Improving Constrained Random Testing by Achieving Simulation Verification Goals through Objective Functions, Rewinding and Dynamic Seed Manipulation

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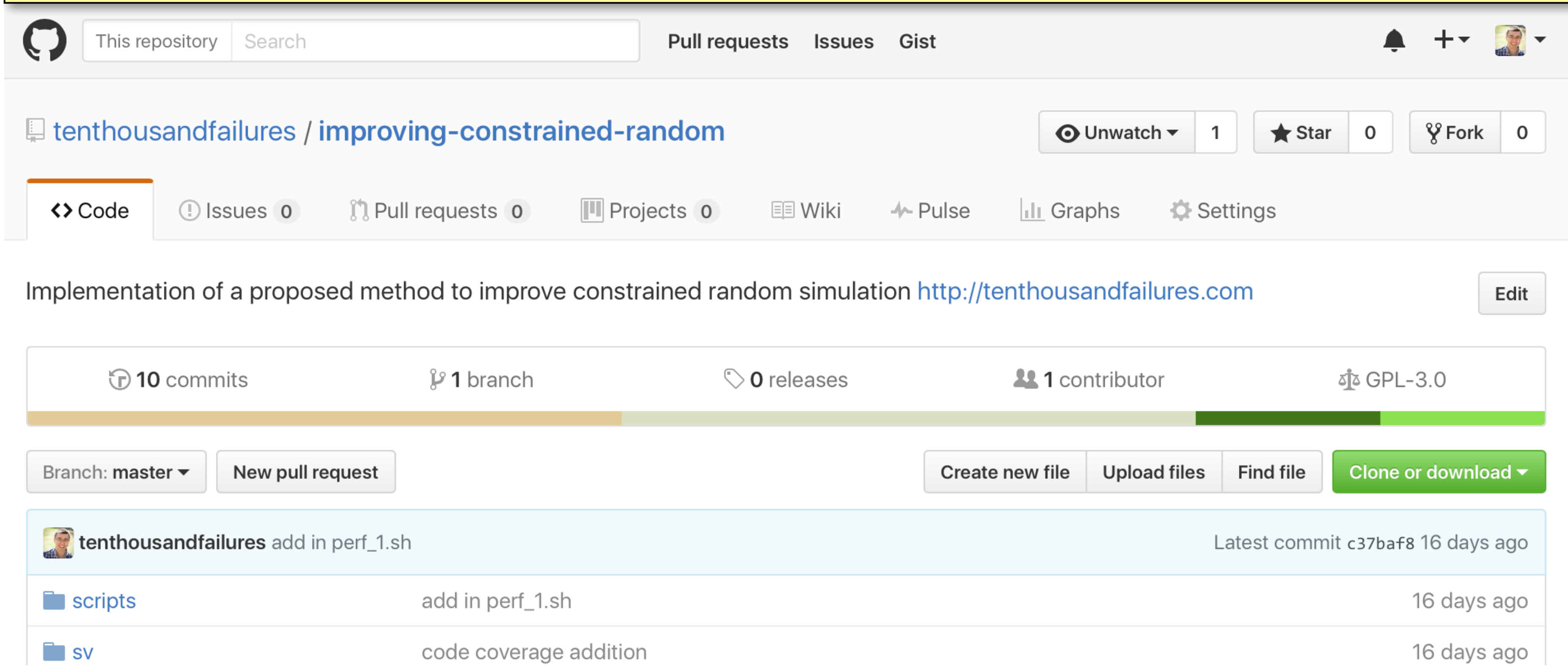
Intel Corporation

Outline

- Inspiration from Nintendo Playing AI Paper
  - Objective Function
- Application to Simulation
  - Seeds and Dynamic Re-Seeding
  - Objective Function in Verification
  - Checkpointing Feedback Loop
- Scaling
- Results

Full Code Implementation

https://github.com/tenthousandfailures/improving-constrained-random



Tom Murphy VII

The First Level of Super Mario Bros. is Easy with Lexicographic Orderings and Time Travel ...after that it gets a little tricky.

Dr. Tom Murphy VII Ph.D.*

1 April 2013

Abstract

This paper presents a simple, generic method for automating the play of Nintendo Entertainment System games.

Keywords: computational super mario brothers, memory inspection, lexicographic induction, networked entertainment systems, pit-jumping, ...

paper is mainly as a careful record of the current status for repeatability and further development on this important research subject. A short video version of this paper is available for those that hate reading, at `http://tom7.org/mario`, and is the more fun way to consume the results. This page also contains audiovisual material that makes this work more entertaining (for example, its output) and source code.

