmodule

// Make every mut variable available in
// mut_formal with a variable of the same
// name
bind mut mut_formal mut_instance (*.);
```

- In order to use `.*`, names must match

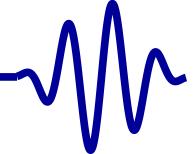
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- Can bind to specific named variables
- Can also make *all* variables available to your properties
- Can pass parameters through as well

```
module mut( input i, output o );
    parameter ONE = 5;
    // Your logic here
endmodule
```

```
module mut_formal( input i, input o, input r );
    parameter TWO = 14;
    // Your formal properties go here
endmodule
```

```
bind mut mut_formal #(TWO(ONE))
    mut_instance (.*);
```



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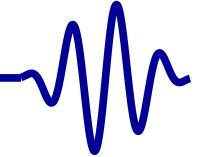
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So far with properties,

- We haven't done anything really all that new.
- We've just rewritten what we've done before in a new form.

Sequences are something new

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With sequences, you can

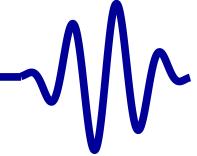
- Specify a series of actions

sequence EXAMPLE ;

```
@(posedge i_clk) a ##1 b ##1 c ##1 d;
```

endsequence

In this example, b always follows a by one clock, c follows b, and d follows c

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With sequences, you can

- Specify a series of actions, separated by some number of clocks

```
sequence EXAMPLE;  
  @( posedge i_clk) a ##2 b ##5 c;  
endsequence
```

In this example, b always follows a two clocks later, and c follows five clocks after b

Sequence



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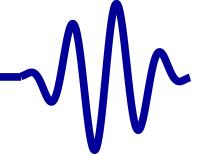
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With sequences, you can

- Specify a series of predicates, separated in time
- Can express range(s) of repeated values

```
sequence EXAMPLE;
    @(posedge i_clk) b[*2:3] ##1 c;
endsequence
// is equivalent to ...
sequence EXAMPLE_A_2x; // 2x
    @(posedge i_clk) b ##1 b ##1 c;
endsequence
// or
sequence EXAMPLE_A_3x; // 3x
    @(posedge i_clk) b ##1 b ##1 b ##1 c;
endsequence
```

Sequence



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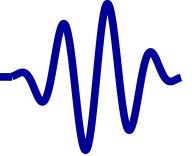
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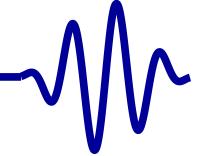
With sequences, you can

- Specify a series of predicates, separated in time
- Can express range(s) of repeated values
 - $[*0:M]$ Predicate may be skipped
 - $[*N:M]$ specifies from N to M repeats
 - $[*N:$]$ Repeats at least N times, with no maximum
- Ranges can include empty sequences, such as $\#\#[*0:4]$
- Compose multiple sequences together
 - AND, seq_1 **and** seq_2
 - OR, seq_1 **or** seq_2
 - NOT, **not** seq

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The **and** and **intersect** operators are very similar

- **and** is only true if both sequences are true
- **intersect** is only true if both sequences are true *and* have the same length

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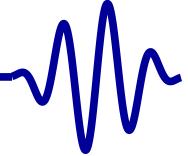
- Throughout

```
sequence A;  
  @(posedge i_clk)  
  (EXP) [*0:$] intersect SEQ;  
endsequence
```

is equivalent to

```
sequence B;  
  @(posedge i_clk)  
  (EXP) throughout SEQ;  
endsequence
```

The EXP expression must be true from now until SEQ ends

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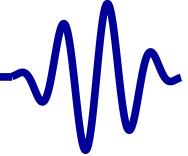
- Throughout
- Until

```
property A;  
  @(posedge i_clk)  
    (E1) [*0:$] ##1 (E2);  
endproperty
```

is equivalent to

```
property B;  
  @(posedge i_clk)  
    (E1) until E2;  
endproperty
```

- **until** can only be used in a **property**, not within a **sequence**

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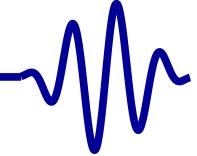
- Throughout
- Until

```
property A;  
  @(posedge i_clk)  
    (E1) [*0:$] ##1 (E2);  
endproperty
```

is equivalent to

```
property B;  
  @(posedge i_clk)  
    (E1) until E2;  
endproperty
```

- **until** can only be used in a **property**, not within a **sequence**
- There is an ugly subtlety here
 - Must E2 ever take place?

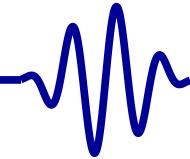
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- Throughout
- Until
- Within

```
sequence A ;  
  @(posedge i_clk)  
  (1[*0:$] ##1 S1 ##1 1[*0:$])  
    intersect S2 ;  
endsequence
```

is equivalent to

```
sequence B ;  
  @(posedge i_clk)  
  (S1) within S2 ;  
endsequence
```

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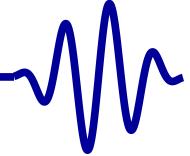
Properties can reference sequences

- Directly

```
assert property (seq);  
assert property (expr |-> seq);
```

- Implication: sequences can imply properties

```
assert property (seq |-> some_other_property);  
assert property (seq |=> another_property);
```



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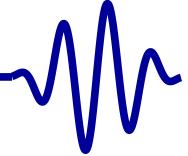
Properties can include . . .

- **if** statements

```
assert property ( if ( A ) P1 else P2 );
```

- **not**, **and**, or even **or** statements

```
assert property ( not P1 );
assert property ( P1 and P2 );
assert property ( P1 or P2 );
```



A bus request will not change until it is accepted

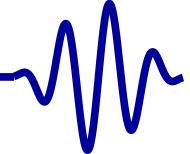
```
property BUS_REQUEST_HOLD;  
  @(posedge i_clk)  
  ( STB)&&(STALL)  
  |=> ( STB)&&($stable(REQUEST));  
endproperty  
  
assert property ( BUS_REQUEST_HOLD);
```

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A request persists until it is accepted

```
sequence BUS_REQUEST;  
  @( posedge i_clk )  
    // Repeat up to MAX_STALL clks  
    ( STB ) && ( STALL ) [ *0 : MAX_STALL ]  
    ##1 ( STB ) && ( !STALL );  
endsequence  
  
assert property ( STB |-> BUS_REQUEST );
```

You no longer need to count stalls yourself.

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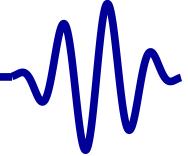
A request persists until it is accepted

```
sequence BUS_REQUEST;
    @(posedge i_clk)
        // Repeat up to MAX_STALL clk
        (STB)&&(STALL) [*0:MAX_STALL]
        ##1 (STB)&&(!STALL);
endsequence

assert property (STB |-> BUS_REQUEST);
```

You no longer need to count stalls yourself.

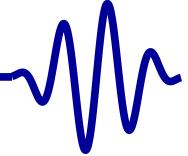
Could we do this with an **until** statement?

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A request persists until it is accepted

```
sequence BUS_REQUEST;  
  @( posedge i_clk )  
    ( STB )&&(STALL) until ( STB )&&(!STALL);  
endsequence  
  
assert property ( STB |→ BUS_REQUEST );
```

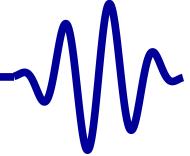
What is the difference?

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A request persists until it is accepted

```
sequence BUS_REQUEST;  
  @(posedge i_clk)  
  (STB)&&(STALL) until (STB)&&(!STALL);  
endsequence  
  
assert property (STB |> BUS_REQUEST);
```

What is the difference? The **until** statement goes forever, our prior example was limited to MAX_STALL clock cycles.

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A request persists until it is accepted

```
sequence BUS_REQUEST;  
  @( posedge i_clk )  
    ( STB )&&(STALL) until ( STB )&&(!STALL);  
endsequence  
  
assert property ( STB |→ BUS_REQUEST );
```

What is the difference?

But . . . what happens if RESET is asserted?

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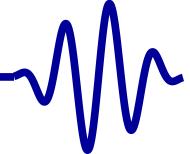
A property can be conditionally disabled

```
sequence BUS_REQUEST;
    // Repeat up to MAX_STALL c/ks
    (STB)&&(STALL) [*0:MAX_STALL]
    ##1 (STB)&&(!STALL);

endsequence

assert property (
    @(posedge i_clk)
    disable iff (i_reset)
    STB |-> BUS_REQUEST);
```

The assertion will no longer fail if `i_reset` clears the request
What if the request is aborted?

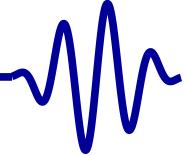
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A property can be conditionally disabled

```
sequence BUS_REQUEST;
    @(posedge i_clk)
        // Repeat up to MAX_STALL clks
        (STB)&&(STALL) [*0:MAX_STALL]
        ##1 (STB)&&(!STALL);
endsequence

assert property (
    @(posedge i_clk)
    disable iff ((i_reset)||(!CYC))
    STB |-> BUS_REQUEST);
```

Will this work?

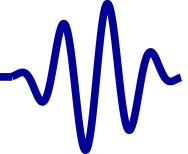
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A property can be conditionally disabled

```
sequence BUS_REQUEST;
  @(posedge i_clk)
    // Repeat up to MAX_STALL clks
    (STB)&&(STALL) [*0:MAX_STALL]
    ##1 (STB)&&(!STALL);
endsequence

assert property (
  @(posedge i_clk)
  disable iff ((i_reset)||(!CYC))
  STB |-> BUS_REQUEST);
```

Will this work? Yes!

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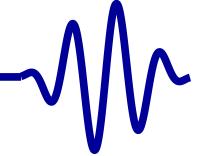
Some peripherals will only ever accept one request

```
sequence SINGLE_ACK(MAX_DELAY);
  @(posedge i_clk)
    (!ACK)&&(STALL) [*0:MAX_DELAY]
    ##1 (ACK)&&(!STALL);
endsequence

assert property (
  disable iff ((i_reset)||(!CYC))
  (STB)&&(!STALL) |=> SINGLE_ACK(32);
);
```

This peripheral will

- Stall up to 32 clocks following any accepted request, until it
- Acknowledges the request, and
- Releases the bus on the same cycle

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Some peripherals will

- Never stall the bus, and
- Acknowledge every request after a fixed number of clock ticks

```
property NEVER_STALL(DELAY);
  @(posedge i_clk)
  disable iff ((i_reset)||(!CYC))
    (STB) |-> ##[*DELAY] (ACK);
endproperty

assert property (NEVER_STALL(DELAY)
  and (!STALL));
```

This is illegal. Can you spot the bug?

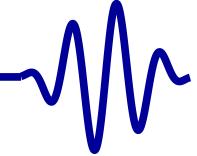
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Some peripherals will

- Never stall the bus, and
- Acknowledge every request after a fixed number of clock ticks

```
property NEVER_STALL(DELAY);  
  @(posedge i_clk)  
  disable iff ((i_reset) || (!CYC))  
    (STB) |-> ##[*DELAY] (ACK);  
endproperty  
  
assert property (NEVER_STALL(DELAY)  
  and (!STALL));
```

This is illegal. Can you spot the bug? What logic does the **disable iff** apply to?

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Some peripherals will

- Never stall the bus, and
- Acknowledge every request after a fixed number of clock ticks

```
property NEVER_STALL(DELAY);  
  @(posedge i_clk)  
  disable iff ((i_reset)||(!CYC))  
  (STB) |-> ##[*DELAY] (ACK);  
endproperty  
  
assert property (NEVER_STALL(DELAY));  
assert property (!STALL);
```

This is valid



Cannot ACK or ERR when no request is pending

```
assert property (@(posedge i_clk)
    ((!i_CYC)||| (i_reset))
    ##1 ((!i_CYC)||| (i_reset))
    |-> ((!o_ACK)&&(!o_ERR));
```

Or as we did it before

```
always @(posedge i_clk)
if ((f_past_valid)
    &&(!$past(i_reset))|| (! $past(i_CYC)))
    &&((i_reset)|| (! i_CYC))
    assert ((!o_ACK)&&(!o_ERR));
```

Which is simpler to understand?



Let's look at an serial port transmitter example.
A baud interval is CKS clocks . . .

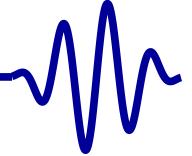
- Output data is constant
- Logic doesn't change state
- Internal shift register value is known
- Ends with zero_baud_counter

```
sequence BAUD_INTERVAL(CKS, DAT, SR, ST);
    ((o_uart_tx == DAT)&&(state == ST)
     &&(lcl_data == SR)
     &&(!zero_baud_counter))[* (CKS - 1)]
    ##1 ((o_uart_tx == DAT)&&(state == ST)
          &&(lcl_data == SR)
          &&(zero_baud_counter))
endsequence
```

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A byte consists of 10 Baud intervals

```
sequence SEND(CKS, DATA);  
    BAUD_INTERVAL(CKS, 1'b0, DATA, 4'h0)  
##1 BAUD_INTERVAL(CKS, DATA[0],  
                  {{(1){1'b1}},DATA[7:1], 4'h1})  
##1 BAUD_INTERVAL(CKS, DATA[1],  
                  {{(2){1'b1}},DATA[7:2], 4'h2})  
//  
##1 BAUD_INTERVAL(CKS, DATA[6],  
                  {{(7){1'b1}},DATA[7], 4'h7})  
##1 BAUD_INTERVAL(CKS, DATA[7],  
                  7'hff,DATA[7], 4'h8)  
##1 BAUD_INTERVAL(CKS, 1'b1, 8'hff, 4'h9);  
endsequence
```

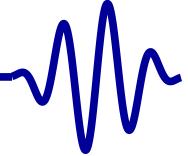
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Transmitting a byte requires

```
always @(posedge i_clk)
if ((i_wr)&&(!o_busy))
    fsv_data <= i_data;

assert property (@(posedge i_clk)
    (i_wr)&&(!o_busy)
    |=> ((o_busy) throughout
          SEND(CLOCKS_PER_BAUD, fsv_data))
    ##1 ((!o_busy)&&(o_uart_tx)
        &&(zero_baud_counter)));
```

- A transmit request is received
- The data is sent
- The controller returns to idle

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Transmitting a byte requires

```
assert property (@(posedge i_clk)
    (i_wr)&&(!o_busy)
    |=> ((o_busy) throughout
          SEND(CLOCKS_PER_BAUD, fsv_data))
    ##1 ((!o_busy)&&(o_uart_tx)
        &&(zero_baud_counter));
```

Make sure . . .

- The sequence has a defined beginning
Only ever triggered once at a time
- Doesn't reference changing data
- **throughout** is within parenthesis
- You tie all relevant state information together



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Using SystemVerilog Assertions with Yosys requires Verific

```
[ options ]
mode prove
[ engines ]
smtbmc
[ script ]
#
#
read -formal module.v
# ... other files would go here
prep -top module
opt_merge -share_all

[ files ]
../demo-rtl/module.v
```

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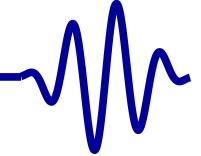
Using SystemVerilog Assertions with Yosys requires Verific

```
[options]
mode prove
[engines]
smtbmc
[script]
# The read command works both with and without Verific
# SymbiYosys script doesn't change therefore
read -formal module.v ←
# ... other files would go here
prep -top module
opt_merge -share_all

[files]
../demo-rtl/module.v
```



SysVerilog Conclusions



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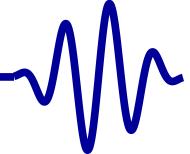
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SystemVerilog Concurrent Assertions . . .

- can be very powerful
- can be very confusing
- can be used with immediate assertions

You can keep using the simpler property form we've been using

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Let's formally verify a synchronous FIFO

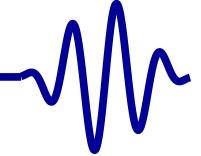
```
module sfifo(i_clk, i_reset,
             i_wr, i_data, o_full,
             i_rd, o_data, o_empty,
             o_err);

    // ...

    'ifdef FORMAL
        // Properties understood by either
        // Yosys or Verific
        // ...
    'endif

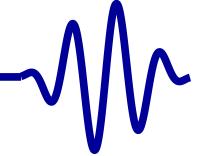
    'ifdef VERIFIC_SVA
        // Verific-only properties
        // ...
    'endif

endmodule
```



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Let's formally verify a synchronous FIFO
What properties do you think would be appropriate?



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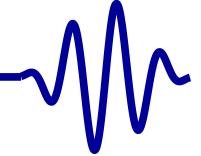
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What properties do you think would be appropriate?

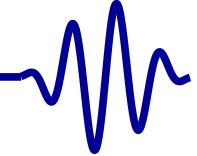
- Should never go from full to empty

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Let's formally verify a synchronous FIFO

What properties do you think would be appropriate?

- Should never go from full to empty except on a reset

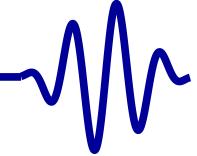
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Let's formally verify a synchronous FIFO

What properties do you think would be appropriate?

- Should never go from full to empty except on a reset
- Should never go from empty to full

Last Exercise



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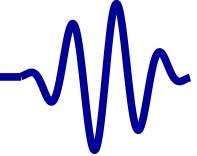
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Let's formally verify a synchronous FIFO

What properties do you think would be appropriate?

- Should never go from full to empty except on a reset
- Should never go from empty to full
- The two outputs, `o_empty` and `o_full`, should properly reflect the size of the FIFO
 - `o_empty` means the FIFO is currently empty
 - `o_full` means the FIFO has 2^N elements within it

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Let's formally verify a synchronous FIFO

What properties do you think would be appropriate?

- Should never go from full to empty except on a reset
- Should never go from empty to full
- The two outputs, `o_empty` and `o_full`, should properly reflect the size of the FIFO
 - `o_empty` means the FIFO is currently empty
 - `o_full` means the FIFO has 2^N elements within it
- **Challenge:** Use sequences to prove that
 - Given any two values written successfully
 - Verify that those two values can (some time later) be read successfully, and in the right order
(Unless a reset takes place in the meantime)

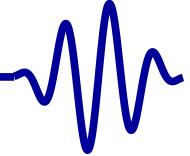
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When using sequences, . . .

- It can be very difficult to figure out what part of the sequence failed.
The assertion that fails will reference the entire failing sequence.

Suggestions:

- Sequences must be triggered
Be aware of what triggers a sequence
- Use combinational logic to define wires that will then represent steps in the sequence
- Build the sequences out of these wires

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Here's an example:

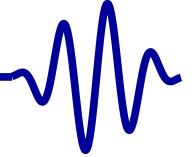
```
wire f_a, f_b, f_c;  
//  
assign f_a = // your logic  
assign f_b = // your logic  
assign f_c = // your logic  
//  
sequence ARBITRARY_EXAMPLE_SEQUENCE  
    f_a [*0:4] ##1 f_b ##1 f_c [*12:16];  
endsequence
```

If you use this approach

- Interpreting the wave file will be much easier
- The f_a, etc., lines will be in the trace



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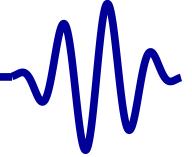
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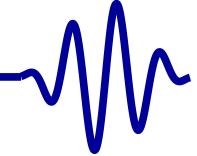
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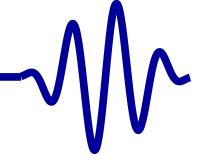
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Will the assertion below ever fail?

```
reg [15:0] counter;  
  
initial counter = 0;  
always @(posedge clk)  
    counter <= counter + 1'b1;  
  
always @(*)  
begin  
    assert(counter <= 100);  
    assume(counter <= 90);  
end
```

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No, it will never fail.

The assumption will prohibit the assertion from being evaluated.

```
always @(*)  
begin  
    assert(counter <= 100);  
    assume(counter <= 90);  
end
```

This is an example of what I call a *careless assumption*.



Quiz #2



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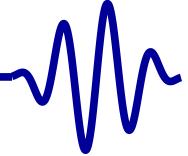
Will this simple counter ever pass formal verification?