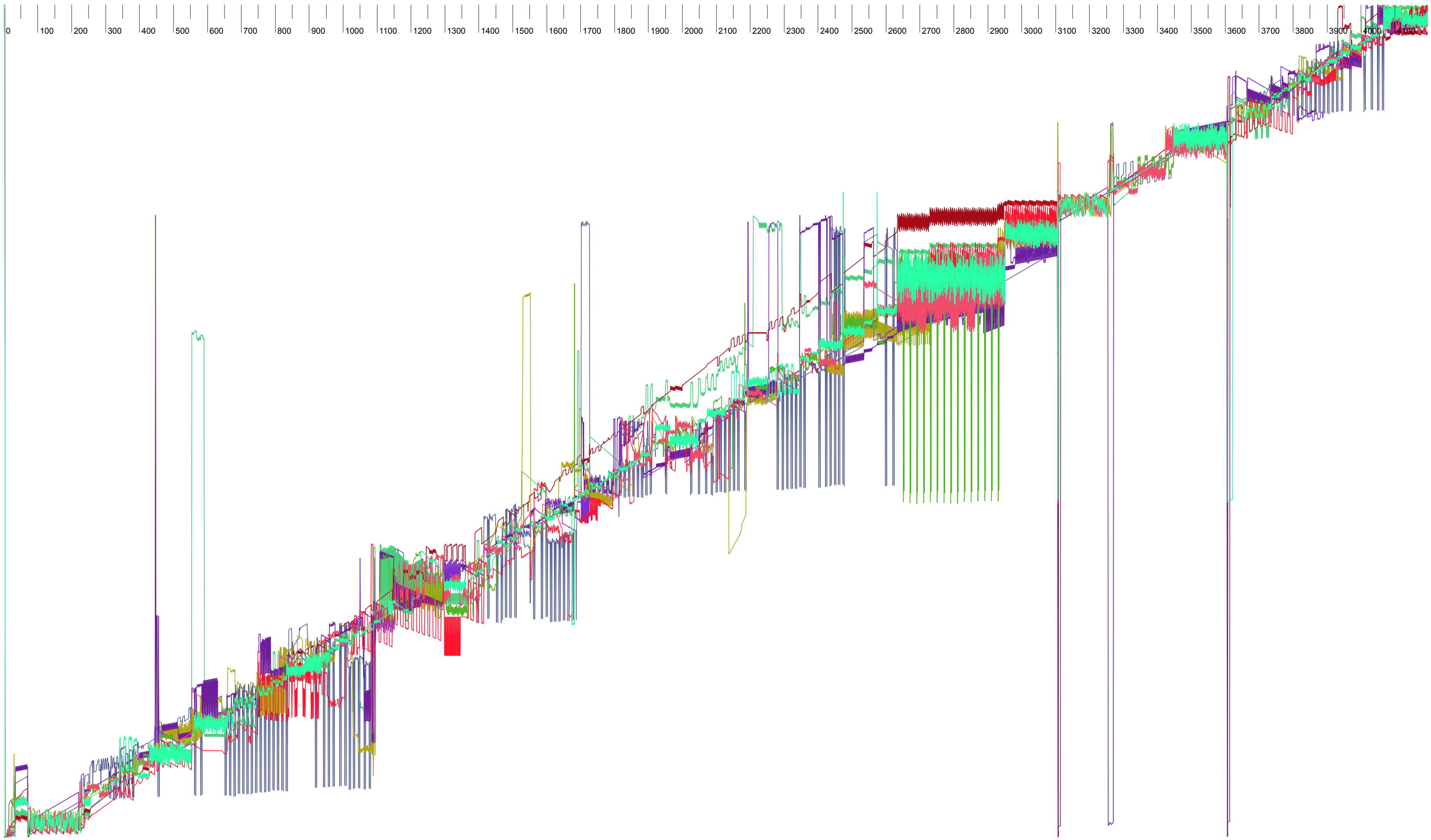
The basic idea is to deduce an objective function from

Novel Alternative Solution

RAM Locations

0x01	0x35	0x21	0xff
0x53	0x41	0x42	0x00
0x5e	0x32	0x20	0x00
0x32	0xee	0xfe	0x00

10 Objective Functions



Proposal

- Faster Automated Coverage Closure
- Efficient Final Stimulus Solution
- Proposed Higher Quality of Coverage

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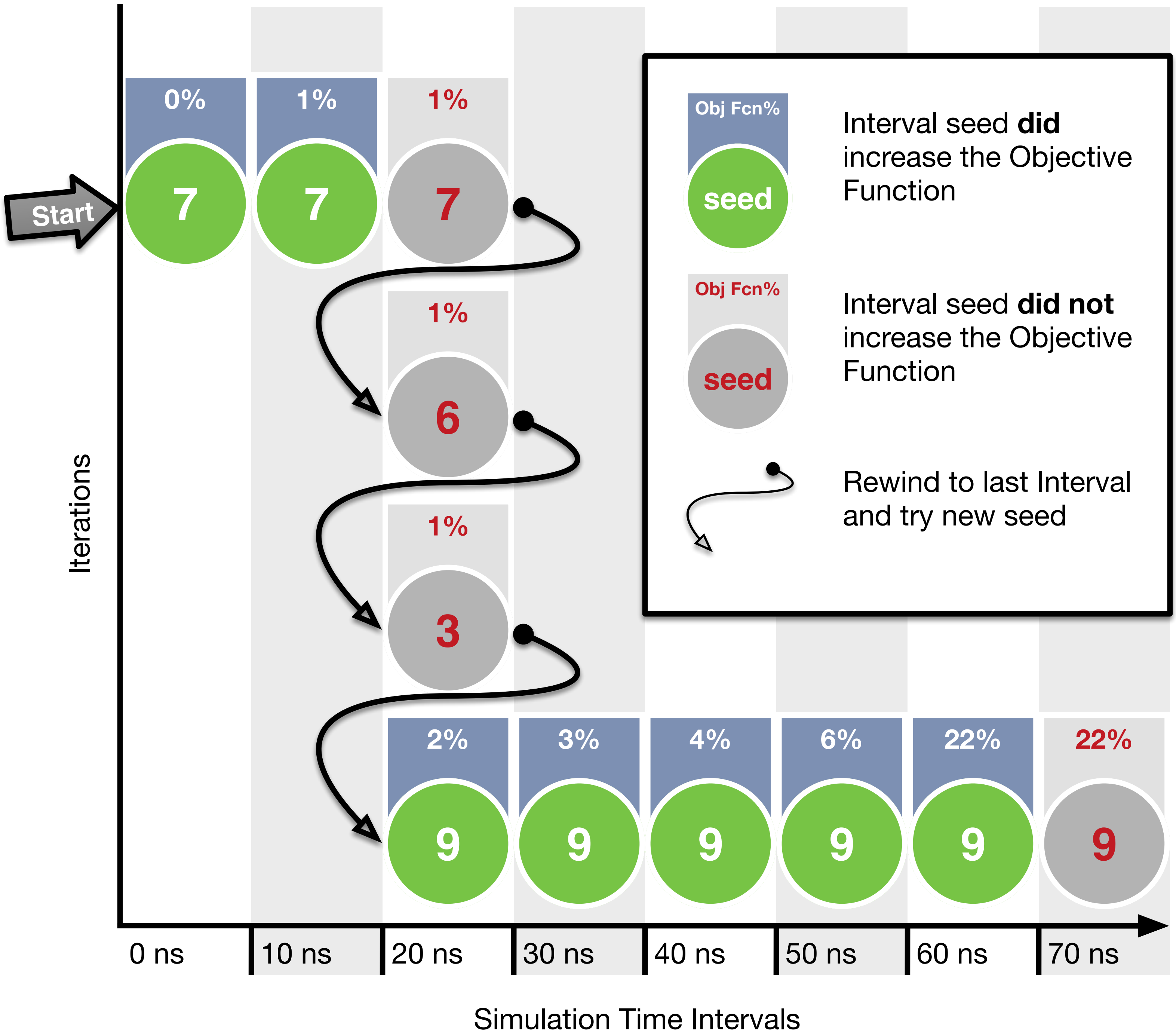
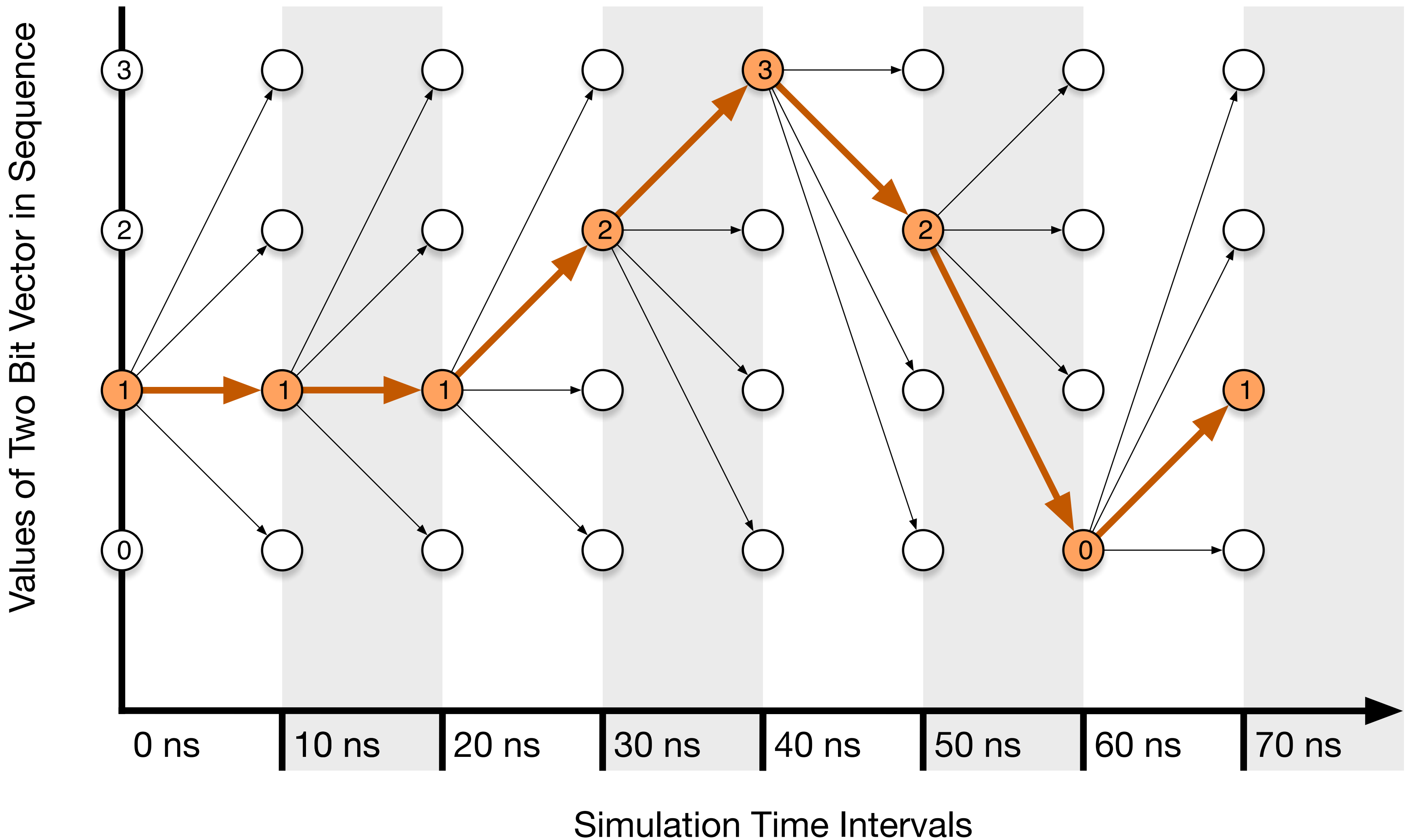