```
parameter [15:0] MAX_AMOUNT = 22;
reg [15:0] counter;

always @ (posedge i_clk)
if ((i_start_signal)&&(counter == 0))
    counter <= MAX_AMOUNT - 1'b1;
else if (counter != 0)
    counter <= counter - 1;

always @ (*)
    o_busy = (counter != 0);

`ifdef FORMAL
    always @ (*)
        assert(counter < MAX_AMOUNT);
`endif
```

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This design just needs an initial counter value to pass

```
parameter [15:0] MAX_AMOUNT = 22;
reg [15:0] counter = 0;

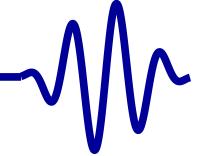
always @ (posedge i_clk)
if ((i_start_signal)&&(counter == 0))
    counter <= MAX_AMOUNT - 1'b1;
else if (counter != 0)
    counter <= counter - 1;

always @ (*)
    o_busy = (counter != 0);

`ifdef FORMAL
    always @ (*)
        assert(counter < MAX_AMOUNT);
`endif
```



Quiz #3



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Will the following design pass formal verification?

```
reg [15:0] counter;  
  
initial counter = 0;  
always @(posedge clk)  
if (counter == 16'd22)  
    counter <= 0;  
else  
    counter <= counter + 1'b1;  
  
always @(*)  
    assert(counter != 16'd500);
```

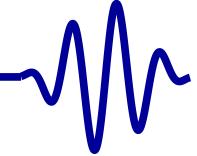
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The following approach will pass both BMC and induction.

```
reg [15:0] counter;  
  
initial counter = 0;  
always @(posedge i_clk)  
if (i_reset) // Keep ASIC designers happy  
    counter <= 0;  
else if (counter == 16'd22)  
    counter <= 0;  
else  
    counter <= counter + 1'b1;  
  
// The correct assertion should reference  
// all of the unreachable counter values  
always @(*)  
    assert(counter <= 16'd22);
```



Quiz #4



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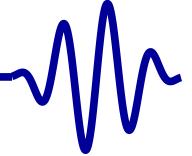
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Will the following design pass formal verification?

```
initial counter = 0;
always @(posedge i_clk)
if ((i_start_signal)&&(counter == 0))
    counter <= 23;
else if (counter != 0)
    counter <= counter - 1'b1;

always @(*)
    assert(counter < 24);
always @(*)
    assume(!i_start_signal);

always @(posedge i_clk)
    assert($past(counter == 0));
```

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If you replace **assert(\$past(counter==0));** with
assert(counter==0);, then this design passes.

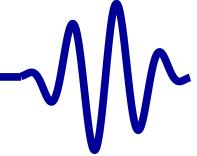
```
initial counter = 0;
always @(posedge i_clk)
if ((i_start_signal)&&(counter == 0))
    counter <= 23;
else if (counter != 0)
    counter <= counter - 1'b1;

always @(*)
    assert(counter < 24);
always @(*)
    assume(!i_start_signal);

always @(posedge i_clk)
    assert(counter == 0);
```



Quiz #5



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How are the following two assertions different?

```
initial f_past_valid = 1'b0;
always @(posedge i_clk)
    f_past_valid <= 1'b1;

always @(posedge i_clk)
if ((f_past_valid)&&($past(o_wb_stb))
    &&($past(i_wb_stall)))
    assert((o_wb_stb)
        &&($stable({i_wb_addr, i_wb_we})));
```

```
assert property (@(posedge i_clk)
    (o_wb_stb)&&(i_wb_stall)
    |=> o_wb_stb
        &&($stable({i_wb_addr, i_wb_we})));
```

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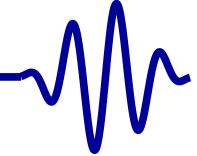
- The first assertion was an “immediate” assertion, the second a “concurrent assertion”.
- While the Symbiotic EDA Suite supports both assertions, the free version of Yosys only supports immediate assertions
- The second assertion is more compact, and perhaps even easier to read

```
assert property (@(posedge i_clk)
    (o_wb_stb)&&(i_wb_stall)
    |=> o_wb_stb
        &&($stable({i_wb_addr, i_wb_we})));
```

Functionally, the two assertions are *identical!*



Quiz #6



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When using multiclock techniques, which of the below descriptions describes a signal that only changes on the positive edge of a clock?

```
(* gclk *) reg gbl_clk;  
always @ (posedge gbl_clk)  
if ($fell(i_clk))  
    assert ($stable(signal));
```

```
always @ (posedge gbl_clk)  
if (! $rose(i_clk))  
    assert ($stable(signal));
```

```
always @ (posedge gbl_clk)  
if (! $past(i_clk))  
    assert ($stable(signal));
```

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The correct way to assert that a signal will only change on a positive clock edge requires asserting that the signal will be stable in all other cases.

```
always @(posedge gbl_clk)
if ((f_past_valid_gbl)&&(!$rose(i_clk)))
    assert($stable(signal));
```

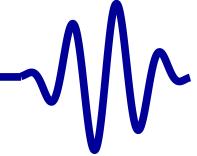
Be aware, **\$rose()** depends upon the **\$past()**, so don't forget an **f_past_valid** signal!

With (* **gclk** *), I like to call it **f_past_valid_gbl**, and define it as,

```
reg f_past_valid_gbl = 1'b0;
always @(posedge gbl_clk)
    f_past_valid_gbl <= 1'b1;
```



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Will this simple counter ever pass formal verification?

```
reg [15:0] counter = 0;  
  
always @ (posedge i_clk)  
if ((i_start_signal)&&(counter == 0))  
    counter <= 21;  
else if (counter != 0)  
    counter <= counter - 1;  
  
always @ (*)  
o_busy = (counter != 0);  
  
always @ (posedge i_clk)  
if ($past(i_start_signal))  
    assert(counter == 21);
```

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No, the assertion would not pass: it neither checked for the past counter == 0, nor did it make sure **\$past()** was valid.

The modified assertion, below, will pass.

```
always @(posedge i_clk)
if ((f_past_valid)
    &&($past(i_start_signal))
    &&($past(counter) == 0))
    assert(counter == 21);
```

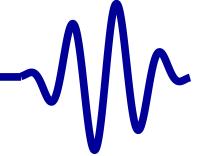
Alternatively, the following concurrent assertion would also work:

```
assert property @(posedge i_clk)
    (i_start_signal)&&(counter == 0)
        |=> (counter == 21);
```

This exercise is a good example of how formal methods force you to look just a little harder at a problem.



Quiz #8



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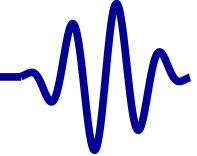
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Will this design pass a Bounded Model Check (BMC)?

```
reg [15:0] counter;  
  
initial counter = 0;  
always @ (posedge clk)  
    counter <= counter + 1'b1;  
  
always @ (*)  
    assert(counter < 16'd65000);
```

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Will this design pass a Bounded Model Check (BMC)?

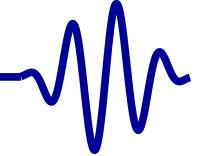
```
reg [15:0] counter;  
  
initial counter = 0;  
always @ (posedge clk)  
    counter <= counter + 1'b1;  
  
always @ (*)  
    assert(counter < 16'd65000);
```

Not unless you prove it with a depth of over 65,000!

This is a classic example of a proof that is easier to do with induction. Less than five steps of induction would find this problem.



Quiz #9



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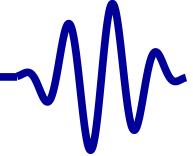
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Will the following design pass formal verification?

```
reg [15:0] counter;  
  
always @(*)  
begin  
    counter = 2;  
    assert(counter == 5);  
    counter = counter + 3;  
end
```

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Will the following design pass formal verification?

```
always @(*)  
begin  
    counter = 2;  
    assert(counter == 5);  
    counter = counter + 3;  
end
```

No, it will not pass.

- counter = 2 is a blocking statement. It is completed before the **assert()**.
- counter==2 when the **assert** is applied
- Only after the **assert** is counter set to 5.
- Were the **assert** the last line of the block, it would've passed
- This is one reason why I separate my assertions from my logic



Quiz #10



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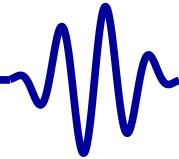
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Goal: to prove that whenever a request is being made, the request will stay stable until it is accepted.

Will this assertion capture what we want?

```
if (( $past( o_REQUEST ))&&( $past( i_STALL )))  
begin  
    assert( o_REQUEST );  
    assert( $stable( o_REQUEST_DETAILS ));  
end
```

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Not quite, there's a couple of things missing

Two examples would be `i_reset` and `f_past_valid`

Here's an updated assertion that should fix those lacks

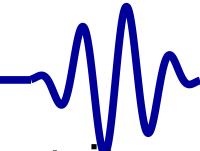
```
if ((f_past_valid)&&(!$past(i_reset))  
    &&($past(o_REQUEST))&&($past(i_STALL)))  
begin  
    assert(o_REQUEST);  
    assert($stable(o_REQUEST_DETAILS));  
end
```

Alternatively, we could have written,

```
assert property @ (posedge i_clk)  
    disable iff (i_reset)  
    (o_REQUEST)&&(i_STALL)  
    |=> (o_REQUEST)  
        &&($stable(o_REQUEST_DETAILS));
```



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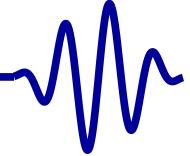
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The following design fails induction. How would you adjust it so that it would pass?

```
reg [15:0] sa = 0, sb = 0;  
  
always @ (posedge i_clk)  
if (i_ce)  
begin  
    sa <= { sa[14:0], i_bit };  
    sb <= { i_bit, sb[15:1] };  
end  
  
always @ (*)  
    assert (sa[15] == sb[0]);
```

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There are many solutions to this problem

1. Use a non-smtbmc engine, such as abc pdr
2. Force i_ce

```
always @(posedge i_clk)
if (! $past(i_ce))
    assume(i_ce);
```

3. Assert all bits

```
always @(*)
begin
    assert(sa[14] == sb[1]);
    assert(sa[13] == sb[2]);
    assert(sa[12] == sb[3]);
    assert(sa[11] == sb[4]);
    // ... through all combinations
```

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The logic below is designed to ensure that the design will only acknowledge requests and nothing more: one acknowledgment per request. It almost works. Can you spot any problem(s)?

```
initial f_nreqs = 0;
always @(posedge i_clk)
  if ((i_reset)||(!i_wb_cyc))
    f_nreqs <= 1'b0;
  else if ((i_wb_stb)&&(!o_wb_stall))
    f_nreqs <= f_nreqs + 1'b1;
  // f_nack is a similarly defined counter,
  // only one that counts acknowledgments
  always @(*)
    if (f_nreqs == f_nacks)
      assert (!o_wb_ack);
```

Assume a sufficient number of bits in f_nreqs and f_nacks.

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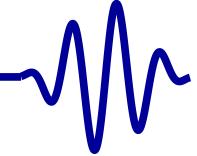
No, it will not pass. The problem is that it may be possible to ACK a request on the same clock it is received. The following updated assertion will fix this.

```
always @(*)
if ((f_nreqs == f_nacks)
    &&((!i_wb_stb)||(o_wb_stall)))
    assert (!o_wb_ack);
```

Originally, I disallowed ACK's on the same clock as the STB. Then I tried formally verifying someone else's design. When it didn't pass, I went back and re-read the WB-spec only to discover the error in my ways.



Quiz #13



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Given that X is defined somehow, which of the following assertions will fail?

```
always @(posedge i_clk)
if (f_past_valid)
begin
    assert ($stable(X)
            == (X == $past(X)));
    assert ($changed(X)
            == (X != $past(X)));
    assert ($rose(X)
            == ((X)&&(!$past(X))));
    assert ($fell(X)
            == ((!X)&&($past(X))));

end
```

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Two of these assertions will fail if x is wider than one bit

```
assert($rose(x) == ((x)&&(!$past(x))));  
assert($fell(x) == ((!x)&&($past(x))));
```

From the 2012 SystemVerilog standard,

- `$rose` returns true if the LSB of the expression changed to 1. Otherwise, it returns false.
- `$fell` returns true if the LSB of the expression changed to 0. Otherwise, it returns false.
- `$stable` returns true if the value of the expression did not change. Otherwise, it returns false.
- `$changed` returns true if the value of the expression changed. Otherwise, it returns false.

These updated assertions will succeed,

```
assert($rose(x) == ((x[0])&&(!$past(x[0]))));  
assert($fell(x) == ((!x[0])&&($past(x[0]))));
```



Quiz #14



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The following logic creates two clocks with nearly identical frequencies. Can you spot any missing assumptions?

```
(* gclk *) reg gbl_clk;
(* anyconst *) reg [7:0] f_step_one, f_step_two;
always @(*)
if (f_step_one > f_step_two)
    assume(f_step_one - f_step_two < 8'h2);
else
    assume(f_step_two - f_step_one < 8'h2);
always @(posedge gbl_clk) begin
    f_counter_one <= f_counter_one + f_step_one;
    f_counter_two <= f_counter_two + f_step_two;
//
assume(i_clk_one == f_counter_one[7]);
assume(i_clk_two == f_counter_two[7]);
end
```

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The step sizes cannot ever be zero, and steps greater than $8'h80$ will alias.

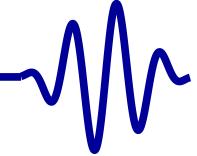
```
always @(*)
begin
    assume(f_step_one != 0);
    assume(f_step_two != 0);
    assume(f_step_one <= 8'h80);
    assume(f_step_two <= 8'h80);
end
```

For performance reasons, you may choose to assume the speed of the fastest clock.

```
always @(*)
    assume((f_step_one == 8'h80)
        ||( f_step_two == 8'h80));
```



Quiz #15



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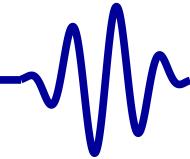
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Will the following assertion pass?

```
always @(posedge i_clk)
begin
    if (i_write)
        mem[i_waddr] <= i_data;
    if (i_read)
        o_data <= mem[i_raddr];
end

always @(posedge i_clk)
if ((f_past_valid)
    &&($past(i_write))&&($past(i_read))
    &&($past(i_waddr)==$past(i_raddr)))
    assert(o_data == $past(i_data));
```

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Will the following assertion pass?

```
always @(posedge i_clk)
begin
    if (i_write)
        mem[i_waddr] <= i_data;
    if (i_read)
        o_data <= mem[i_raddr];
end

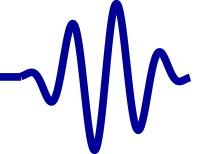
always @(posedge i_clk)
if ((f_past_valid)
    &&($past(i_write))&&($past(i_read))
    &&($past(i_waddr)==$past(i_raddr)))
    assert(o_data == $past(i_data));
```

No.

How would you describe a write-through block RAM?



Quiz #16



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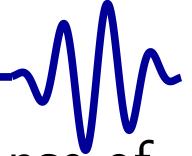
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The formal property below was written for the case of a synchronous reset. How would you adjust it so that it accurately reflects the behavior of the flip-flop under an asynchronous reset?

```
always @(posedge i_clk, negedge i_areset_n)
  if (!i_areset_n)
    a <= 0;
  else
    a <= something;

always @(posedge i_clk)
  if ((f_past_valid)&&($past(i_areset_n))
    assert(a == $past(something));
```

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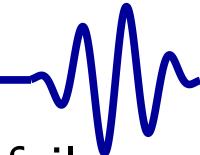
The following assertion can be used to describe the response of logic to a negative logic asynchronous reset.

```
always @(posedge i_clk, negedge i_areset_n)
  if (!i_areset_n)
    a <= 0;
  else
    a <= something;

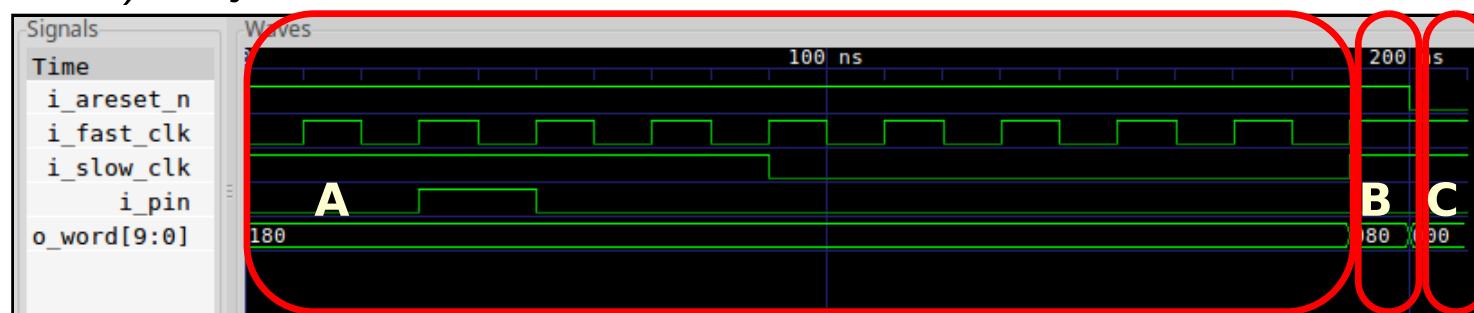
always @(posedge i_clk)
  if (!i_areset_n)
    assert(a == 0);
  else if ((f_past_valid)&&($past(i_areset_n))
    assert(a == $past(something));
```

Don't forget to assume an initial reset!

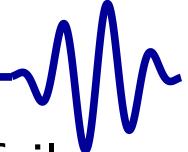
```
initial assume(!i_areset_n);
```

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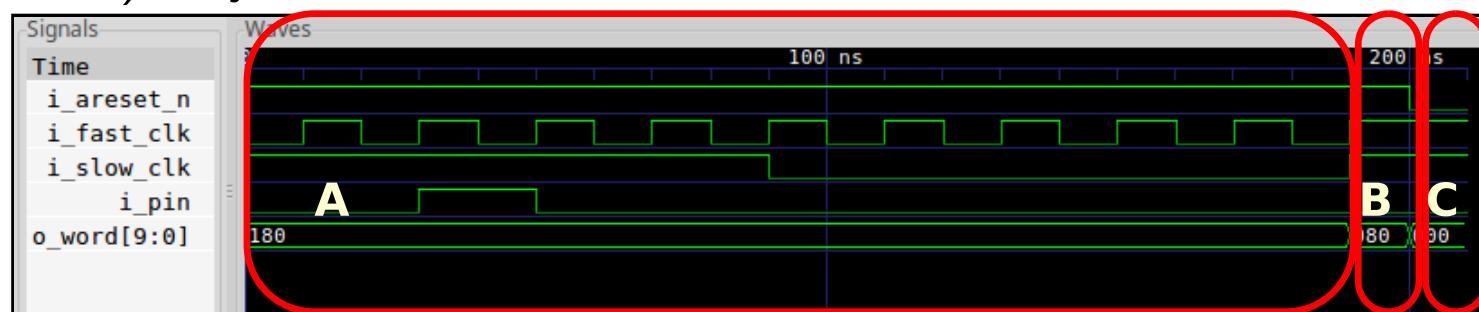
Your design passes a bounded model check (BMC), but fails during induction. Upon inspection, you find a failure in section A (below) of your trace.



How should you address this problem?

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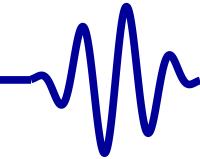
Your design passes a bounded model check (BMC), but fails during induction. Upon inspection, you find a failure in section A (below) of your trace.



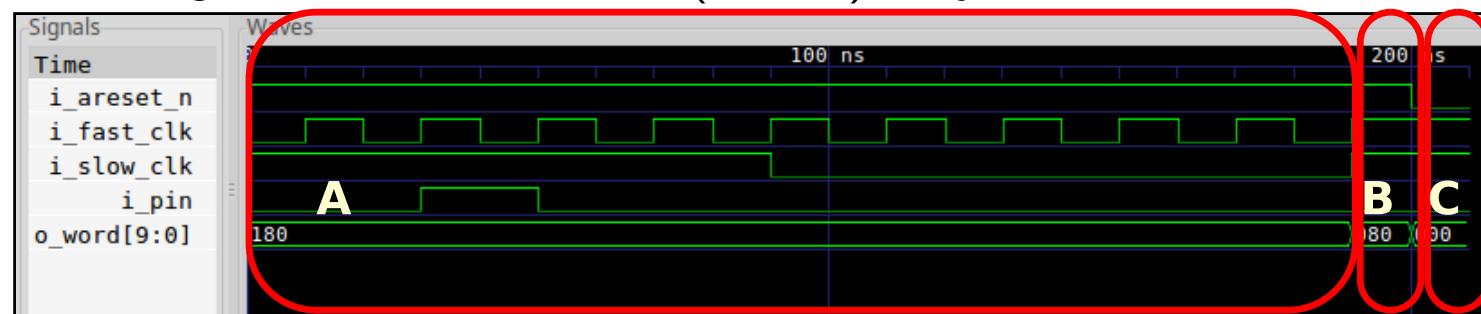
How should you address this problem?

This is not a problem with your logic. Rather, the formal properties that are constraining your logic are insufficient

- You need more properties to keep the design from failing
- If an input is out of bounds, **assume** it will be within bounds
- If your design starts in an invalid state, **assert** such invalid states will never happen
- **initial** statements will not help during induction

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Your design fails in section C (below) of your trace.



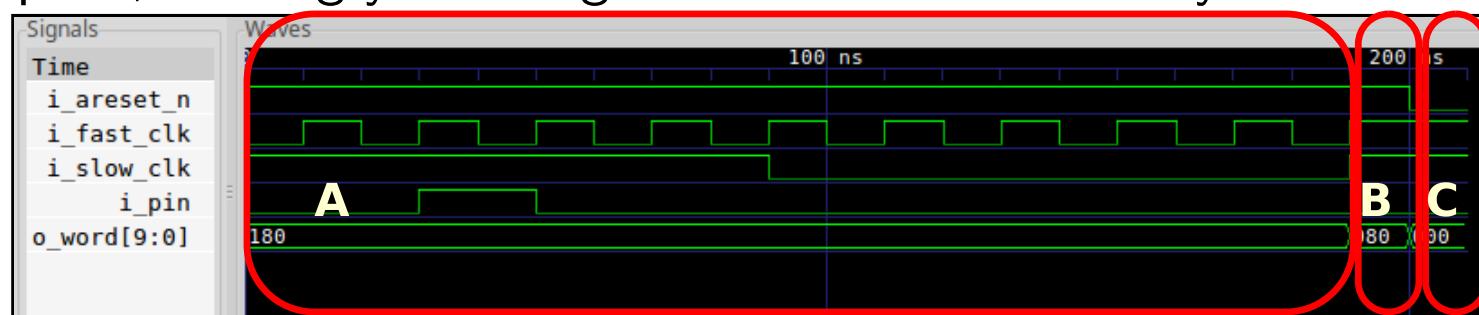
Upon inspection, you discover an

always @(posedge i_clk) assume(x); property is not getting applied.

How would you fix this situation?

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An **always @(posedge i_clk) assume(X);** property is not getting applied, causing your design to fail in section C of your trace



The problem is that **always @(posedge i_clk)** properties are not applied until the the next clock edge (i.e. section B of the trace)

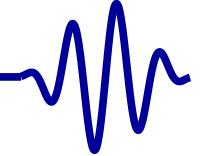
- This can cause an **always @(*) assert(Y);** to fail in section C

How would you fix this situation?

- You can make the **always @(*)** property a clocked property
- You can evaluate the **always @(posedge i_clk)** assumption as an **always @(*)** assumption instead
 - You might need to create your own **\$past** value to do this



Quiz #19



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Will the following design pass formal verification?

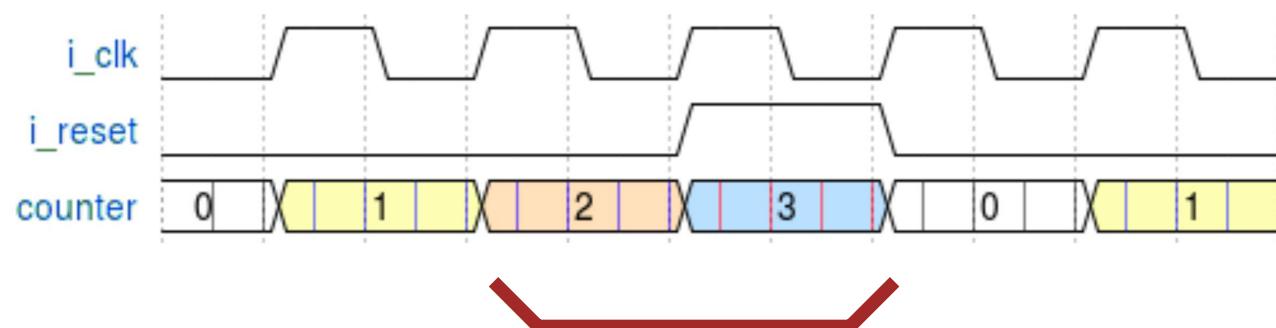
```
reg [15:0] counter = 0;
always @ (posedge i_clk)
if (i_reset)
    counter <= 0;
else
    counter <= counter + 1;