Start
0%
1%
1%
7
7
7
1%
6
1%
3
2%
3%
4%
6%
22%
22%
9
9
9
9
9
9
Iterations
0 ns
10 ns
20 ns
30 ns
40 ns
50 ns
60 ns
70 ns
Simulation Time Intervals
Obj Fcn%
seed
Interval seed **did** increase the Objective Function
Obj Fcn%
seed
Interval seed **did not** increase the Objective Function
Rewind to last Interval and try new seed


Values of Two Bit Vector in Sequence
3
2
1
0
1
1
2
3
2
0
1
0 ns
10 ns
20 ns
30 ns
40 ns
50 ns
60 ns
70 ns
Simulation Time Intervals

Dynamic Re-Seeds

- SystemVerilog RNG (Random Number Generator)
  - `.randomize()`

Dynamic Re-Seeds

- SystemVerilog RNG (Random Number Generator)
  - `.randomize()`
  - `.srandom(int) or UVM reseed()`

Objective Function

- Measure of progress
- Covergroup as a simple “Objective Function”
  - Convenient covergroup percentage never decreases during simulation

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- Measure of progress
- Covergroup as a simple “Objective Function”
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```
real coverage_value = 0;
coverage_value = dut.objective.match.get_coverage();
```

Checkpointing

- Saving a simulation point in time with all state
  - performance penalty
  - disabling some optimizations
  - vendor specific, but universal capability

Murphy VII / Nelson Translations

Murphy VII	Nelson
Objective Function	Objective Function
Steps / Iterations	Interval
Motifs	Constrained Sequences
Backtracking	Rewinding

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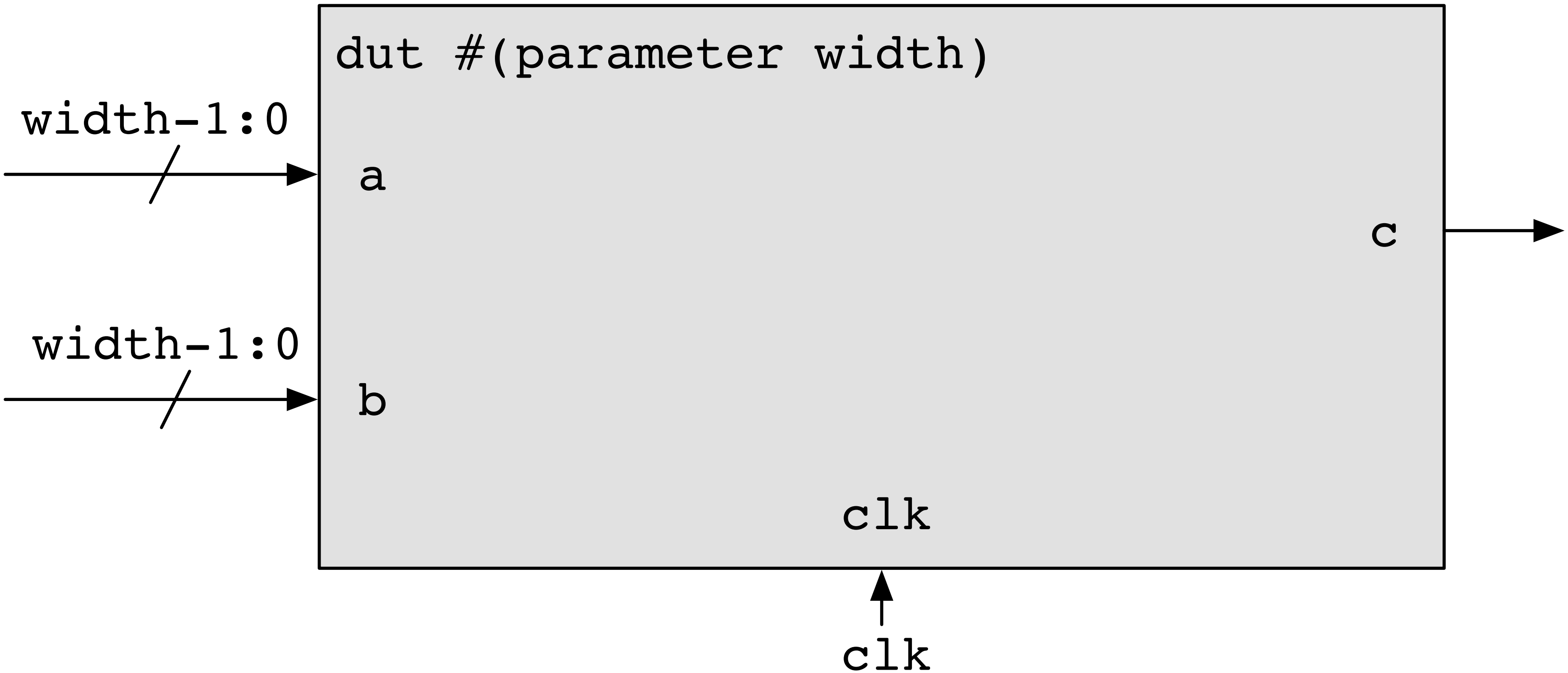
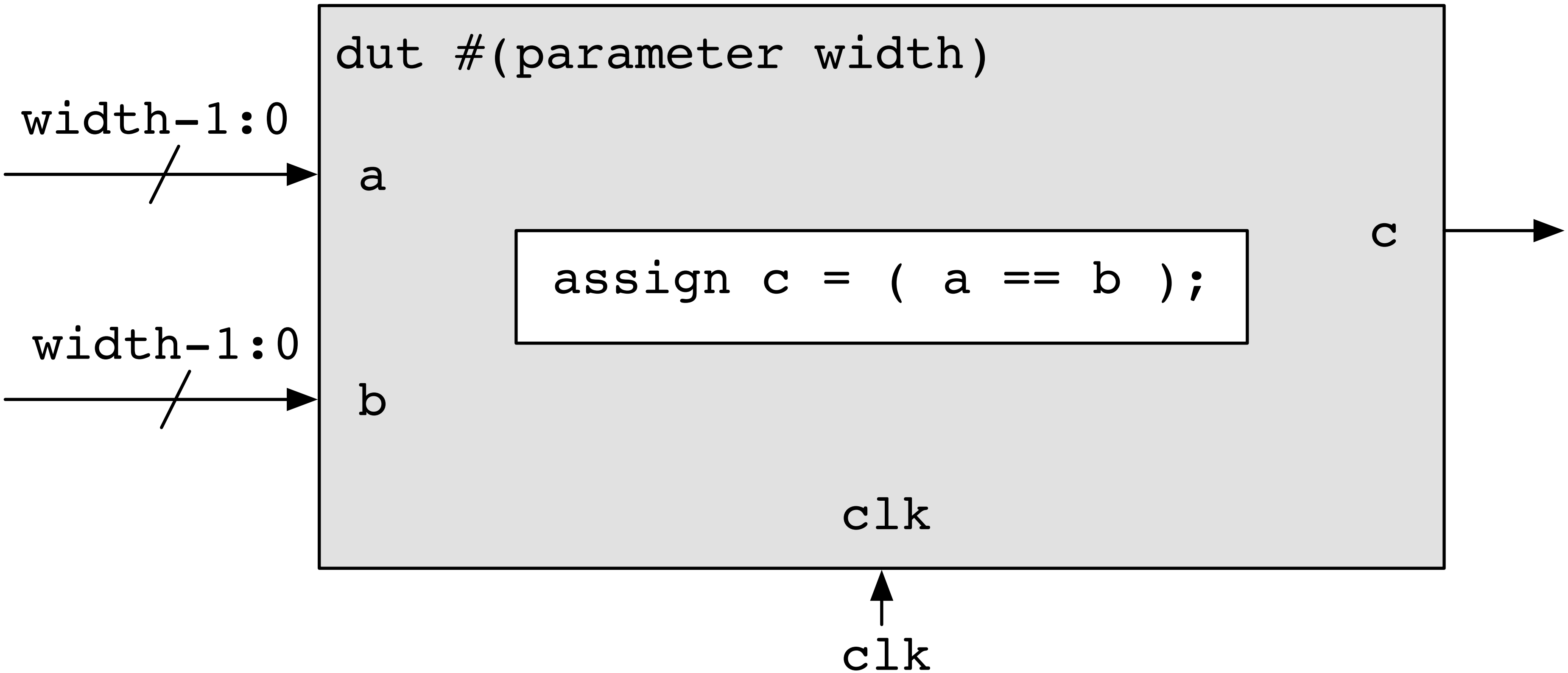
Design Under Test

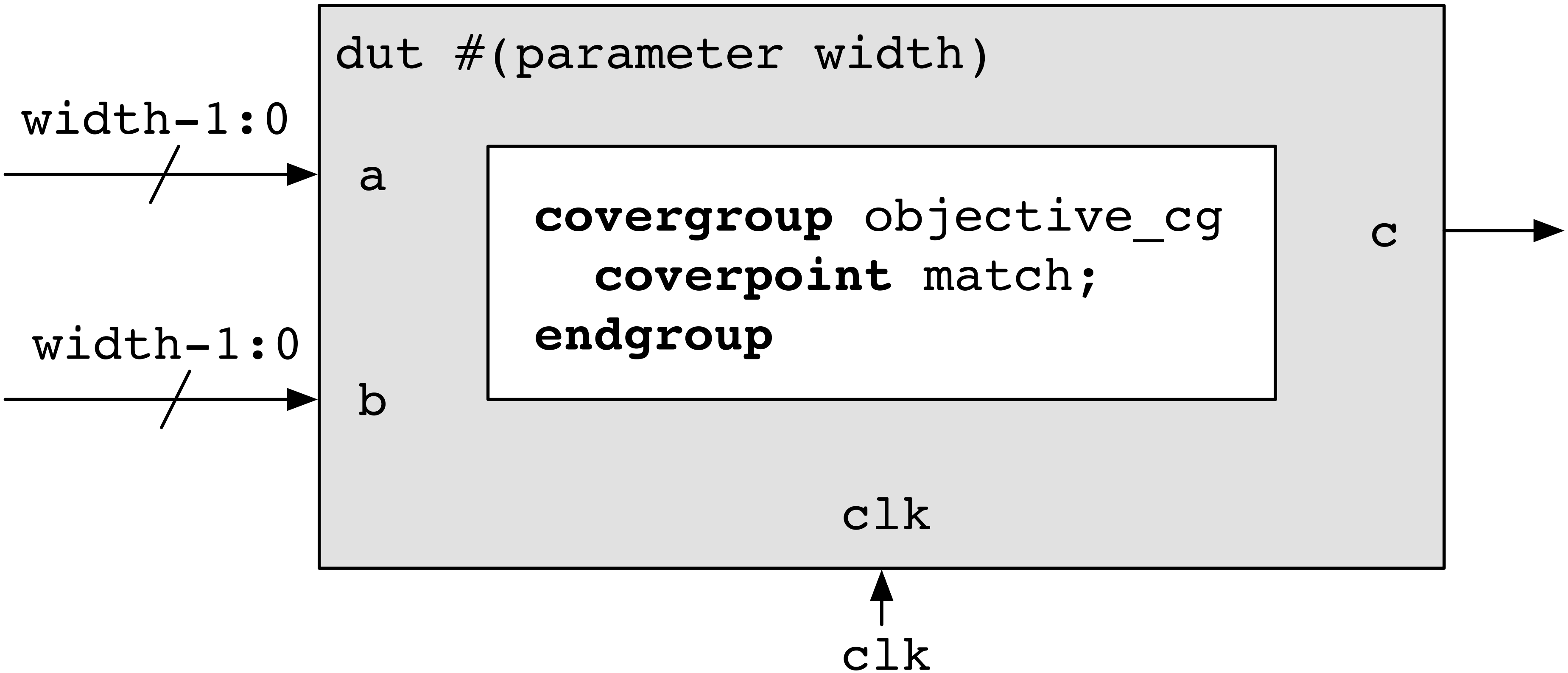


Design Under Test



Digital Comparator

Design Under Test

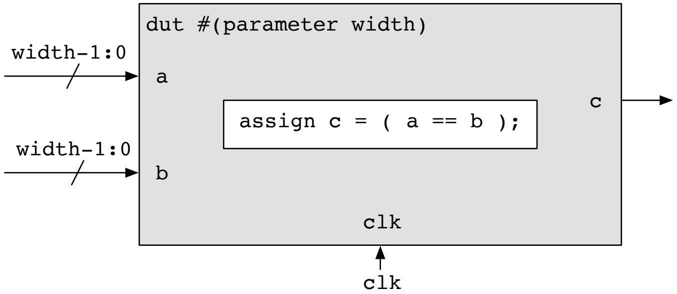


Digital Comparator

Getting the Optimal Solution

- *width = 2; about 4% chance of all seeds*

$$\frac{4!}{(2^4)^4} = \frac{4!}{16^4}$$



- *width = 5;* ***probable no seed*** *would solve optimally*

$$\frac{32!}{(2^{10})^{32}} = \frac{32!}{1024^{32}}$$

Sim Log Example

```
-------------------------- START eval_loop
DEBUG current simulation time is ctime : 27 ns
INFO STATUS : TCL : LOCAL REJECTED seed: 3552075441 at time: 17 ns
INFO STATUS : TCL : 27 ns : NO PROGRESS : false: 0.000000 > 0.000000
REWINDING TO CHECKPOINT {2} at 17 ns
All the Checkpoints created after checkpoint 2 are removed...
-------------------------- END eval_loop
```

Sim Log Example

------------------------- START eval_loop

DEBUG current simulation time is ctime : 27 ns

INFO STATUS : TCL : LOCAL REJECTED seed: **3552075441** at time: **17 ns**

INFO STATUS : TCL : 27 ns : NO PROGRESS : false: 0.000000 > 0.000000

REWINDING TO CHECKPOINT {2} at 17 ns

All the Checkpoints created after checkpoint 2 are removed...

------------------------- END eval_loop

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Sim Log Example

```
UVM_INFO sv/dut.sv(14) @ 20: reporter [dut_if] AFTER drive regs a: 0 b: 3
------------------------- START eval_loop
DEBUG current simulation time is ctime : 27 ns
INFO STATUS : TCL : LOCAL REJECTED seed: 3552075441 at time: 17 ns
INFO STATUS : TCL : 27 ns : NO PROGRESS : false: 0.000000 > 0.000000 REWINDING TO CHECKPOINT {2} at 17 ns
All the Checkpoints created after checkpoint 2 are removed...
------------------------- END eval_loop
UVM_INFO sv/dut.sv(14) @ 20: reporter [dut_if] AFTER drive regs a: 1 b: 3
------------------------- START eval_loop
DEBUG current simulation time is ctime : 27 ns
INFO STATUS : TCL : LOCAL REJECTED seed: 3981500775 at time: 17 ns
INFO STATUS : TCL : 27 ns : NO PROGRESS : false: 0.000000 > 0.000000 REWINDING TO CHECKPOINT {2} at 17 ns
All the Checkpoints created after checkpoint 2 are removed...
------------------------- END eval_loop
UVM_INFO sv/dut.sv(14) @ 20: reporter [dut_if] AFTER drive regs a: 0 b: 0
------------------------- START eval_loop
DEBUG current simulation time is ctime : 27 ns
INFO STATUS : TCL : LOCAL ACCEPTED seed: 1493068099 at time: 17 ns
INFO STATUS : TCL : 27 ns : GOOD : 25.000000 > 0.000000
------------------------- END eval_loop
UVM_INFO sv/dut.sv(14) @ 30: reporter [dut_if] AFTER drive regs a: 1 b: 3
```

Sim Log Example