always @ (*)
if (counter > 2)
    assume(i_reset);

assert property (@(posedge i_clk)
    disable iff (i_reset)
    (counter < 2));
```

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Much to my own surprise, this design will *pass* a formal check.



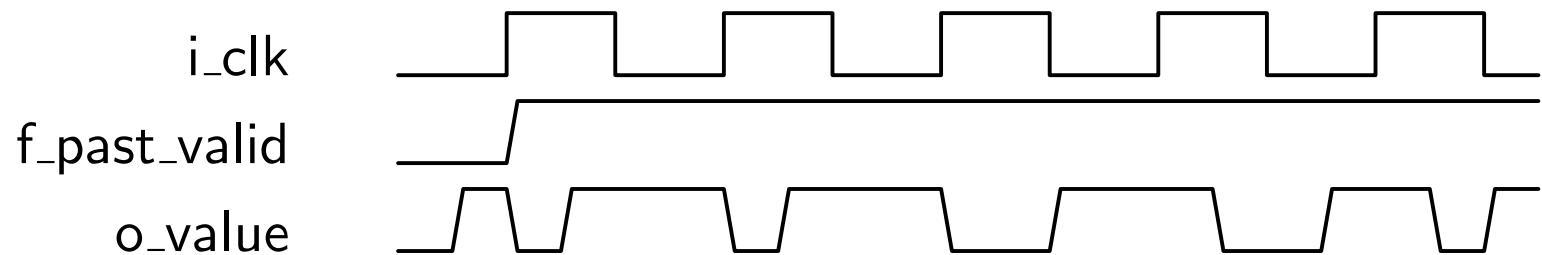
disable iff (*i_reset*) disables the check across both of these cycles

This is roughly equivalent to:

```
reg      check = 1;
always @(*posedge i_clk)
    check <= (counter < 2)||(i_reset);
always @(*)
    if (!i_reset) assert(check);
```

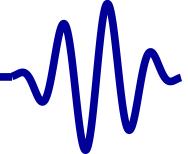
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Consider the following trace from an asynchronous context:

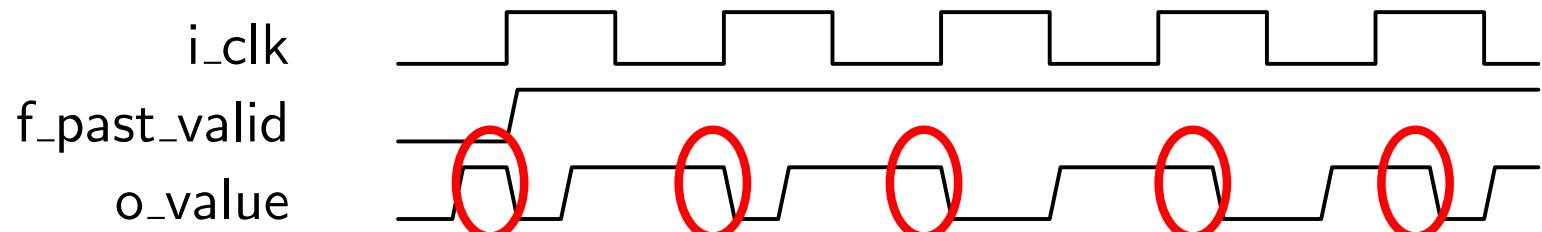


Will this formal stability assertion pass or fail?

```
always @(posedge i_clk)
  if (f_past_valid)
    assert($stable(o_value));
```

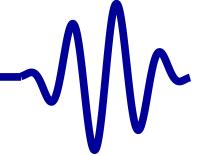
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Yes, this stability assertion will hold.



- Note that everytime **\$rose(i_clk)** is true, **\$past(o_value)** is also true.
- Since the check is only accomplished on the positive edge of **i_clk**, **o_value** is *only* checked at this time.
- Since **\$past(o_value)** is always true just prior to **@(posedge i_clk)**, the assertion passes

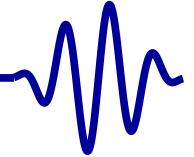
```
always @(posedge i_clk)
if (f_past_valid)
    assert ($stable(o_value));
```

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Your design contains the following generate block:

```
parameter [0:0] A = 1;
parameter [0:0] B = 1;
// ...
generate if (A)
begin : A_BLOCK
    // Some logic
end else if (B)
begin : B_BLOCK
    // Some other logic
end else begin : ELSE_BLOCK
    // Some final set of logic
end endgenerate
```

How should this impact the design of your SymbiYosys configuration file?

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How should conditional generate blocks be handled?

- By creating a separate task for each parameter set
- Each set of parameters can then be verified independently

[**tasks**]

A

B

Other

[**script**]

read –formal toplvl.v

—pycode—begin—

cmd=" hierarchy --top_toplvl "

cmd+=" -chparam_A %d " % (1 if "A" in tags else 0)

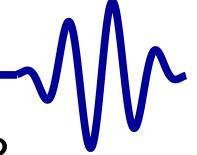
cmd+=" -chparam_B %d " % (1 if "B" in tags else 0)

output(cmd)

—pycode—end—

prep –top toplvl

GT Quiz #22



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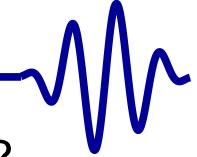
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When working with **cover()**, how do you handle a failure?

- On a **cover()** success a trace is generated.
No trace is generated on a **cover()** failure.
- At first glance, you have nothing to go with

How do you debug your design in this situation?

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When working with **cover()**, how do you handle a failure?

- Suppose your design needs to accomplish a sequence of steps, and then cover the last one.

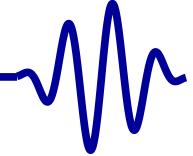
```
always @(*)  
    cover(step_24);
```

- How shall you debug this failure?

Solution: cover the intermediate steps

```
always @(*)  
begin  
    cover(step_01);  
    // ...  
    cover(step_23);  
end
```

This will lead you to the failing clock cycle

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Consider the following design:

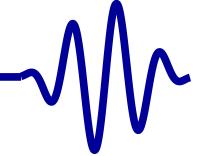
```
input wire [31:0] i_v;
output wire o_v;

assign o_v = (i_v == 32'hdeadbeef);

always @(*)
    assert(i_v != 32'hdeadbeef);

always @(*)
    assume (!o_v);
```

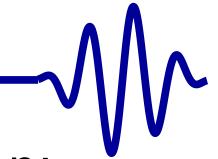
Given that the solver can pick any value for `i_v`, will the assertion ever fail?

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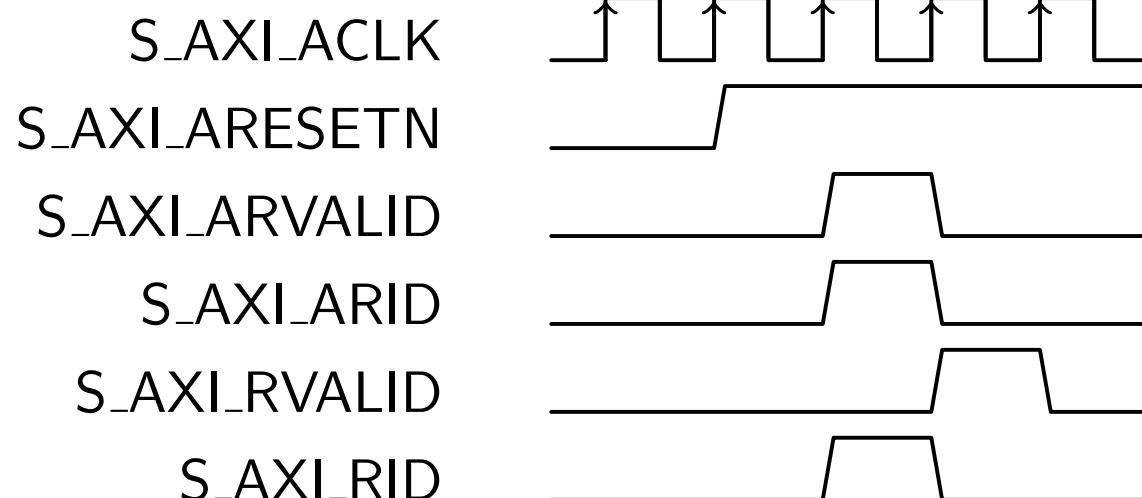
Consider the following design:

```
assign o_v = (i_v == 32'hdeadbeef);
always @(*)
    assert(i_v != 32'hdeadbeef);
always @(*)
    assume (!o_v);
```

- The assumption is forced to be true before evaluating any assertions
- $\neg o_v$ will only ever be true if $i_v \neq 32'hdeadbeef$
- Therefore, the solver will never even consider the case where $i_v == 32'hdeadbeef$
- The assertion can *never* fail

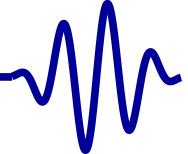
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Consider the following trace from an AXI read interaction:

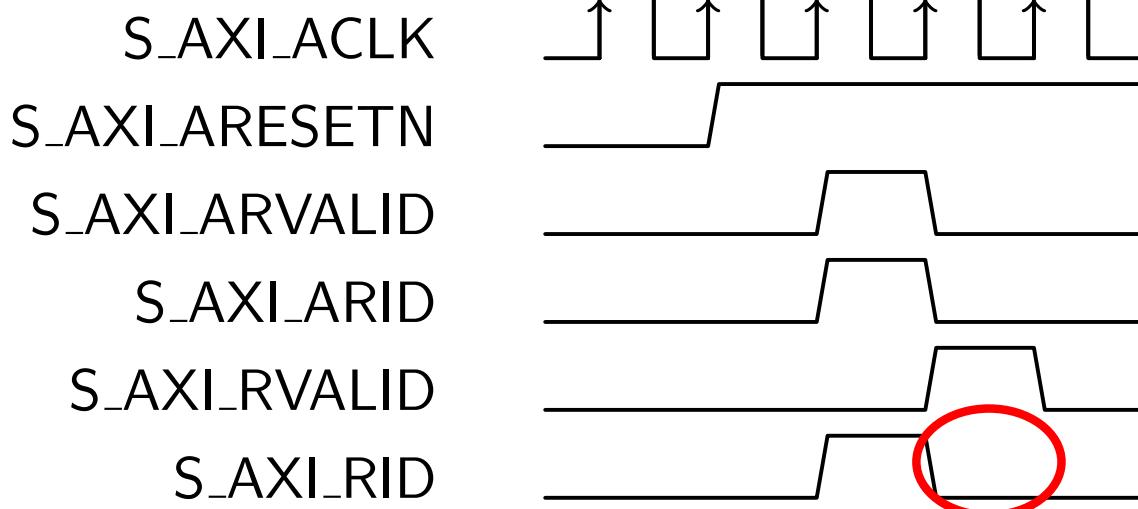


- Assume all of the relevant xREADY lines are high

Can you spot the bug?

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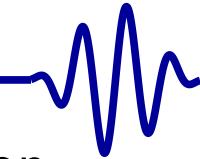
Can you spot the bug?



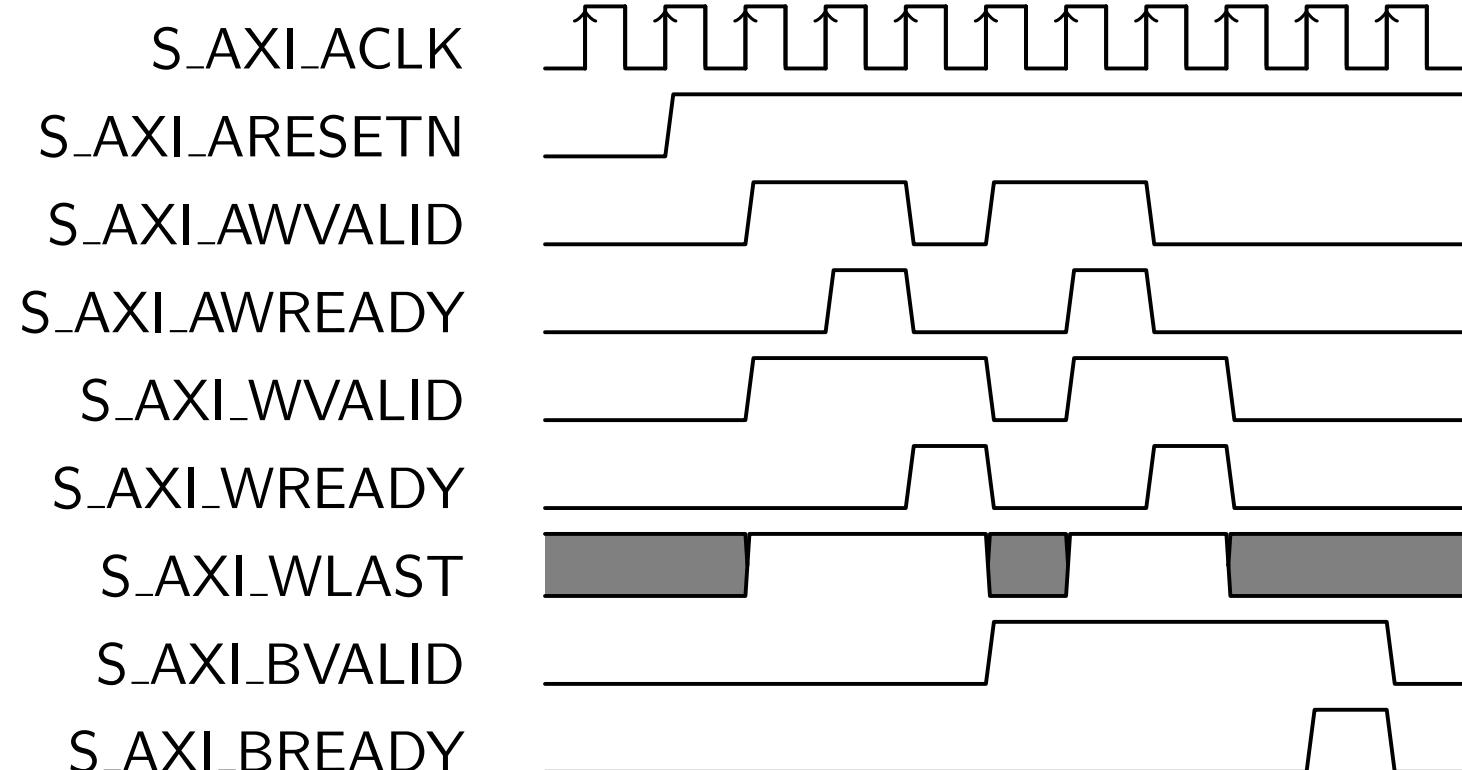
The request response has the wrong ID

- Request was made for ID=1, response has ID=0
- The cause? Xilinx's example core doesn't register the ID

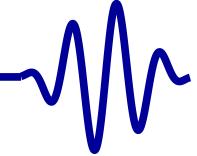
The trace above was found by applying the Symbiotic EDA Suite to Xilinx's example AXI4 core

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Consider the following trace from an AXI write interaction, ending in a steady state



What sort of formal property would catch this bug?

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A transaction timeout can find this bug