```
------------------------- START eval_loop
DEBUG current simulation time is ctime : 27 ns
INFO STATUS : TCL : LOCAL ACCEPTED seed: 1493068099 at time: 17 ns
INFO STATUS : TCL : 27 ns : GOOD : 25.000000 > 0.000000
------------------------- END eval_loop
```

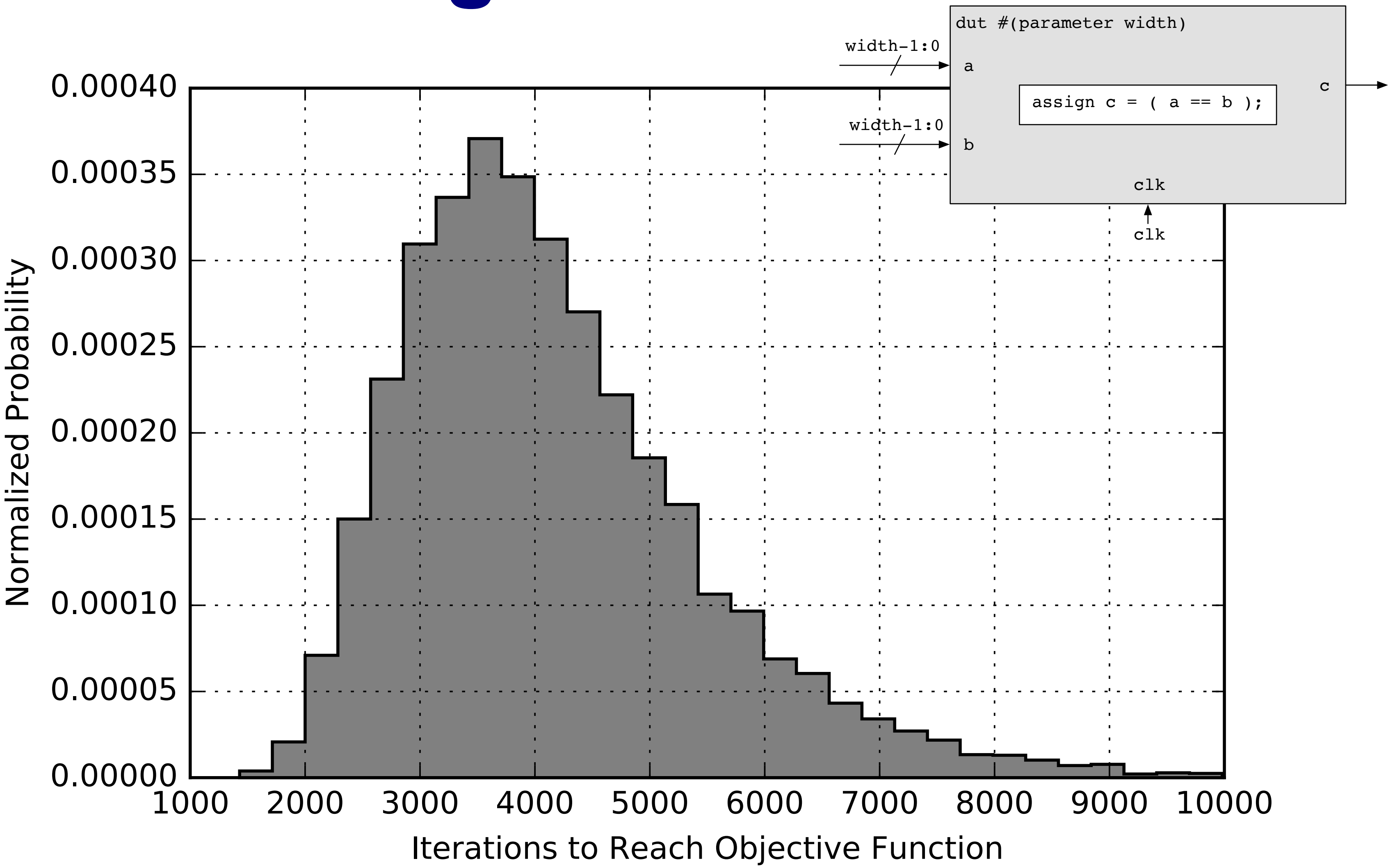
Sim Log Example