```
always @(posedge i_clk)
if ((!i_axi_reset_n)||(!i_axi_awvalid)
    ||(i_axi_awready)
    ||(f_axi_wr_pending > 0))
    f_axi_awstall <= 0;
else if ((!i_axi_bvalid)||(i_axi_bready))
    f_axi_awstall <= f_axi_awstall + 1'b1;

always @(*)
    assert(f_axi_awstall < F_AXI_MAXWAIT);
```

where `f_axi_wr_pending` is a reference to the number of remaining write data transactions in this burst

The bug in this question was found by applying the Symbiotic EDA Suite to Xilinx's example AXI4 core

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Oops, the last timeout logic captured when the incoming write address channel was *stalled*, not the *delay* on the write response channel.

- Here's the timeout logic that actually found this bug.

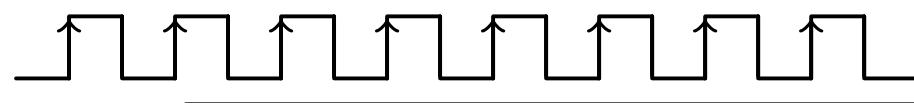
```
always @ (posedge i_clk)
if ((!i_reset_n) || (i_bvalid) || (i_wvalid)
    || ((f_awr_nbursts == 1)
        && (f_wr_pending > 0))
    || (f_awr_nbursts == 0))
    f_awr_ack_delay <= 0;
else
    f_awr_ack_delay <= f_awr_ack_delay + 1'b1;

always @ (posedge i_clk)
assert (f_awr_ack_delay < F_AXI_MAXDELAY);
```

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Consider the following trace drawn from an AXI interconnect I had the opportunity to verify. It had never seen a formal check before.

S_AXI_ACLK



S_AXI_ARESETN



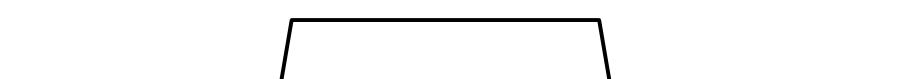
S_AXI_AWVALID



S_AXI_AWLEN



S_AXI_WVALID



S_AXI_WLAST

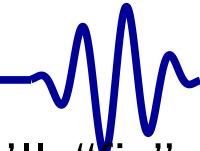


S_AXI_BVALID



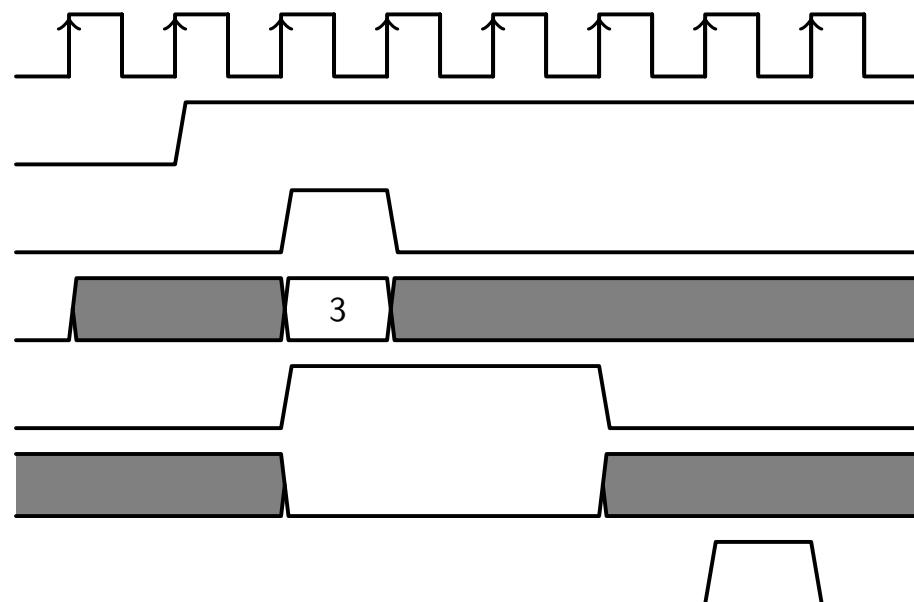
Assume all *READY signals are true

Can anyone see the bug? What formal property would catch this bug?

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Correctly identifying the bug is important, otherwise you'll "fix" the wrong "bug"

S_AXI_ACLK
S_AXI_ARESETN
S_AXI_AWVALID
S_AXI_AWLEN
S_AXI_WVALID
S_AXI_WLAST
S_AXI_BVALID



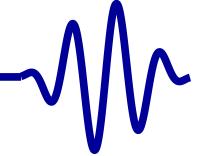
In this case, there is no missing S_AXI_WLAST signal. According to spec, the burst is S_AXI_AWLEN+1 beats long, so there's still a missing write beat. The bus master just hasn't sent the final beat yet.

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The bug? You can't return a BVALID response until the first write burst has completed.

To verify this, you need to count items remaining in the burst, I use f_wr_pending, as well as the number of bursts outstanding, something I call f_awr_nbursts. You can then check,

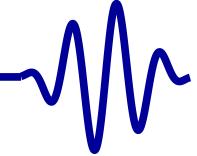
```
always @(*)
  if (f_awr_nbursts == 0)
    // If there are no bursts outstanding
    // then no BVALID can be returned
    assert(!S_AXI_BVALID);
  else if (f_awr_nbursts == 1)
    // If the write channel is still sending
    // data, then the BVALID cannot (yet) be
    // returned.
    assert((f_wr_pending == 0)
           || !S_AXI_BVALID);
```

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Can you explain why the following cover statement fails?

```
reg      read_counter;
initial read_counter = 0;
always @(*posedge i_clk)
if (i_reset)
    read_counter <= 0;
else if (some_event)
    read_counter <= read_counter + 1;

always @(*)
    cover(read_counter > 4);
```

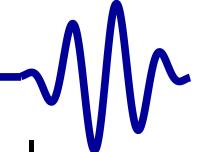
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Can you explain why the following cover statement fails?

```
reg      read_counter;
initial read_counter = 0;
always @(*posedge i_clk)
if (i_reset)
    read_counter <= 0;
else if (some_event)
    read_counter <= read_counter + 1;

always @(*)
    cover(read_counter > 4);
```

Did you notice the number of bits in the `read_counter`? At only one bit, `read_counter` can never be more than one.

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Let NM be the number of masters, and NS the number of slaves.
You want to cover a full set of write grants.

```
reg      cvr_property;
always @(*)
begin
    cvr_property = 1;
    for(iN=0; iN < (NM > NS) ? NS:NM; iN=iN+1)
        if (!write_grant[iN])
            cvr_property = 0;
end
always @(*)
    cover(cvr_property);
```

Much to my surprise, yosys ran out of memory while elaborating this design.

Can anyone see why?

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This is an order of operations issue. The example design is equivalent to

```
always @(*)
begin
    cvr_property = 1;
    for(iN=0; (iN < (NM > NS)) ? NS : NM;
        iN=iN+1)
        if (!write_grant[iN])
            cvr_property = 0;
end
```

The end condition will therefore elaborate to either NM or NS, both of which are non-zero and therefore “true”.

As for the out-of-memory error, remember this is hardware. Yosys is elaborating new hardware circuits every time through the loop, and the loop doesn't have an end.

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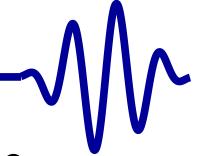
There are three steps required to verify an AXI-lite interface:

1. First, attach the [formal interface property file](#)

```
'ifdef FORMAL
    faxil_slave #(
        .C_AXI_ADDR_WIDTH(C_S_AXI_ADDR_WIDTH))
    properties (
        .i_clk(S_AXI_ACLK),
        .i_axi_reset_n(S_AXI_ARESETN),
        // ...
```

2. If using SymbiYosys, you'll also need to create [an SBY file](#)

What's the missing step that's required to formally verify an AXI-lite slave interface matches bus requirements for all time?

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3. Reference the state information from the property file,

```
'ifdef FORMAL
    faxil_slave #(/* ... */)
    properties (
        .f_axi_rd_outstanding(rd_inproc),
        // ...
    )
```

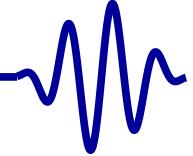
and use it to **assert()** that the state matches your logic

```
always @(*)
    assert(rd_inproc == (axi_rvalid ? 1:0)
          +(axi_already ? 0:1));
    // ...
```

The example above is from [one of my own designs](#), as this step can be very design dependent.



Quiz #30



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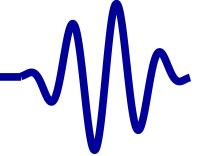
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The following illustrates a common FIFO mistake

```
always @ (posedge i_clk)
  if (i_reset)
    { rd_addr, wr_addr } <= 0;
  else if (i_rd)
    rd_addr <= rd_addr + 1;
  else if (i_wr)
    wr_addr <= wr_addr + 1;
```

Can you identify the bug, and suggest a way of fixing it?

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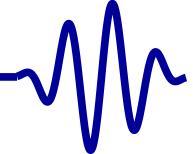
The first bug is not setting the pointers initially

```
initial {rd_addr, wr_addr } = 0;
```

The next bug is not checking for underflow or overflow

```
always @(posedge i_clk)
if (i_reset)
    { rd_addr, wr_addr } <= 0;
else if (i_rd && !o_empty)
    rd_addr <= rd_addr + 1;
else if (i_wr && !o_full)
    wr_addr <= wr_addr + 1;
```

That leaves at least one more bug

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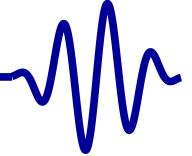
The real problem is that the whole structure is wrong.

- This really needs ot be handled in either two logic blocks, or
- Using a case statement, as shown below

```
initial {rd_addr, wr_addr } = 0;
always @(posedge i_clk)
if (i_reset)
    { rd_addr, wr_addr } <= 0;
else case({i_rd & !o_empty, i_wr && !o_full})
2'b10: rd_addr <= rd_addr + 1;
2'b01: wr_addr <= wr_addr + 1;
2'b11: begin
        rd_addr <= rd_addr + 1;
        wr_addr <= wr_addr + 1;
    end
endcase
```



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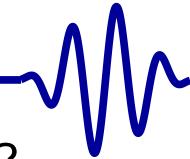
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The following proof passes.

```
reg      f_past_valid = 0;  
always @(posedge i_clk)  
    f_past_valid <= 1;  
  
always @(*)  
if (f_past_valid)  
    assume(i_reset);  
  
always @(posedge i_clk)  
    counter <= really_complex_logic;  
  
always @(*)  
if (f_past_valid && !i_reset)  
    assert(counter == counter + 1);
```

Can you spot the bug?

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Did you notice the assumption that `i_reset` is held high?

```
always @(*)
if (f_past_valid)
    assume(i_reset);
```

The assertion never got checked!

```
always @(*)
if (f_past_valid && !i_reset)
    assert(counter == counter + 1);
```

A basic cover test would find this problem

```
always @(*)
    cover(f_past_valid && !i_reset);
// or even
always @(posedge i_clk)
    cover(counter == $past(counter + 1));
```



Quiz #32



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How would you verify the o_empty and o_full properties of a FIFO, given the read and write addresses?

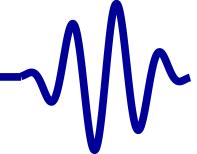
- The o_empty flag

```
assign fill = wr_addr - rd_addr;  
always @(*)  
begin  
    assert(o_empty == (fill == 0));
```

- The o_full flag, given a FIFO with FIFO_SIZE elements

```
assert(o_full == (fill >= FIFO_SIZE));  
// ...  
end
```

What property is missing?

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The missing property?

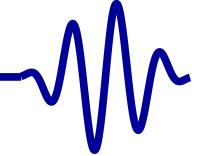
- We checked the `o_empty` flag
- We checked the `o_full` flag
- Don't forget to check that the fill never exceeds the capacity of the FIFO

```
assert(fill <= FIFO_SIZE);
```

Checking the data content of the FIFO still requires the twin write followed by twin read test. You can read more about that in [my on-line tutorial](#).



Quiz #33



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Formally verifying a cache requires three properties

First, let the solver to pick an arbitrary address and value

```
(* anyconst *) reg [AW-1:0] f_const_addr;  
(* anyconst *) reg [DW-1:0] f_const_data;
```

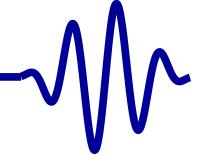
1. Then when the bus returns a value for the given address, **assume** the known value.

```
if (i_wb_ack && ackd_address == f_const_addr)  
    assume(i_wb_data == f_const_data);
```

2. Whenever the cache returns the value for the special address, **assert** that the known value is returned

```
if (o_valid && o_address == f_const_addr)  
    assert(o_value == f_const_data);
```

3. What's missing?

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Formally verifying a cache requires three properties

First, allow the solver to pick an arbitrary address, and an arbitrary data word at that address.

1. **assume** a known bus response from the given address
2. **assert** that same response from the cache when that same address is requested

The missing property?

3. Assert that, if the known address is validly within the cache, that the value associated with that address matches the solver chosen value

```
always @(*)
  if (cache_valid[f_const_addr])
    assert(cache[f_const_addr [CW - 1:0]]
          == f_const_data);
```



Quiz #34



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The following design illustrates a common AXI coding mistake:

```
always @(posedge S_AXI_ACLK)
  if (!S_AXI_ARESETN)
    // Do something
  else if (S_AXI_AWVALID && S_AXI_AWREADY
            && something_else)
    // Write logic
  else if (S_AXI_BREADY)
    // Last condition
    // ....
```

Can you identify the bug, and suggest one or two fixes?

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The following design illustrates a common AXI coding mistake:

```
always @(posedge S_AXI_ACLK)
// ...
if (S_AXI_AWVALID && S_AXI_AWREADY
    && something_else)
    // ...
```

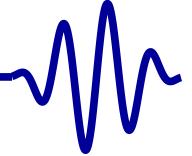
The mistake? Checking for `something_else` when processing information from the bus. To fix it,

1. Adjust the logic for `S_AXI_AWREADY`
2. Prove that every time `something_else` is false, then `S_AXI_AWREADY` is will also be false

```
assert property (@(posedge S_AXI_ACLK)
    !something_else |-> !S_AXI_AWREADY);
```



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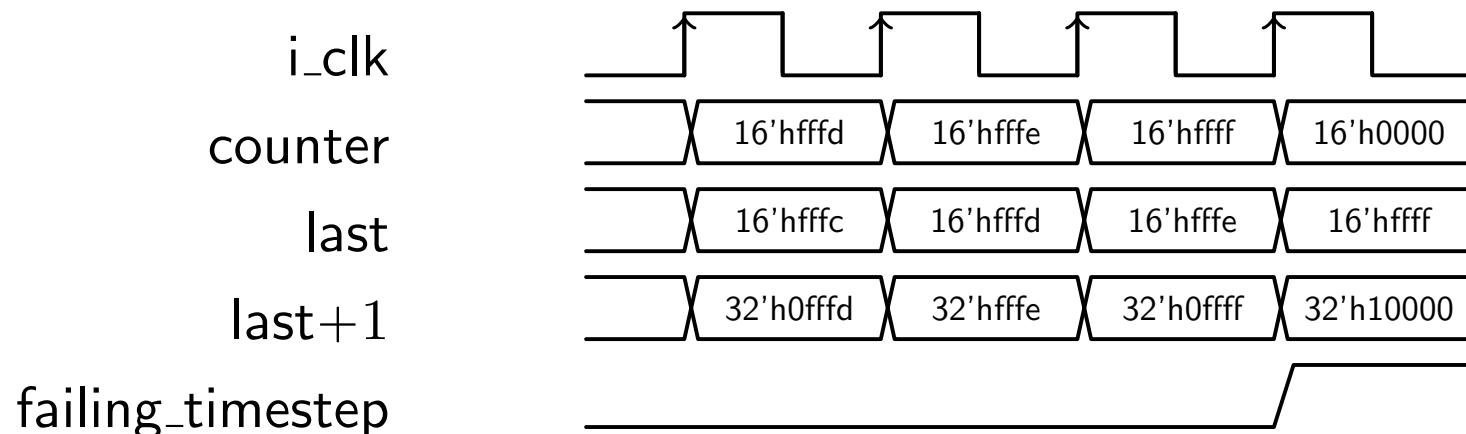
Quizzes

Will the following logic pass formal verification?

```
reg [15:0] counter, last;  
  
initial counter = 1;  
initial last = 0;  
  
always @ (posedge i_clk)  
begin  
    counter <= counter + 1;  
    last <= counter;  
end  
  
always @ (*)  
    assert(last + 1 == counter);
```

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The problem is that `last+1` is a 32-bit value, whereas `counter` is a 16-bit unsigned value. This assertion will always fail when counter rolls over.

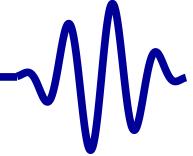


If you map `last+1` to a 16-bit value, the assertion will pass

```
wire [15:0] last_plus_one = last + 1;
always @(*)
    assert(last_plus_one == counter);
```



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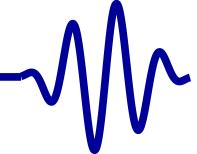
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The following design generates a warmup failure.

```
input    wire    [31:0]  i_a, i_b, i_c;  
  
always @(*)  
begin  
    assume(i_a+  i_b          == 32'h4);  
    assume(        i_b +i_c == 32'h8);  
    assume(i_a+{ i_b, 1'b0}+i_c == 32'h7);  
end
```

Which assumption is at fault?

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Which assumption is at fault?

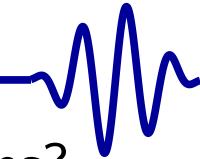
```
input    wire    [31:0]  i_a, i_b, i_c;  
  
always @(*)  
begin  
    assume(i_a+ i_b == 32'h4);  
    assume(      i_b +i_c == 32'h8);  
    assume(i_a+{ i_b, 1'b0}+i_c == 32'h7);  
end
```

Removing any one of these assumptions will resolve the warmup failure.

- This illustrates one of the fundamental problems of warmup failures: Since any one of several assumptions might cause the design to fail, there's no way for the solver to tell which assumption was truly at fault.



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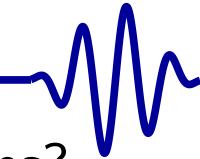
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Quizzes

What are the three most common bus interface properties?

1. Following a reset, the bus should return to an idle state and any pending requests should be dropped
2. If the bus is stalled, the request must not change
3. . . .

There's one other basic, yet common, bus interface property that's missing. What is it?

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What are the three most common bus interface properties?

1. Following a reset, the bus should return to an idle state and any pending requests should be dropped
2. If the bus is stalled, the request must not change
3. *There should be one and only one response for every bus request*

I'll ask about the "contract" property to insure that the bus actually works next week



Quiz #38



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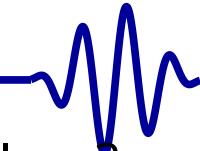
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None of the properties we examined last week truly expresses the “contract” associated with bus transactions. How should that contract be expressed for a generic bus component?

1. Let the solver pick an arbitrary address, and a value to be at that address
2. ...
3. Prove that reads from that address return the value from within the slave found at that address

What's the missing step?

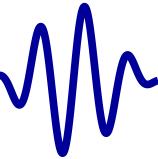
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How should the formal contract be expressed for a bus slave?

1. Let the solver pick an arbitrary address, and a value to be at that address
2. *Adjust the value at that address following any write request*
3. Prove that reads from that address return the value from within the slave found at that address

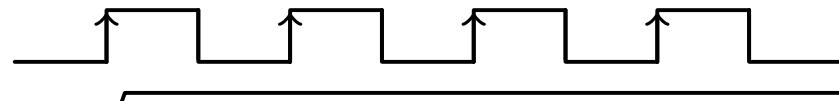
You should find these basic property steps common across many bus components

1. Not-so-generic bus slaves may need to use a slightly different approach, verifying instead that the result matches the value within the bus slave
2. Sequence is important, especially with AXI: the return value might be waiting for a RREADY longer than that return value accurately expresses the register's value within the core

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Can you spot the AXI bug below?

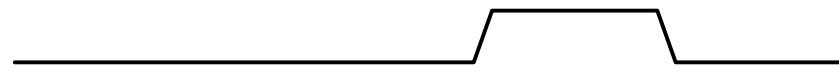
S_AXI_ACLK



S_AXI_ARESETN



S_AXI_AVALID



S_AXI_AREADY



S_AXI_AWADDR



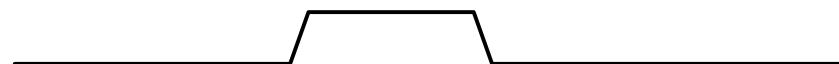
S_AXI_AWLEN



S_AXI_AWSIZE



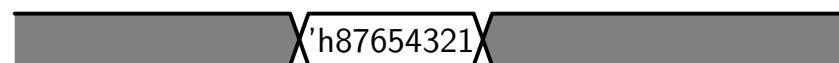
S_AXI_WVALID



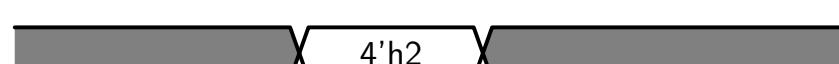
S_AXI_WREADY

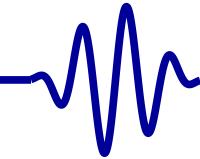


S_AXI_WDATA[31:0]



S_AXI_WSTRB[3:0]



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Take a closer look at AWADDR, AWSIZE, and WSTRB

S_AXI_ACLK



S_AXI_AWVALID



S_AXI_AWADDR



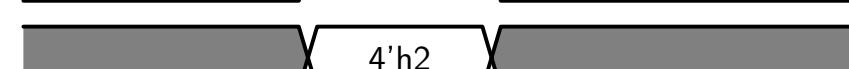
S_AXI_AWSIZE



S_AXI_WVALID



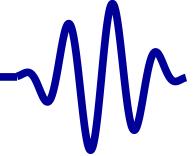
S_AXI_WSTRB[3:0]



If AWADDR ends in 4'h0, for an 8-bit transfer (AWSIZE=0),
WSTRB can only be 4'h0 or 4'h1



Quiz #40



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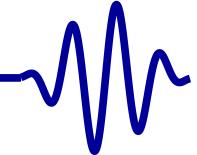
Sequences

Quizzes

Consider the design below

```
reg      A, B, C, D, E, Z;  
always @(posedge clk)  
begin  
    // Assign to A, B, C, D, E, and Z somehow  
end  
  
assert property (@(posedge clk)  
    Z |=> (A && B && C && D && E));
```

Would you consider this to be a good or a bad assertion?

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While the assertion below is *legal*,

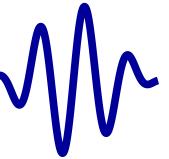
```
assert property (@(posedge clk))
    Z |=> (A && B && C && D && E);
```

because the assertion tests for the *and* of many conditions, it can be difficult to tell from a trace which condition caused the assertion failure. You might find that splitting it up makes it easier to work with.

```
assert property (@(posedge clk)) Z |=> A;
assert property (@(posedge clk)) Z |=> B;
assert property (@(posedge clk)) Z |=> C;
assert property (@(posedge clk)) Z |=> D;
assert property (@(posedge clk)) Z |=> E;
```



Quiz #41



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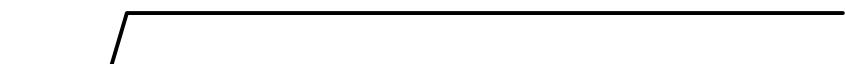
Quizzes

Can you spot the AXI bug below?

S_AXI_ACLK



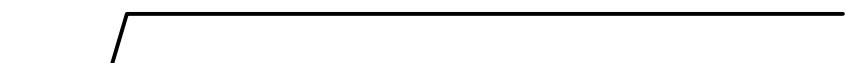
S_AXI_ARESETN



S_AXI_AWVALID



S_AXI_AWREADY



S_AXI_AWADDR



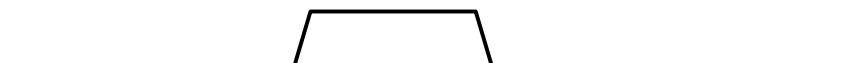
S_AXI_AWLEN



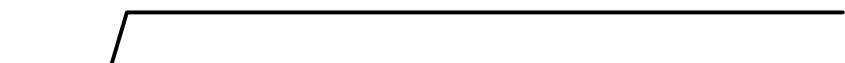
S_AXI_AWSIZE



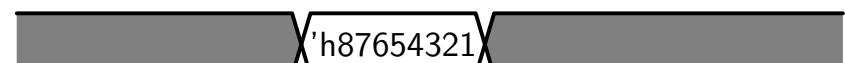
S_AXI_WVALID



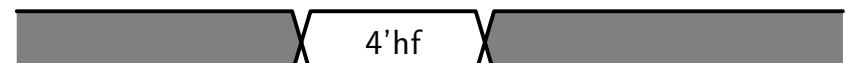
S_AXI_WREADY

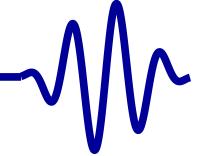


S_AXI_WDATA[31:0]



S_AXI_WSTRB[3:0]



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Can you spot the AXI bug below?

S_AXI_AWVALID



S_AXI_AWADDR



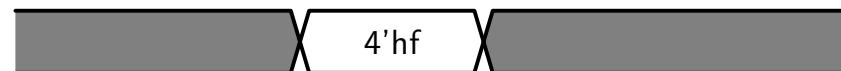
S_AXI_AWSIZE



S_AXI_WVALID



S_AXI_WSTRB[3:0]



1. If AWSIZE==1, then only two bits of WSTRB may ever be set on any given beat. These can either be 4'h3 or 4'hc for a 32-bit bus
2. If AWADDR[1:0]==2'b01, then only bit WSTRB[1] may be set

Note that AXI explicitly allows WVALID before AWVALID



Quiz #42



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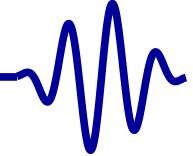
Sequences

Quizzes

Consider the design below

```
reg      A, B, C, D, Z;  
always @(posedge clk)  
begin  
    // Assign to A, B, C, D, and Z somehow  
end  
  
assert property (@(posedge clk)  
    Z |=> A  
    ##1 B [*0:$]  
    ##1 C  
    ##1 B [*0:$]  
    ##1 D);
```

Would you consider this to be a good or a bad assertion?

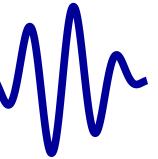
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This assertion will never pass induction

```
assert property (@(posedge clk)
                  Z |=> A ##1 B [*0:$] ##1 C
                                ##1 B [*0:$] ##1 D);
```

Why?

- Because the induction engine doesn't start at $t = 0$
 - There's no way to tell if the design is in the first B state or the second B state
- Worse, if B & C might ever hold, then the induction engine doesn't know how many times B was ever entered
 - The design might start with B true, and then set B & C for any number of clock ticks
 - The same applies to D

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Is this a valid AXI read request?

S_AXI_ACLK



S_AXI_ARVALID



S_AXI_ARREADY



S_AXI_ARADDR



S_AXI_ARLEN



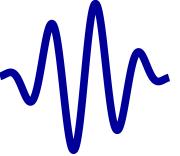
S_AXI_ARBURST



S_AXI_ARSIZE



You may assume the reset is inactive.

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Is this a valid AXI read request?

S_AXI_ACLK



S_AXI_ARVALID



S_AXI_ARREADY



S_AXI_ARADDR



S_AXI_ARLEN

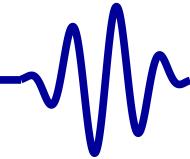


S_AXI_ARBURST



No.

- When using wrapped addressing, the burst length must be either 2, 4, 8 or 16.
AxLEN must be one less than that length
- In this case, ARLEN = 4, indicating a burst length of 5.

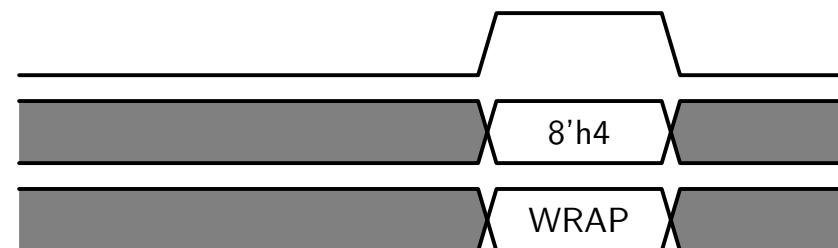
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How would you detect this problem?

S_AXI_ARVALID

S_AXI_ARLEN

S_AXI_ARBURST



The following property would capture this check

```
always @(*)
  if ((S_AXI_ARVALID)&&(S_AXI_ARBURST == WRAP))
    assert((S_AXI_ARLEN == 8'h1)
           ||(S_AXI_ARLEN == 8'h3)
           ||(S_AXI_ARLEN == 8'h7)
           ||(S_AXI_ARLEN == 8'h15));
```

Be aware: Passing induction would take a bit more work

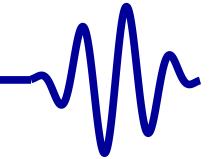
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Consider the following FIFO design that passed its testbench

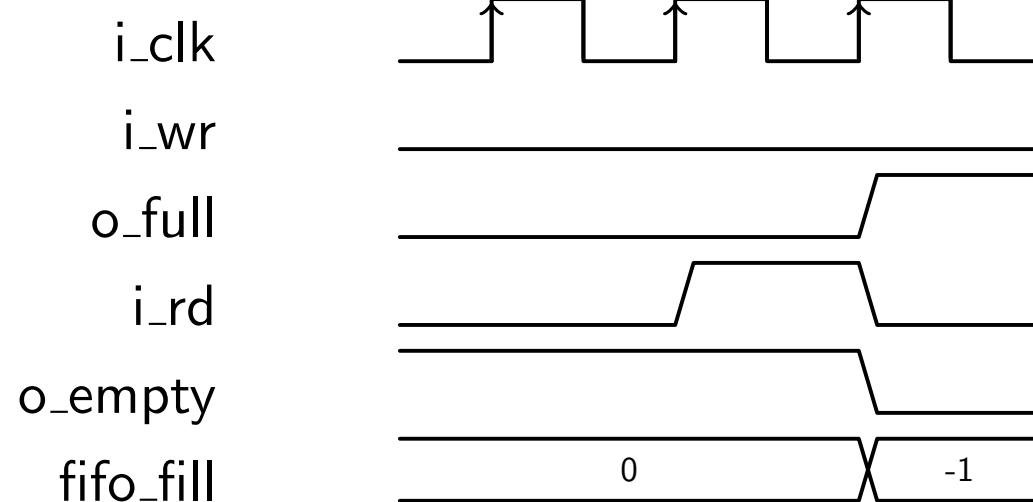
```
always @(posedge i_clk)
begin
    if (i_rd && !o_empty)
        rd_addr <= rd_addr + 1;
    if (i_wr && !o_full)
        wr_addr <= wr_addr + 1;
end

always @(posedge i_clk)
if (i_rd && !i_wr)
    fifo_fill <= fifo_fill - 1;
else if (i_wr && !i_rd)
    fifo_fill <= fifo_fill + 1;
```

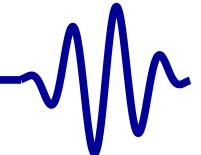
Ignoring the missing reset and initial states, and assuming o_empty and o_full are suitably defined, do you see any bugs?

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Bugs in the FIFO? What about the following sequence?



Did you see any others? (There were more ...)

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What formal properties might have found these bugs?

```
reg [LGFIFO:0] f_fifo_fill;  
  
always @(*)  
    f_fifo_fill = wr_addr - rd_addr;  
always @(*)  
    assert(f_fifo_fill == fifo_fill);
```

This one assertion would've caught these bugs. You could easily pivot from here and catch any o_empty or o_full errors as well,

```
always @(*)  
    assert(o_empty == (f_fifo_fill == 0));  
always @(*)  
    assert(o_full ==  
        (f_fifo_fill == (1<<LGFIFO))));
```

But this goes beyond what was in the quiz question.

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What addresses and in what order is this request asking for?

S_AXI_ACLK

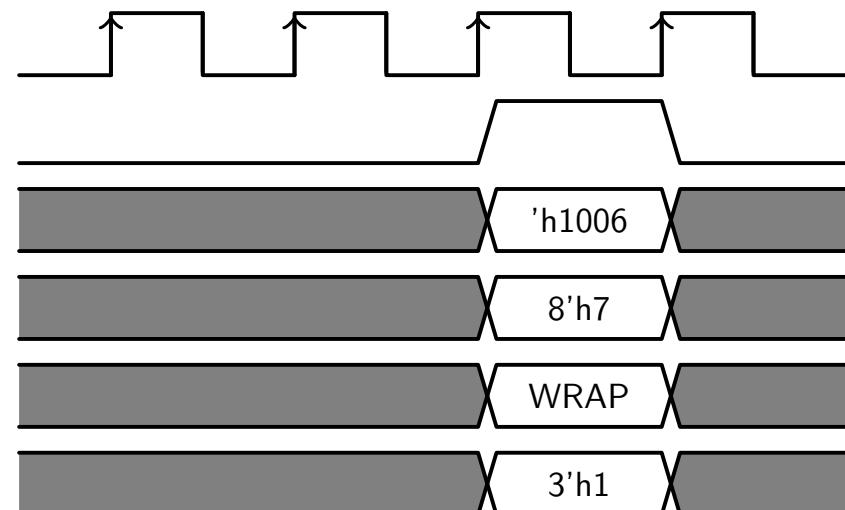
S_AXI_ARVALID

S_AXI_ARADDR

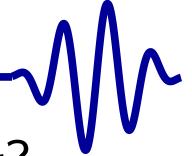
S_AXI_ARLEN

S_AXI_ARBURST

S_AXI_ARSIZE



Assume a 32'bit bus width

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What address and in what order is this request asking for?

S_AXI_ACLK

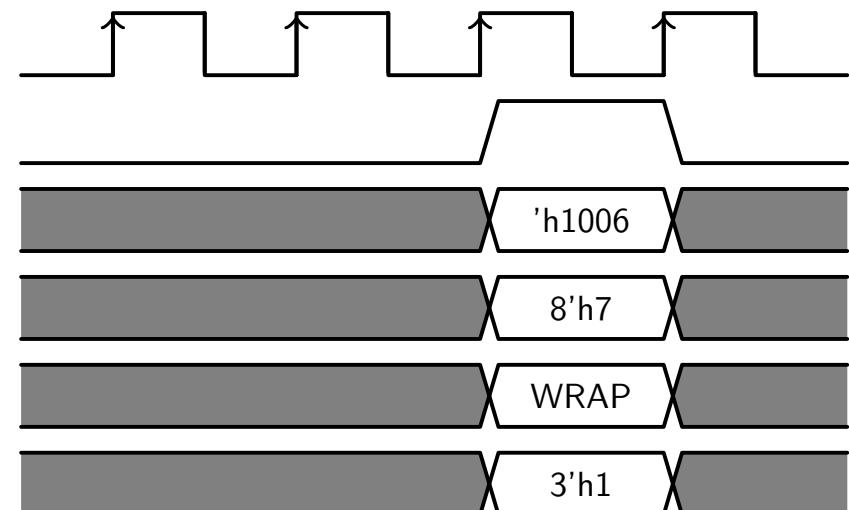
S_AXI_ARVALID

S_AXI_ARADDR

S_AXI_ARLEN

S_AXI_ARBURST

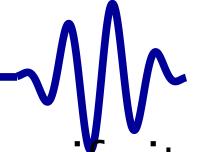
S_AXI_ARSIZE



The addresses read and returned will be 1006h, 1008h, 100Ah, 100Ch, 100Eh, 1000h, 1002h, 1004h in that order



Quiz #46



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You've just built a new peripheral. You'd like to formally verify it.
What properties would you start with?

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This is a very open ended question, so there are many answers to this question.

Here are some of my own:

1. Start with any bus interface formal property files
This will immediately include a set of assumptions and assertions, which will then validate your bus interface
2. Consider assuming an initial reset
3. **cover()** the end of every type of bus request you expect to respond to
Don't forget to **cover()** the design returning back to idle!
4. Create sequences (SVA or poor man's) describing the actions associated with each operation you expect to perform, and ending with the bus response
Don't forget the return to idle!

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There are three basic methods to include formal properties into a design

1. Placing the formal properties within the design itself

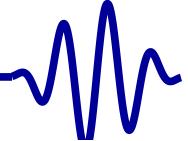
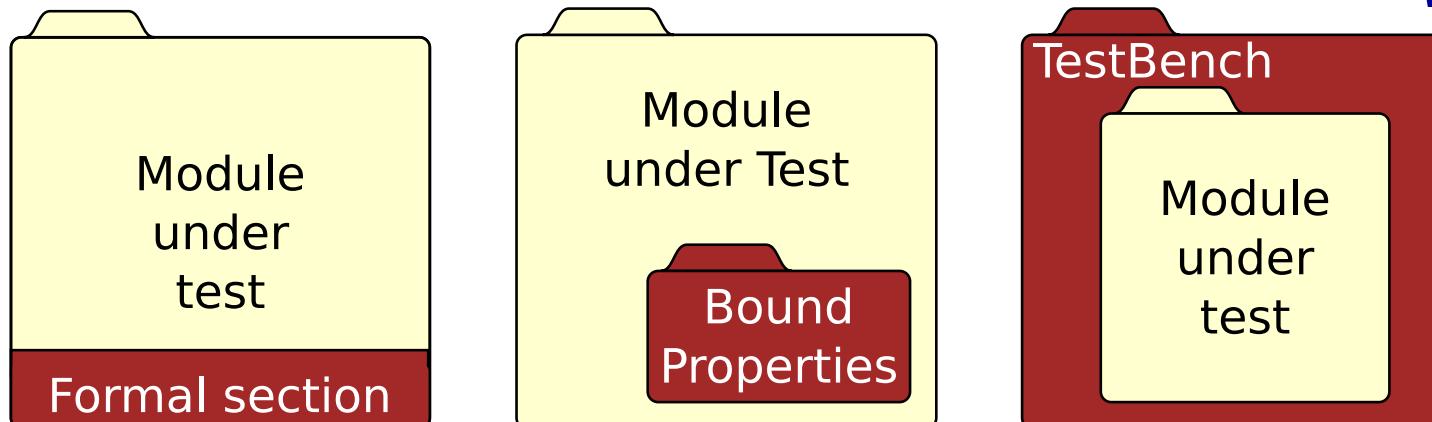
```
module modulename(* ... *);  
    // Design logic  
    #ifdef FORMAL  
        // Properties  
    #endif // FORMAL  
endmodule
```

This works nicely with the open version of SymbiYosys.

2. Binding the properties from one file into the logic of another

```
bind designmodule propertymodule instance (*.);
```

Can anyone think of a third method?

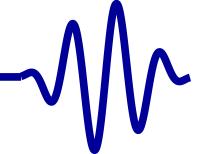
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A third method of adding properties into a design is to wrap the design with the properties like you would with a test bench.

- Without access to internal state values, passing induction can be a challenge
Remember, induction is a form of *white-box* verification
- State registers within the design may still be referenced using dot notation
Dot notation support is currently only available when using commercial formal tools, such as the SymbioticEDA Suite



Quiz #48



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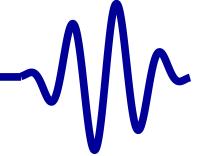
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You are trying to verify a CPU.

- How would you go about verifying that your *instruction fetch* works?
- What formal properties would be appropriate to describe the “contract” between the instruction fetch and the CPU?

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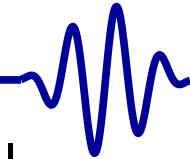
1. Include a formal bus property file, to verify the bus interaction
2. Pick an address in memory, pick a piece of data at that address, decide if the address will return a bus error or not

```
(* anyconst *) reg [AW-1:0] f_fetch_addr;  
(* anyconst *) reg [DW-1:0] f_fetch_data;  
(* anyconst *) reg f_fetch_err;
```

3. **assume()** on the bus interface ...
 - That any request for f_fetch_addr returns f_fetch_data
 - That it also returns a bus error if and only if f_fetch_err
4. **assert()** within your CPU, that any time the instruction address matches f_fetch_addr
 - That the instruction matches f_fetch_data
 - That an error condition exists if f_fetch_err is ever true



Quiz #49



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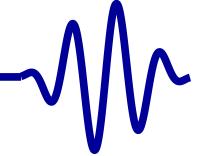
Sequences

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The following design is used to read from either a control register, or sequential elements from a block RAM.

```
always @(posedge i_clk) begin
    if (i_wb_stb && i_wb_we
        i_wb_addr == CONTROL)
        addr <= 0;
    else if (i_wb_stb && !i_wb_we
        && i_wb_addr == DATA)
        addr <= addr + 1;
    memv <= mem[addr];
    case(i_wb_addr)
        CONTROL: o_wb_data <= control_reg;
        DATA:     o_wb_data <= memv;
    endcase
    o_wb_ack <= i_wb_stb; // ...
```

See the bug?

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Did you notice the time it takes to read a value?

- Reads take two clocks: one to read the value from memory, and a second to select the value read.
- By setting `o_wb_ack` immediately after `o_wb_stb`, the memory value doesn't make it into `o_wb_data` in time.
- Delaying `o_wb_ack` by one clock would fix this.

This bug was [living in one of my cores](#) for years.

- Reading all ones or all zeros values never caught it
- Neither did slower serial port commanded reads.
- I only caught this bug recently when reading from a DMA returned elements 0, 0, 1, 2, 3, etc.

What formal properties would you recommend adding to this design in order to catch these bugs?

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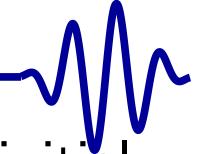
Chances are the process of formal verification would catch this

- Just putting the property together is likely to force you to think through what you want your logic to do
- ... and catch the bug

Once thought out, the following property would double-check the two clock read.

```
assert property (@(posedge i_clk)
    disable iff (i_reset || !i_wb_cyc)
    (i_wb_stb && !o_wb_stall
     && !i_wb_we && i_wb_addr == DATA )
    |=> (addr == $past(addr + 1))
    ##1 o_wb_ack
    && (o_wb_data == $past(mem[addr], 2)));
```

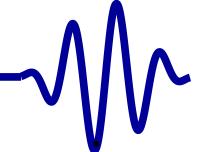
Watch out for overflow in that addition!

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The following construct works well to make certain that initial values and reset values match

```
reg      f_past_valid = 0;  
always @ (posedge i_clk)  
    f_past_valid <= 1;  
  
always @ (posedge i_clk)  
if (!f_past_valid || $past(i_reset))  
begin  
    // Check for reset properties  
    // For example ...  
    assert(counter == 0);  
end
```

How would you go about verifying the reset works on a design with no initial values or for hardware that doesn't support them?

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The key to not having any initial value support lies in assuming an initial reset

```
initial assume(i_reset);  
  
always @ (posedge i_clk)  
if (!i_reset && $past(i_reset))  
begin  
    // Check reset properties  
    // For example ...  
    assert(counter == 0);  
end
```

Bonus: How would you verify a design with an asynchronous reset?



Quiz #51



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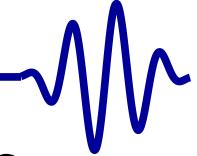
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Your design contains a FIFO. You want to assert a property of its output. How do you go about it?

```
sfifo fifo(i_clk, i_reset, i_wr, i_wval,  
          i_rd, i_rval);  
  
always @(*)  
    assert(something_about_i_rval);
```

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FIFO's are typically verified by following one or two items through the FIFO process. These special values can be used to prove the assertion below.

```
sfifo fifo(i_clk, i_reset, i_wr, i_wval,  
           i_rd, i_rval);  
  
always @(*)  
  if (rval_is_special_value)  
    assert(something_about_i_rval);  
  else // if (!rval_is_special_value)  
    assume(something_about_i_rval);  
always @(*)  
  if (special_value_in_fifo)  
  begin  
    // Assert something about the special  
    // value while it is in the FIFO
```

GT Quiz #52



You are trying to formally verify a CPU. How would you go about verifying that your load/store unit works?

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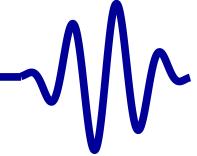
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1. Start by including the formal bus property file
2. As with the instruction fetch, let the solver pick a ...
 - Special address, `f_lsu_addr`,
 - Special data value, `f_lsu_data`, and
 - Whether the bus should return an error, `f_lsu_err`.
3. Track writes to `f_lsu_addr` using the data values
 - Any time a store instruction is issued for `f_lsu_addr`, adjust the value of `f_lsu_data`
 - Any time a write is issued over the bus for `f_lsu_addr`, **assert()** the value written is `f_lsu_data`
4. **assume()** reads from the address return `f_lsu_data`, and return errors if and only if `f_lsu_err`
5. **assert()** within your CPU, that any time `f_lsu_addr` is read, `f_lsu_data` is written to the register file



Quiz #53



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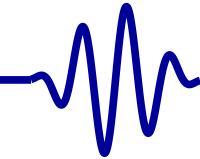
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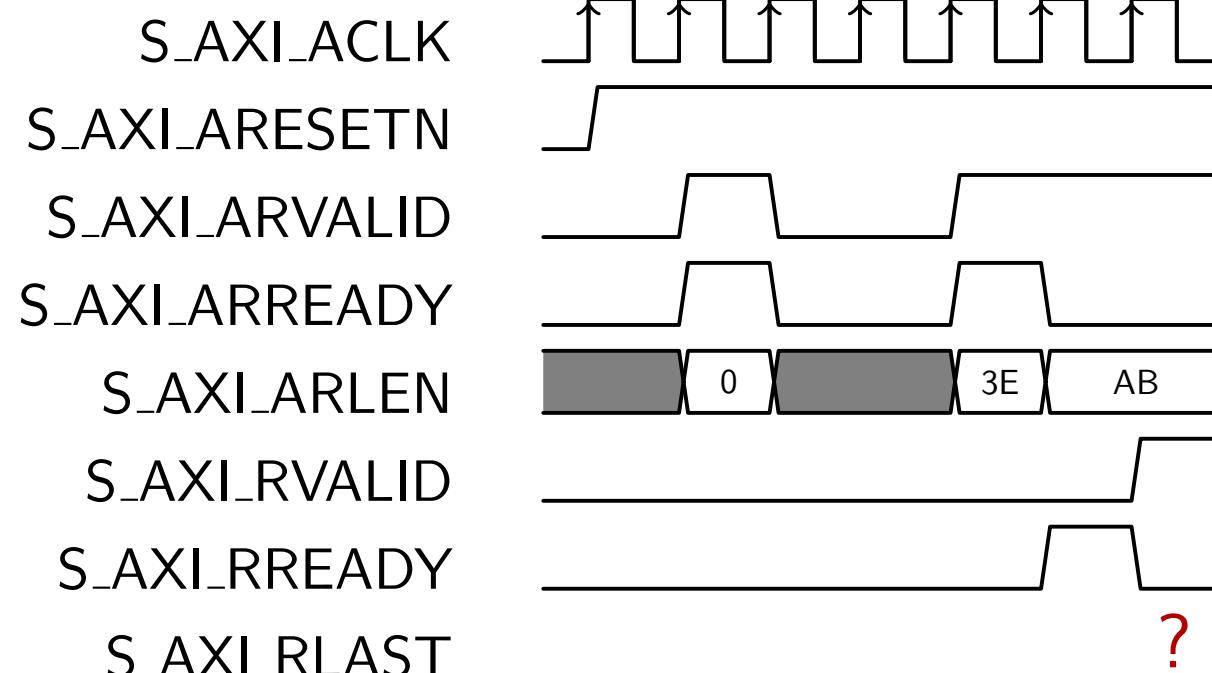
Consider the VHDL design below controlling an AXI slave:

```
AXI_READ_RLAST_P : process (S_AXI_ACLK) is
begin
    if (S_AXI_ACLK'event and S_AXI_ACLK='1') then
        if (S_AXI_ARESETN = '0') then
            S_AXI_RLAST <= '0';
        elsif S_AXI_RREADY = '1' then
            S_AXI_RLAST <= s_axi_rlast_i and rvalid;
        end if;
    end if;
end process AXI_READ_RLAST_P;
```

Can you spot any bugs in this snippet alone?

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SymbiYosys found the following trace,



This bug lived for years in a piece of commercial IP that was regularly checked by a “best in class” property checker. A first ever formal AXI property check turned it up immediately.

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The correct check would include not only S_AXI_RREADY, but also the possibility that !S_AXI_RVALID.

```
AXI_READ_RLAST_P : process (S_AXI_ACLK) is
begin
    if (S_AXI_ACLK'event and S_AXI_ACLK='1') then
        if (S_AXI_ARESETN = '0') then
            S_AXI_RLAST <= '0';
        elsif (S_AXI_RVALID = '0' -- extra check!
               or S_AXI_RREADY = '1') then
            S_AXI_RLAST <= s_axi_rlast_i and rvalid;
        end if;
    end if;
end process AXI_READ_RLAST_P;
```



Quiz #54



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You are trying to verify a CPU. How can you go about verifying that a single ALU instruction works? Let's consider an ADD instruction for this example.

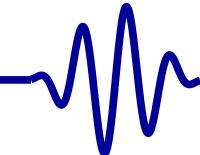
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How shall you verify an ADD instruction within a CPU?

1. Generate a packet as the ADD instruction gets processed
 - Capture the instruction word, current/next program counter, register inputs, ALU output, etc.
2. **cover()** an ADD instruction getting retired
3. When the instruction is retired, use assertions to check . . .
 - Is the output equal to the register inputs summed together?
 - Pick a register. If the input to the instruction is that register, does it match the value of the last time the register was written?
 - Is the current program counter equal to the next program counter from the previous instruction?
 - Is the next program counter the next location in memory?



Quiz #55



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You are working on a bus component, and you want to know how much throughput you can achieve per clock using that component

How might you use formal tools to solve this problem?

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cover() makes a great way of measuring best case throughput. The following formal logic will generate a trace demonstrating the maximum AXI write throughput within a design

```
reg [3:0] cvr_writes;
initial cvr_writes = 0;
always @(*posedge i_clk)
if (!S_AXI_ARESETN)
    cvr_writes <= 0;
else if (S_AXI_BVALID && S_AXI_BREADY)
    cvr_writes <= cvr_writes + 1;

always @(*)
    cover(cvr_writes > 4);
```

This logic will generate *the earliest possible* trace showing a response to five separate write requests (each w/ AWLEN=0)



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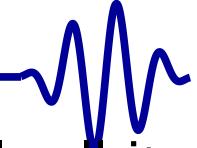
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You are working on an AXI bus slave, and you want to know how much throughput you can achieve per clock. Moreover, your core is able to handle multiple burst sizes.

How might you determine how fast your core can handle burst writes?

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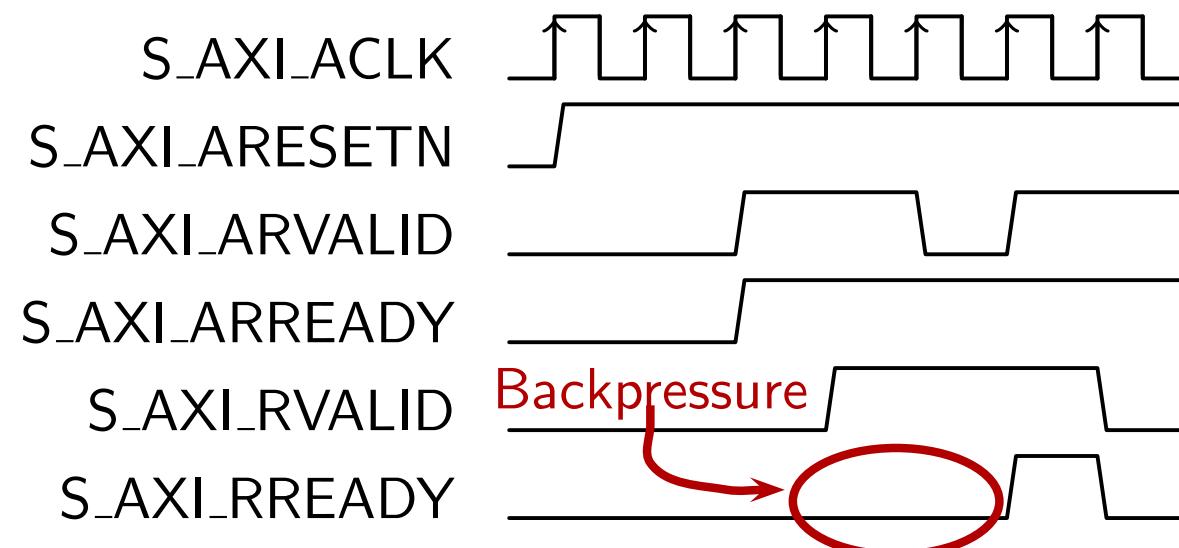
You can use **cover()** again! This time, create a flag, we'll call it `cvr_wr_bursts`, that will only be true if all write requests are of length four or greater.

```
reg                      cvr_wr_bursts = 1;  
always @(*(posedge i_clk))  
if (!S_AXI_ARESETN)  
    cvr_wr_bursts <= 1;  
else if (S_AXI_AWVALID && S_AXI_AWLEN < 3)  
    cvr_wr_bursts <= 0;  
  
// cvr_writes counts BVALID & BREADY as before  
always @(*)  
    cover(cvr_wr_bursts && cvr_writes > 2);
```

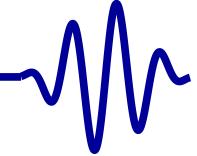
The above example will generate a trace showing a response to three separate write bursts, each with AWLEN=3.

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Many of the AXI bugs I've found have centered around the inability of a slave design to handle backpressure.



What simulation or **cover()** goals might you use to guarantee your design doesn't suffer from an inability to handle backpressure?

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A useful simulation or **cover()** goal might be to hold S_AXI_ARVALID high while holding S_AXI_RREADY low, creating a maximum forward and backpressure. You could then examine the trace to see if it looks right.

- This still requires examining the trace to know if the core handled the backpressure correctly
- A formal property checker, given a bus property file, would automatically check this setup by nature
- Such a checker would also examine the signals for you, to find exactly where a request wasn't properly given a response.

Of course, this is *only one* of the many possible simulation goals

- With simulation, you'll never know if you've done enough



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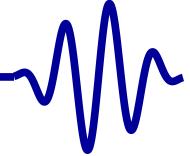
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You've built a complex state machine, and now want to verify that without a start signal the state machine will remain idle. Worse, you want to verify several other consequences of remaining idle as well.

How might you go about building such a proof using Yosys?

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Here's an approach that I've used on several projects

- First, let the solver pick whether to do this check or not

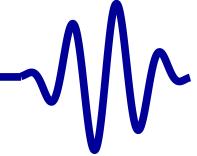
```
(* anyconst *) reg f_idle_check;
```

- Then, if set, assume no start signal

```
always @(*)
  if (f_idle_check)
    begin
      assume (!i_start_signal);
```

- Finally, assert your special case conditions

```
assert(state == IDLE);
assert(consequence_one);
// ... etc.
end
```

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You are trying to verify a hardware DMA

- A DMA is essentially a hardware memory copy
 1. It receives a source address, destination address, and copy length from the bus
 2. Then copies (length) bytes of memory from source to destination address
- Ignoring the obvious undefined behavior associated with overlap between source and destination ...

What formal properties would be appropriate to describe the “contract” that such a DMA is required to fulfill?

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What formal properties would be appropriate to describe the “contract” that a DMA is required to fulfill?

- The first step is easy: connect your bus properties to both control port and the data port.

That might just find most of your bugs, but for completeness you'll want to do one more:

- Pick a value in memory, at some offset within the source region
- **assume** this value is returned by a read of that address
- **assert** this value is written by a write to the same offset, but within the destination region
- If the solver can pick the value and offset arbitrarily, and the resulting proof passes, then the entire DMA will therefore work.



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You are trying to verify a CPU. How can you go about verifying that a multiplication instruction works?

```
always @(* posedge i_clk)
    mpy_out <= i_a * i_b;

always @(* posedge i_clk)
    case(insn_type)
        ALU_INSN: result <= alu_out;
        MPY_INSN: result <= mpy_out;
        DIV_INSN: result <= alu_out;
        LOD_INSN: result <= lsu_out; // Load/Store Insn
    endcase
```

```
always @(*) // What assertion(s) might you use?
if (insn_type == MPY_INSN)
    assert(mpy_out == ?);
```

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This issue is complicated by the fact that formally verifying the result of a multiplication tends to be beyond the capability of the state of the art of formal verification. Given that, here are some things you can do:

- Replace the output of the multiply with a (constrained) arbitrary value
 - Possible constraints include assuming the correct value in the case of multiplication by zero, one, or negative one
 - Alternatively, you might XOR'ing the inputs together with another value

Although these solutions don't check the result of the instruction, they can still catch bugs associated with the pipeline timing, forwarding, etc.

- The actual multiply result can then be checked via simulation



Quiz #61



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Just as formal tools struggle with multiplies, they also struggle with divides. Worse, many divide instructions take many clocks to complete

- How can you go about verifying a divide using either BMC or cover, but without processing all 32 (or more) steps of the divide?

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Verifying that the divide pipeline works is still valuable

- Consider using the approaches we used for a multiply to verify that the divide is properly handled by its context
- You can capture the duration of the divide using a (* `anyseq` *) “free variable.” Let this value range from only a couple of clocks in duration all the way to the correct length of the divide. This will keep things within the range of both BMC and `cover()`

Verifying that the pipeline works for all durations of the divide effectively verifies that it works for the correct duration

- You can use simulation to actually verify the *result* of the divide
- Alternatively, you can use formal to verify the *individual internal steps* of the divide

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You have a counter that is supposed to count down from some programmable value to zero. How can you assert that this counter will never be higher than the programmable value, given that the value might change mid count?

```
always @(posedge i_clk)
begin
    if (set_value) max_value <= new_value;

    if (counter == 0)
        counter <= max_value;
    else
        counter <= counter - 1;

    // This fails if the max_value ever
    // changes mid countdown!
    assert(counter <= max_value);

end
```

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Q: How can you assert that a counter will never be higher than the programmable value, given that the value might change mid count?

Answer: Capture a copy of the maximum value at the time the counter is set

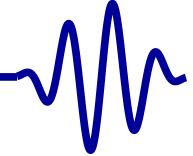
```
always @(posedge i_clk)
  if (counter == 0)
    f_max_value <= max_value;

always @(*)
  assert(counter <= f_max_value);
```

Remember: you can use Verilog to your advantage!



Quiz #63



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You have a CPU component of a larger design.

```
cpu mycpu(i_clk, i_reset,  
          bus_master_outputs, // ...  
          bus_master_inputs, // ...  
          interrupt_line); // or lines
```

Your CPU passes formal verification.

How would you go about formally verifying the rest of the design?

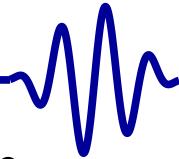
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How would you go about formally verifying the rest of the design?

Replace the CPU with a set of bus interface properties!

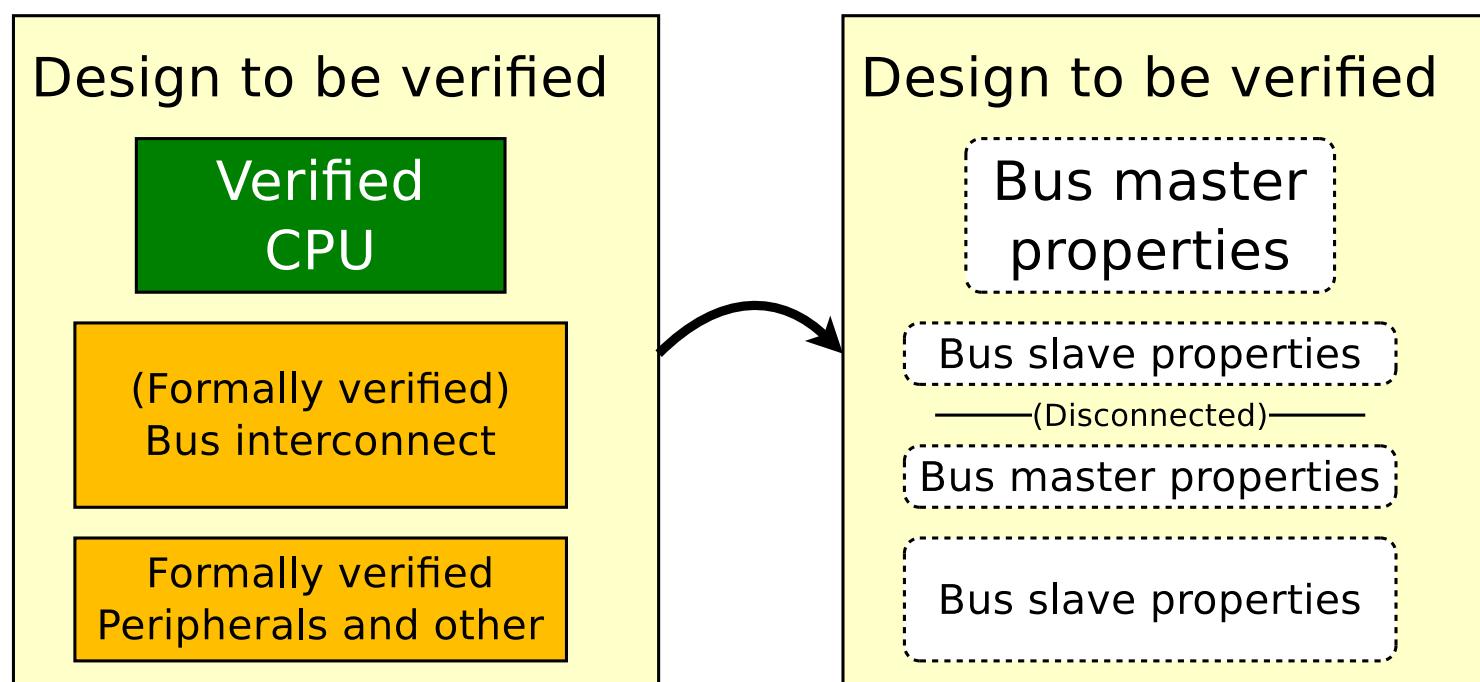
- Assume the CPU is a generic bus master
- This will disconnect any bus transactions from the CPU operation that would cause them
On the other hand, you just proved the CPU would properly execute its instructions
- You will want to do the same thing with your bus slaves as well as the interconnect

This will then allow you to verify the top level of your design

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How would you go about formally verifying the rest of the design?

Replace the bus components with bus interface properties!





Quiz #64



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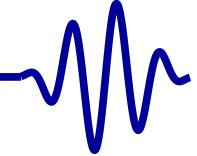
Consider the VHDL design below controlling an AXI slave:

```
AXI_READ_VALID_P : process (S_AXI_ACLK) is
begin
    if (S_AXI_ACLK'event and S_AXI_ACLK='1') then
        if (S_AXI_ARESETN = '0') then
            S_AXI_RVALID <= '0';
        elsif S_AXI_RREADY = '1' then
            S_AXI_RVALID <= rvalid;
        end if;
    end if;
end process AXI_READ_VALID_P;
```

Can you spot any bugs in this snippet alone?



Answer #64



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Can you spot any bugs in this snippet alone?

```
AXI_READ_VALID_P : process (S_AXI_ACLK) is
begin
    if (S_AXI_ACLK'event and S_AXI_ACLK='1') then
        if (S_AXI_ARESETN = '0') then
            S_AXI_RVALID <= '0';
        elsif S_AXI_RREADY = '1' then
            S_AXI_RVALID <= rvalid;
        end if;
    end if;
end process AXI_READ_VALID_P;
```

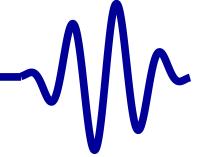
Absolutely!

What happens if (!S_AXI_RVALID && !S_AXI_RREADY)?

If the master hasn't set S_AXI_RREADY in anticipation of a response, something it isn't required to do, the design will hang.



Quiz #65



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SymbiYosys extends Verilog, SV, and VHDL with several attributes, including

- (* `anyconst` *), (* `anyseq` *), and (* `gclk` *)

Let's discuss (* `anyconst` *): How might you achieve the same result as

```
(* anyconst *) wire A;
```

while only using one of the other two attributes?

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SymbiYosys extends Verilog, SV, and VHDL with several attributes, including

- `(* anyconst *), (* anyseq *), and (* gclk *)`

Let's discuss `(* anyconst *)`: How might you achieve the same result as

```
(* anyconst *) wire A;
```

while only using one of the other two attributes?

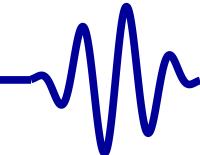
The following declaration and property would be equivalent

```
(* anyseq *) wire A;
always @(posedge i_clk)
    assume($stable(A));
```

Bonus: How would you adjust this to handle multiple clocks?



Quiz #66



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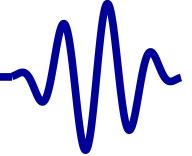
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The following logic comes from a major vendor's AXI stream master implementation. Can you spot the bug?

```
always @(posedge ACLK)
  if (!ARESETN)
    // ...
  else begin
    TVALID <= (state == SEND_STREAM) && rptr < MAX;
    TLAST <= (rptr == MAX - 1);

    if (rptr < MAX) begin
      if (TVALID && TREADY) begin
        done <= 0; rptr <= rptr + 1;
      end end else begin
        done <= 1; rptr <= 0;
    end end
```

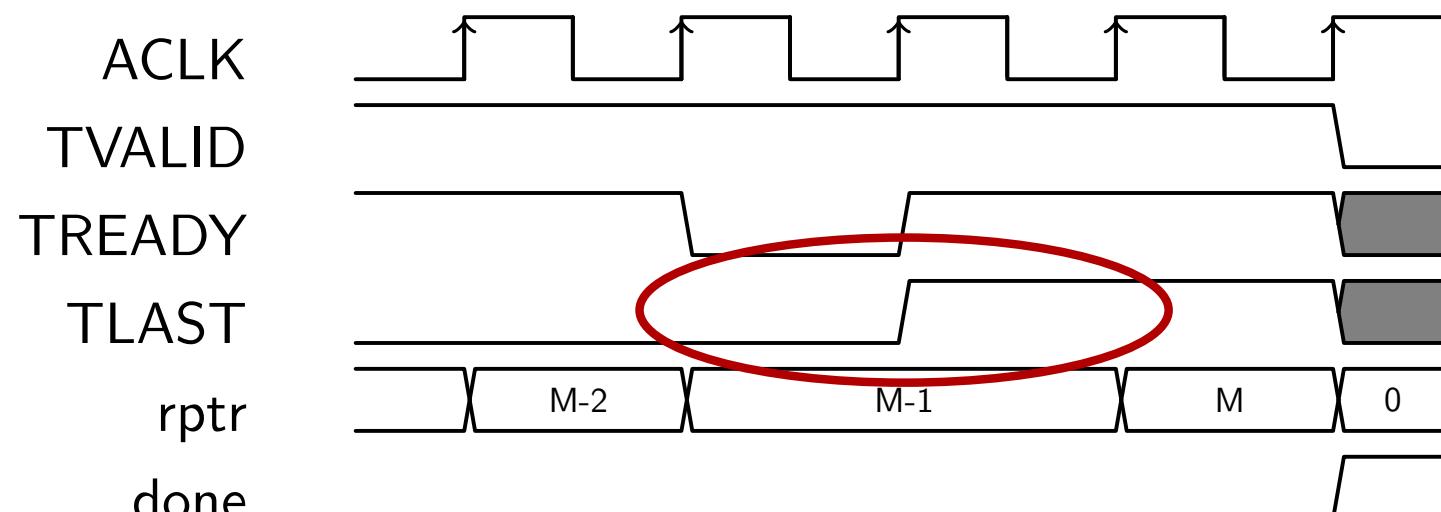
Hint: the bug is not in the reset logic, nor is it in rptr or state

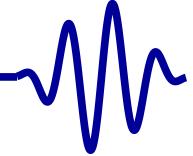
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What happens when

`TVALID && !TREADY && !TLAST && rptr == MAX-1?`

- TLAST will change when things should've been stalled

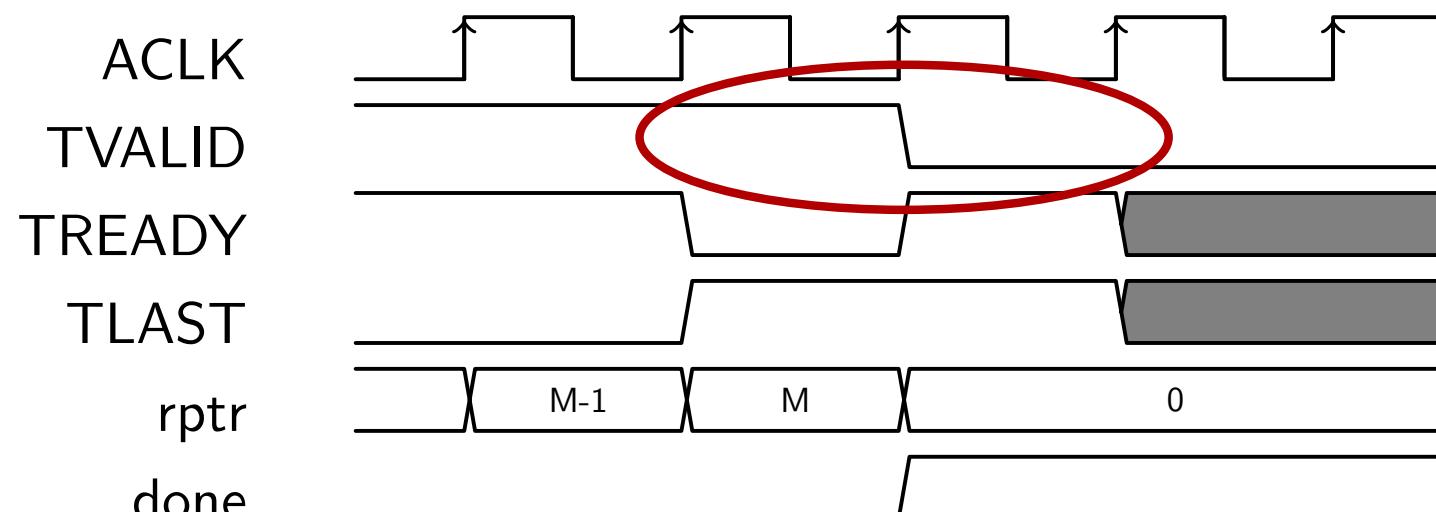


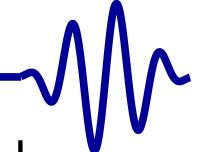
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What happens when

TVALID && !TREADY && !TLAST && rptr == MAX?

- TVALID will change when things should've been stalled



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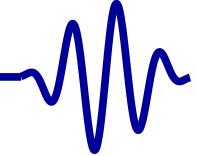
Adding a check for `!TVALID || TREADY` fixes both of these bugs

```
// ...
else if (!TVALID || TREADY) begin
    TVALID <= (state == SEND_STREAM) && rptr < MAX;
    TLAST <= (rptr == MAX - 1);

    if (rptr < MAX) begin
        if (TVALID && TREADY) begin
            done <= 0; rptr <= rptr + 1;
        end end else begin
            done <= 1; rptr <= 0;
    end end
```



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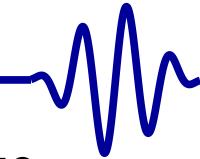
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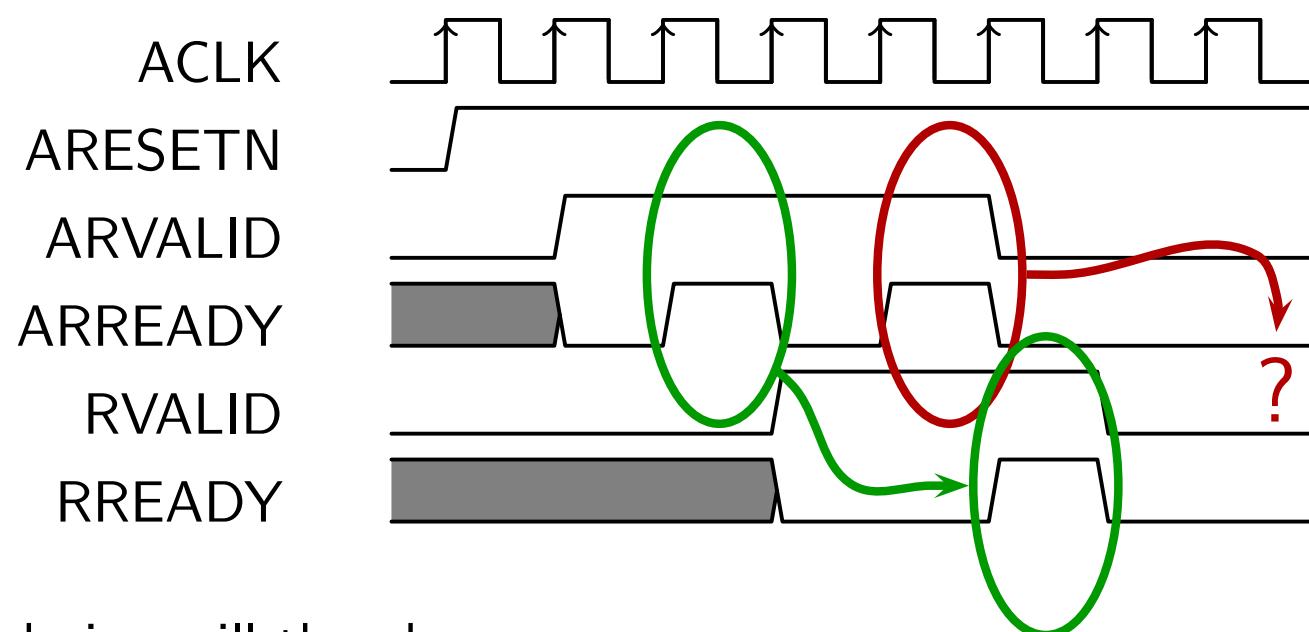
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Can you spot the AXI-lite bug below?

```
always @(posedge S_AXI_ACLK)
if ( S_AXI_ARESETN == 1'b0 )
    axi_already <= 1'b0;
else if (!axi_already && S_AXI_ARVALID)
    axi_already <= 1'b1;
else
    axi_already <= 1'b0;
```

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AWREADY, WREADY and ARREADY all need to be responsive to backpressure from the master. In this case, if RREADY is low long enough then subsequent responses to consecutive requests will get dropped.



Your design will then hang.

Example courtesy of Vivado, from 2016.3 to the present (2020.1)



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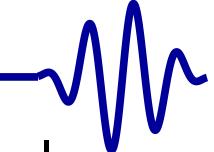
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Here's a second AXI4-lite bug, also courtesy of Vivado 2020.1.
Can you spot it?

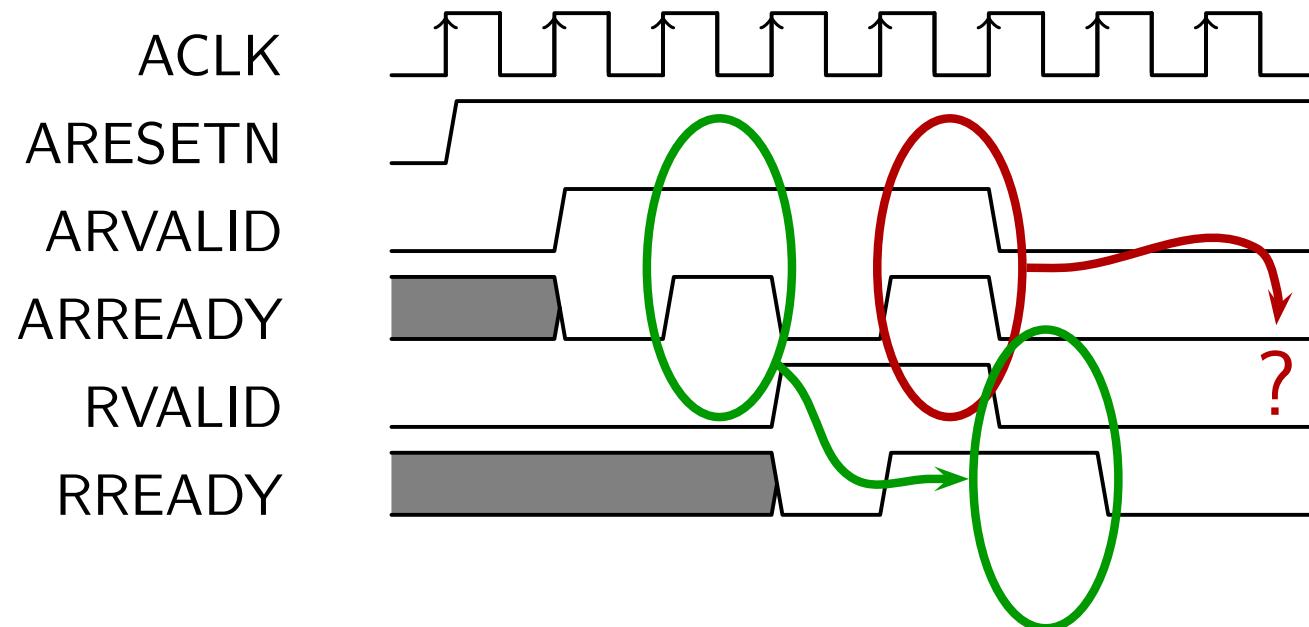
```
always @(posedge S_AXI_ACLK)
if (S_AXI_ARESETN == 1'b0)
    axi_rvalid <= 0;
else if (axi_arready && S_AXI_ARVALID
          && ~axi_rvalid)
    axi_rvalid <= 1'b1;
else if (axi_rvalid && S_AXI_RREADY)
    axi_rvalid <= 1'b0;
```

Yes, let me assure you, there is a bug in this code.

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Never transition on VALID && READY and anything thing else.

- What happens if axi_arready && S_AXI_ARVALID && axi_rvalid? axi_rvalid is dropped.



If your design isn't ready to accept a transaction for some reason or other, then it's your responsibility to hold READY low.

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Several individuals have suggested that this answer depends upon how axi_already is assigned.

- Had it been combinatorially assigned, there would be no error.

```
assign axi_already = !axi_rvalid;
```

This is true.

- Had it been assigned that way, the logic could've also been simplified to the correct answer

```
always @(posedge S_AXI_ACLK)
if (S_AXI_ARESETN == 1'b0)
    axi_rvalid <= 0;
else if (axi_already && S_AXI_ARVALID)
    axi_rvalid <= 1'b1;
else if (axi_rvalid && S_AXI_RREADY)
    axi_rvalid <= 1'b0;
```



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SymbiYosys extends Verilog, SV, and VHDL with several attributes, including

- (* `anyconst` *), (* `anyseq` *), and (* `gclk` *)

To formally verify an asynchronous design, you need access to the formal time-step. How might you use (* `gclk` *) for this purpose? What other changes would be required in your design?



Answer #69



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The formal timestep can be described using (* gclk *) by first declaring a global time-step,

```
(* gclk *) wire gbl_clk;
```

and then using it in your design:

```
always @ (posedge gbl_clk)
```

Don't forget to add the SymbiYosys **multiclock** option:

```
[options]
#
# ...
multiclock on
```



Quiz #70



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Looking at the following vendor supplied AXI master design, do you see any AXI protocol errors?

```
parameter AXI_BASE_ADDR = 32'h4000_0000;
parameter BURST_LEN = 8;
assign burst_size_bytes
      = BURST_LEN * (AXI_DATA_WIDTH/8);

always @(*posedge ACLK)
if (!M_AXI_ARESETN || init_pulse)
    axi_awaddr <= 0;
else if (M_AXI_AWREADY && axi_awvalid)
    axi_awaddr <= axi_awaddr + burst_size_bytes;

assign M_AXI_AWADDR = BASE_ADDR + axi_awaddr;
assign M_AXI_AWLEN = BURST_LEN-1;
```

You may assume init_pulse |-> !M_AXI_AWVALID.

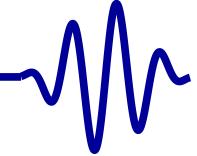
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This bug is rather subtle, if present at all. (We can argue that.)

- As currently parameterized, there are no bugs.
- What happens if the parameters are overridden?
- Specifically, what if $\text{BASE_ADDR}[11:0] > 12'hfe0$ for a 32-bit bus?
- The AXI Spec prohibits bursts from crossing a 4kB boundary
- Nothing in the demo indicates that the address can not be arbitrarily overridden

What do you think? Is this a bona fide “bug”?

- It's led to many broken user designs based upon this demonstration code

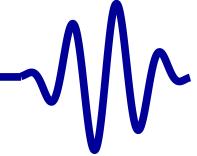
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Can you spot any bugs in the AXI4-lite code below?

```
initial BVALID = 0;
always @(posedge ACLK)
if (!ARESETN)
    BVALID <= 0;
else if (AWVALID && AWREADY
          && WVALID && WREADY
          && !BVALID)
    BVALID <= 1;
else if (BREADY && BVALID)
    BVALID <= 0;
```

- Hint: Xilinx's VIP won't necessarily find these bugs

If you're not sure if there is a bug, how would you find out?

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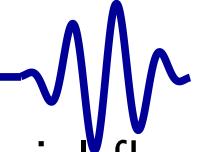
What happens if ...

1. Either of AWVALID or WVALID but not both,
2. (AWVALID && WVALID) && AWREADY != WREADY, or even
3. (AWVALID && WVALID) && AWREADY && BVALID?

A couple assertions can quickly determine if any of these conditions would ever be a problem:

- assert**(AWREADY == WREADY);
- if** (AWREADY) **assert**(AWVALID && WVALID);
- if** (BVALID) **assert**(!AWREADY);

Of course, if these assertions would pass, then the logic could've been greatly simplified

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To fix this logic, I like using skid buffers and a combinatorial flag

```
always @(*)
    write_ready = awskd_valid && wskd_valid
        && (!BVALID || BREADY);

always @ (posedge ACLK)
if (!ARESETN)
    BVALID <= 0;
else if (write_ready)
    BVALID <= 1;
else if (BREADY)
    BVALID <= 0;
```

Using the skidbuffer gets around the requirement that all AXI outputs be registered, since the skid buffer ready input doesn't need to be registered.

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You could also fix this logic without the skid buffers but only at a loss of 50% throughput

```
always @(*posedge i_clk)
if (!ARESETN)
    write_ready <= 0;
else begin
    write_ready <= (AWVALID && AWREADY);
    if (write_ready)
        write_ready <= 0;
    // Note you *must* check for
    // backpressure when using AXI
    if (BVALID && !BREADY)
        write_ready <= 0;
end
assign AWREADY = write_ready;
assign WREADY = write_ready;
```

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(* `anyconst` *) and (* `anyseq` *) can both be used to create random values *carefully chosen by the solver* within your proof. If these values need to be constrained, what kind of constraints should be used on them?

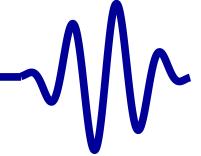
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(`* anyconst *`) and (`* anyseq *`) can both be used to create random values *carefully chosen by the solver* within your proof. If these values need additional constraints, what kind of constraints should be used on them?

- Because (`* anyconst *`) and (`* anyseq *`) values act like inputs, assumptions are appropriate for constraining them
- Beware, these two attributes will be ignored by a simulator
 - In simulation, `assume()` constraints will become `assert()`s
 - This will likely cause any simulation depending upon their assumed values to fail
 - You might wish to `ifdef` out any free variable sections when running simulations, or
 - Arrange them so they'll work without additional constraints under simulation



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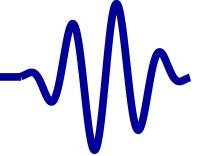
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Let's talk about the **depth** of a proof

- For bounded and cover checks
 - The depth is the number of steps that get checked
- For induction passes
 - The depth is the number of steps where assertions are assumed to be valid
- Be aware, the time required for the proof typically increases exponentially with the **depth**

When building a full proof (i.e. with induction), what **depth** should you start with?

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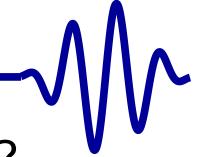
I recommend the following rules for setting the **depth**

- Start with the length of the longest operation the design must accomplish before returning to idle – if possible
 - Otherwise shorten to what you have the patience for
- Start with the bounded check. Once it passes, add induction
- Once induction succeeds,
 - Reduce the **depth** to the number of steps the induction check took to succeed

Remember, a trace generated from a bounded check is easier to debug



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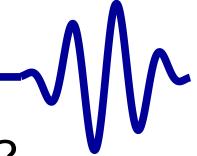
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Can you see anything wrong with the following assertion?

```
assert property (@(posedge i_clk)
                  A ###1 B ###1 C
                );
```

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Can you see anything wrong with the following assertion?

```
assert property (@(posedge i_clk)
                  A ##1 B ##1 C
                );
```

Yes. Assertions need *triggers*. Without an trigger, this assertion requires that A be true *on every cycle*, and that B and C follow. Chances are what you mean to assert was something closer to,

```
assert property (@(posedge i_clk)
                  A |=> B ##1 C
                );
```

This says that if A is ever true, then B and then C must follow, not that A must be true on every cycle.



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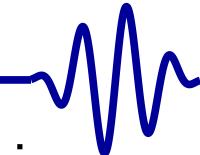
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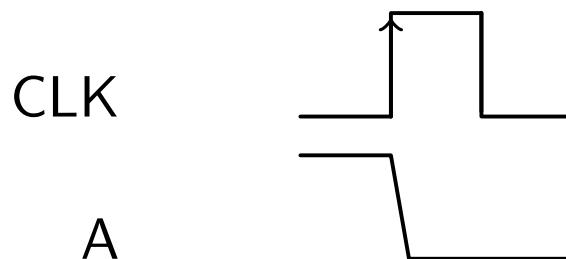
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Will the following assertion pass a formal verification check?

```
input wire A;  
  
initial assume(A);  
assume property (@(posedge CLK) A);  
  
always @(*)  
    assert(A);
```

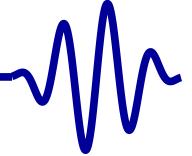
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No, it will not. You'll get something similar to the following trace:



It's as though the assumption never took effect!

What went wrong? *Clocked properties require a clock edge before taking effect.*

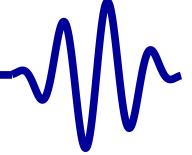
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The assertion is equivalent to the following:

```
reg      p_assumption = 1, f_initial = 1;  
  
always @(*)
    begin
        if (f_initial) assume(A);
        assume(p_assumption);
        assert(A);
    end  
  
always @(*)
    begin
        f_initial <= 0;
        // Register the clocked assumption
        p_assumption <= A;
    end
```

As you can see, p_assumption only gets checked *after* the clock edge

GT Quiz #76



How do you know if your design has enough assertions?

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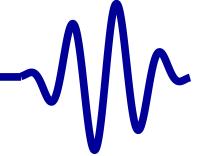
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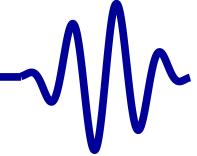
How do you know if your design has enough assertions?

Here are some tests you can use:

- Is every assumption made by a module depending on your design covered by an assertion?
I like using shared interface property files for this, to make certain that assumptions don't get lost.
- Is every output pinned down? Could you tell, for example via an assertion failure, if an output had the wrong value?
- Does the design pass induction?

You can also use mcy (mutation coverage with yosys) to find things that aren't covered by any assertions.

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The following example was inspired by some endianness adjustment logic.

Will the following assertion pass?

```
input    wire      [31:0]  in;
input    wire      [2:0]    shift;
output   reg       [31:0]  out;

always @(*)
    out = in >> 4*(~shift);

assert property (@(posedge clk)
    in == 32'hfeedbead && shift == 3'h7
    |-> out == 32'hfeedbead);
```



Answer #77



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No, it will not pass.

- When evaluating logic with multiple widths, the synthesis tool is supposed to first expand every term to the maximum width used
 - shift[2:0] thus gets expanded to 32'h7
 - ~shift[2:0] becomes 32'hffff_fff8
 - 32'd4 * 32'hffff_fff8 is then 32'hffff_ff80, and
 - 32'dfeedbead >> 32'hffff_ff80 is zero, not 32'hfeedbead

Note: I didn't get this right the first time either.



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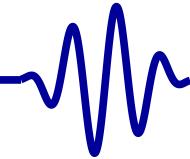
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The following student **cover()** statement was intended to generate a trace showing a FIFO go from empty to full and back again.

```
cover property (@(posedge i_clk)
    o_empty ##1 1[*0:$]
    ##1 o_full   ##1 1[*0:$]
    ##1 o_empty );
```

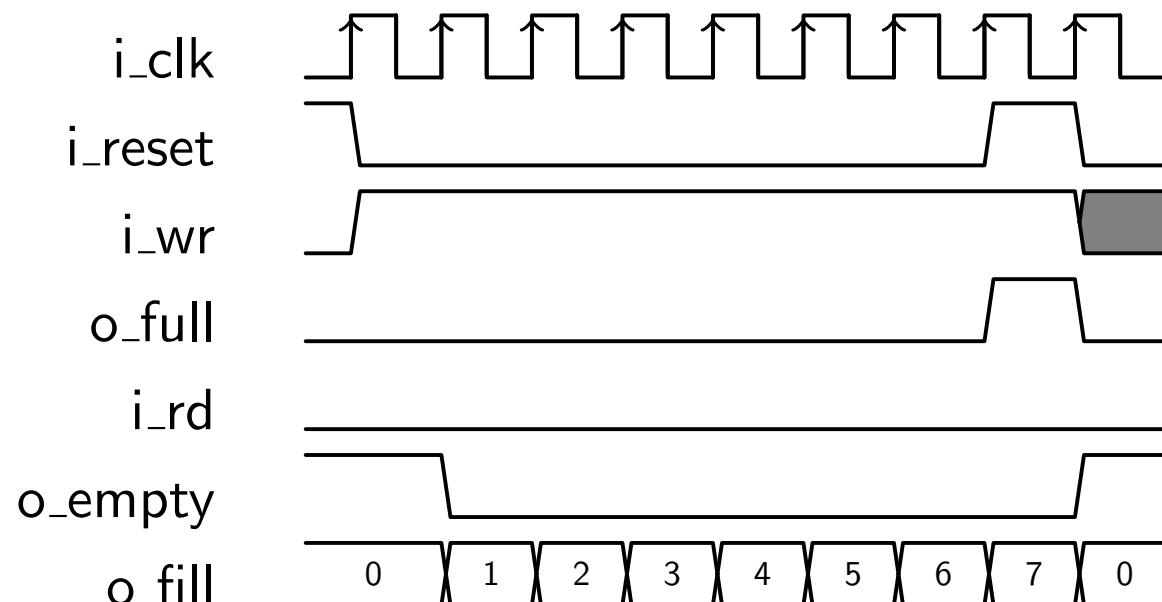
Much to the student's surprise, the resulting trace wasn't at all what he was expecting.

Judging from the **cover()** statement above, what do you think went wrong?

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The student forgot to keep the reset low (inactive)

- The solver jumped from full to empty on a reset
- This short-circuited his desired cover proof



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Disabling the **cover()** statement on a reset solves this problem

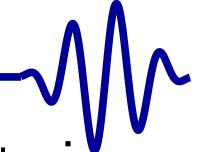
```
cover property (@(posedge i_clk)
    disable iff (i_reset)
        o_empty ##1 1[*0:$]
        ##1 o_full   ##1 1[*0:$]
        ##1 o_empty );
```

Since the student also wanted to see some non-zero data passing through the FIFO, we made the **disable** iff statement a touch more complex.

```
cover property (@(posedge i_clk)
    disable iff (i_reset || i_data != wr_addr)
        o_empty ##1 1[*0:$]
        ##1 o_full   ##1 1[*0:$]
        ##1 o_empty );
```



Quiz #79



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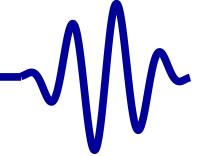
Your UART appears to be running at the wrong baud rate in hardware. Tracing this problem down further, it appears as though your clock may be running at the wrong frequency. What's an easy way to verify the frequency your clock is running at?

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Here's my personal favorite approach to verifying a clock's rate:

```
reg [31:0] counter;  
  
always @(*posedge i_clk)  
// 43 = 2^32 / 100 MHz  
counter <= counter + 32'd43;  
  
always @(*)  
o_led = counter[31];
```

A 100MHz system clock will now cause this LED to blink at 1Hz.

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For those in an engineering lab, there's also the obvious

- Forward the clock to a pin, and examine it with an external oscilloscope

Other approaches to this problem deserve an honorable mention, if for no other reason than for their creativity:

- Output a square wave to a piezo speaker and compare it to a tuning fork
- Causing a pin to transmit on the AM band (1MHz or so), look for its signal using a nearby radio receiver
- Use a known frequency to count edges from the unknown clock
- Transmit a perpetual 0x55 over UART, and looking for the resulting square wave with an oscilloscope



Quiz #77



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Here's a formal property describing a write-through RAM with a registered output port.

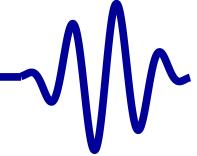
- When written to and read from on the same clock cycle, ...
- and from the same address, ...
- the read data result should equal the prior write data.

```
assert property (@(posedge i_clk)
                  write_request && read_request
                  && write_address == read_address
                  |=> read_data == write_data);
```

What logic can be used to generate this RAM?



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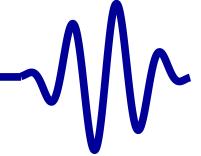
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What's the logic for a write through RAM?

```
always @(* posedge i_clk)
    bypass_memory <= (write_request && read_request)
        && write_address == read_address;

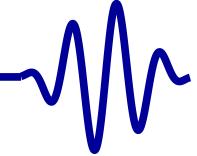
always @(* posedge i_clk)
if (write_request) begin
    mem[write_address] <= write_data;
    bypass_data <= write_data
end

always @(* posedge i_clk)
if (read_request)
    r_data <= mem[read_address];
always @(*)
    o_data <= (bypass_memory)
        ? bypass_data : r_data;
```

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Which type of proof can prove that . . .

- Your design has bugs within it
 - i.e., There exists a failing property
- Your design has no bugs within it
 - i.e., None of the properties will ever fail

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Which type of proof can prove that . . .

- Your design has bugs within it
 - i.e., There exists a failing property
 - Answer: A bounded model check, **mode bmc**
 - This is the easiest proof to do, and can be set up using basic *black box* properties
 - A bounded proof cannot prove that no bugs exist
- Your design has no bugs within it
 - Answer: A proof using induction, **mode prove**
 - The induction pass itself is a more complicated proof
 - ▷ Tends to be intrusive into the implementation details
 - ▷ Requires comprehensive *white box* properties
 - Of the two **mode prove** passes, the induction pass alone cannot prove that a bug exists



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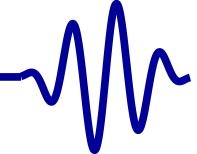
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You are currently verifying a design

- The proof of the basecase is stuck on the 6th step
- Induction has succeeded after 17 steps
- Your design has an idle state within it, where nothing takes place
- This idle state may be reached in one clock following any reset

Can you kill the proof and conclude that your design passes?

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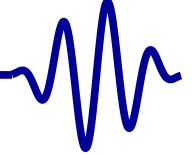
You are currently verifying a design

- The proof of the basecase is stuck on the 6th step
- Induction has succeeded after 17 steps
- Your design has an idle state within it, where nothing takes place
- This idle state may be reached in one clock following any reset

Can you kill the proof and conclude that your design passes?

Yes! The purpose of the base case is to prove that N steps exist with no bugs. This includes any set of N steps with the reset asserted.

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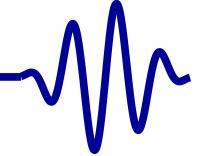
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You are formally verifying a CPU.
What properties would you start with?



Answer #78



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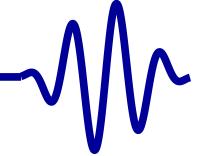
What properties would you use to verify a CPU?

This is also an open ended question. Here are some categories I would use:

1. Verify the results written to the register file, per instruction
2. Use a bus property file to verify bus operation
3. Verify values read from / written to the bus end up on the bus
- 4.



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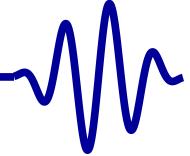
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What's the minimum depth necessary to verify a design containing a **\$past()** operator?

```
assert property (@(posedge i_clk)
                  ##1 last_count == $past(counter));
```



Answer #79



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What's the minimum depth necessary to verify a design containing a **\$past()** operator?

```
assert property (@(posedge i_clk)
                 ##1 last_count == $past(counter));
```

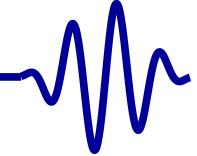
The minimum depth is two.

depth 2

Anything less will fail induction



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FPGAs support initial values, ASICs typically do not.

What modifications would you need to make to your SymbiYosys script in order to properly handle the property below

```
'ifndef ASIC
    initial past_initial = 1;
'else
    initial assume(i_reset);
'endif
    always @(posedge i_clk)
        if (i_reset)
            past_initial = 1;

    always @(*)
        assert(past_initial);
```

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asic

1. Create an ASIC SymbiYosys Task

fpga

~~## ...~~**[script]**

```
asic: read -define ASIC  
read -formal asicinitial.v  
prep -top asicinitial
```

2. You can (optionally) use it to define the macro ASIC

3. Next, remove any **initial** statements from your design by removing all register init attributes

```
asic: attrmap -remove init
```

4. Finally, skip any assertion evaluations until after the reset

```
asic: chformal -assert -skip 2 *
```



Quiz #81



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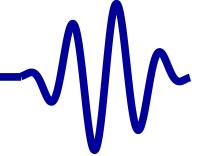
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Describe the difference between the following i_ce signals.

```
always @(posedge i_clk)
    assume(i_ce);
```

```
always @(posedge i_clk)
if ((f_past_valid)&&(!$past(i_ce)))
    assume(i_ce);
```

```
always @(posedge i_clk)
if ((f_past_valid)&&(!$past(i_ce))
    &&(!$past(i_ce,2)))
    assume(i_ce);
```

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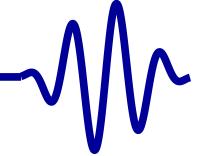
The following ominous warning,

```
warning: @* found no sensitivities so it will \
          never trigger.
```

was generated from this simple design

```
always @(*)
    idle = 0;
```

Today's useless warning reminder was brought to you by Icarus Verilog.

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The following ominous warning,

```
warning: Port 5 (i_in) of submodule expects \
          24 bits, got 32.
          : Pruning 8 high bits of the expression.
```

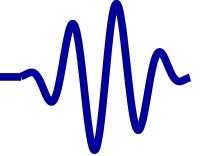
was generated from this design

```
module foo(* ... *);
  parameter W = 24;
  // ...
  wire C;
  wire [W-1:0] V;
  // ...
  submodule foobar(// ...
    (c) ? 0:V);
```

This useless warning was brought to you by Icarus Verilog. Zero is zero in any width.



Quiz #75



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You have two implementations of a given core

```
core a(i_clk, i_reset, i_in, a_out);
```

```
core b(i_clk, i_reset, i_in, b_out);
```

How would you go about to formally check whether or not these implementations are identical?

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The obvious answer is to assert that the outputs will be identical

```
core a(i_clk, i_reset, i_in, a_out);  
core b(i_clk, i_reset, i_in, b_out);  
  
always @(*)  
    // For each core output, check ...  
    assert(a_out == b_out);
```

For many cores, this is sufficient. For cores with internal memory and state, assertions that the internal state remains identical will still be required to pass induction.

Of course, cores that maintain the same functionality but not the same timing will also fail here as well.

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The following picture based on an ISSI SDRAM data sheet illustrates that ckRCD=2 clocks must take place between an ACTIVATE command and the next command to use the same bank

Will the following property capture this relationship?

```
assert property (@(posedge clk)
    (cmd == ACTIVATE)&&(bank == 0)
    |=> (cmd == NOOP )||( bank != 0) [*X]
    (( cmd == READ )||( cmd == WRITE ))
        &&(bank == 0));
```

GT Quiz #77



What is the minimum latency when accessing an AXI slave through an AXI crossbar?

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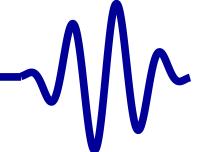
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What is the minimum latency when accessing an AXI slave through an AXI crossbar? **3 clocks**

This is a natural consequence of the AXI specification

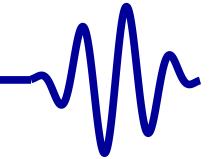
- One clock to forward the request to the slave
- One clock for the slave to process the request
- One clock for the interconnect to return the response to the master

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Practically, maintaining a high clock speed may require two more clocks

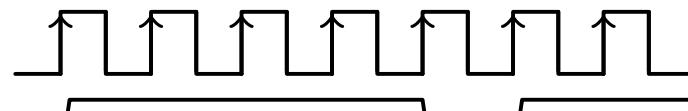
- One clock to decode the address
- One clock to arbitrate among many masters

If your solver allows reverse link arbitration by the packet ID, you may then need to add an additional clock cycle as well for reverse link arbitration.

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Consider the trace below:

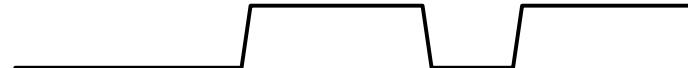
S_AXI_ACLK



S_AXI_ARESETN



S_AXI_ARVALID



S_AXI_ARREADY



Does this AXI master follow the protocol?