```
------------------------- START eval_loop
DEBUG current simulation time is ctime : 27 ns
INFO STATUS : TCL : LOCAL ACCEPTED seed: 1493068099 at time: 17 ns
INFO STATUS : TCL : 27 ns : GOOD : 25.000000 > 0.000000
------------------------- END eval_loop
```

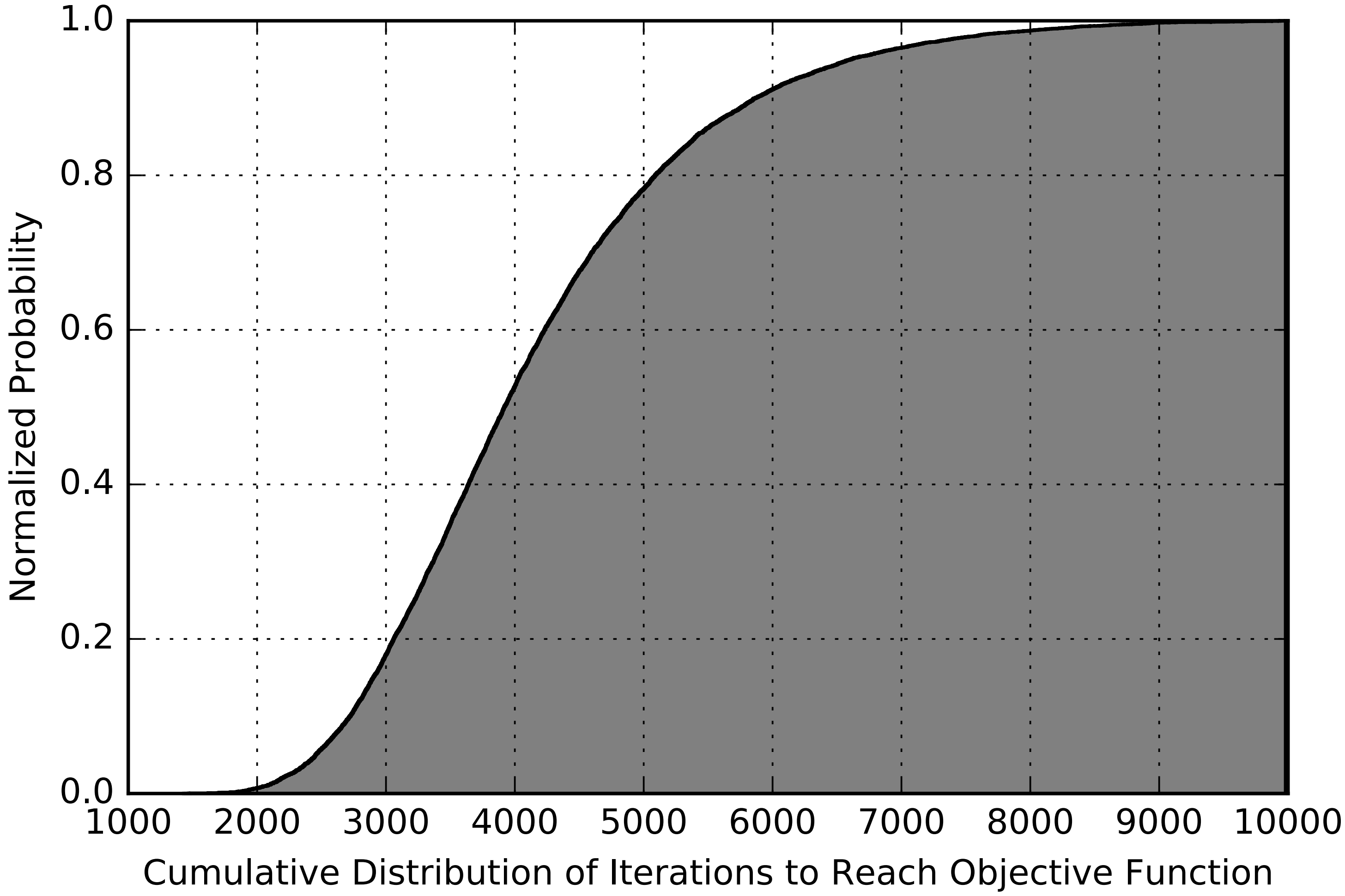
replicate file

```
0  ns : -1          ->   0.000000 : seed 2
17 ns :  0.000000 ->  25.000000 : seed 1493068099
27 ns : 25.000000 ->  50.000000 : seed 765542315
37 ns : 50.000000 ->  75.000000 : seed 1532361113
47 ns : 75.000000 -> 100.000000 : seed 893445949
```

Normalized Probability Histogram width=5



Cumulative Distribution width=5



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Scaling

- Imagine many simulations each trying seeds independently
  - all results sent to a central Server

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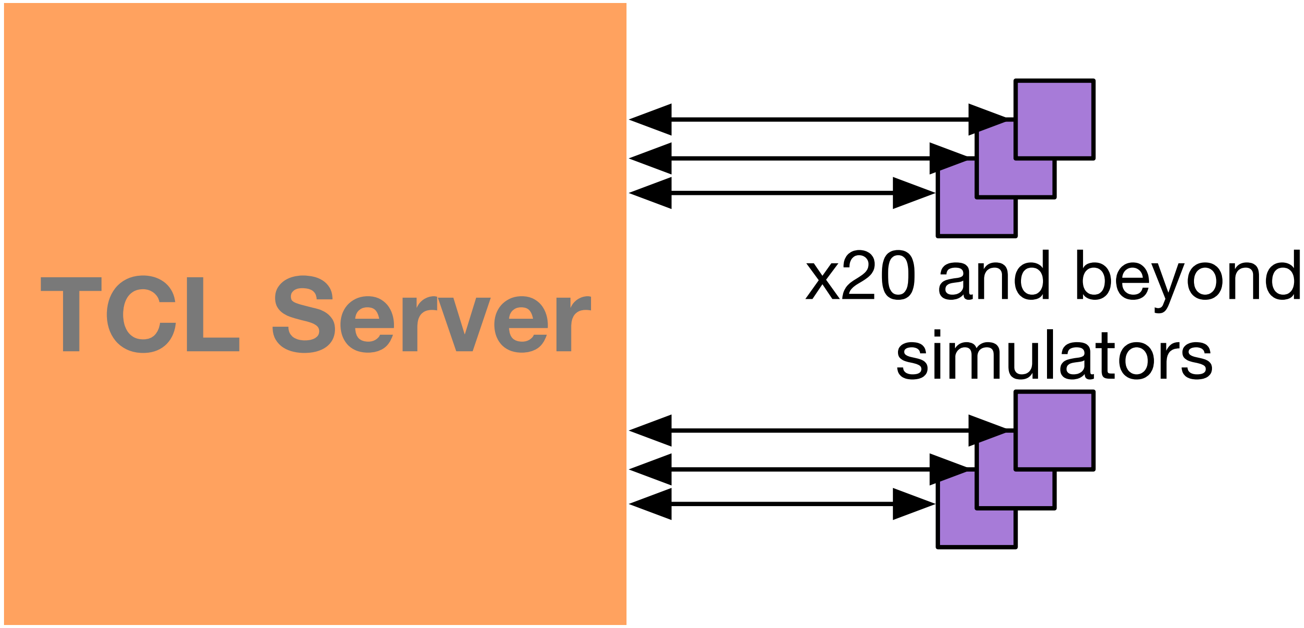
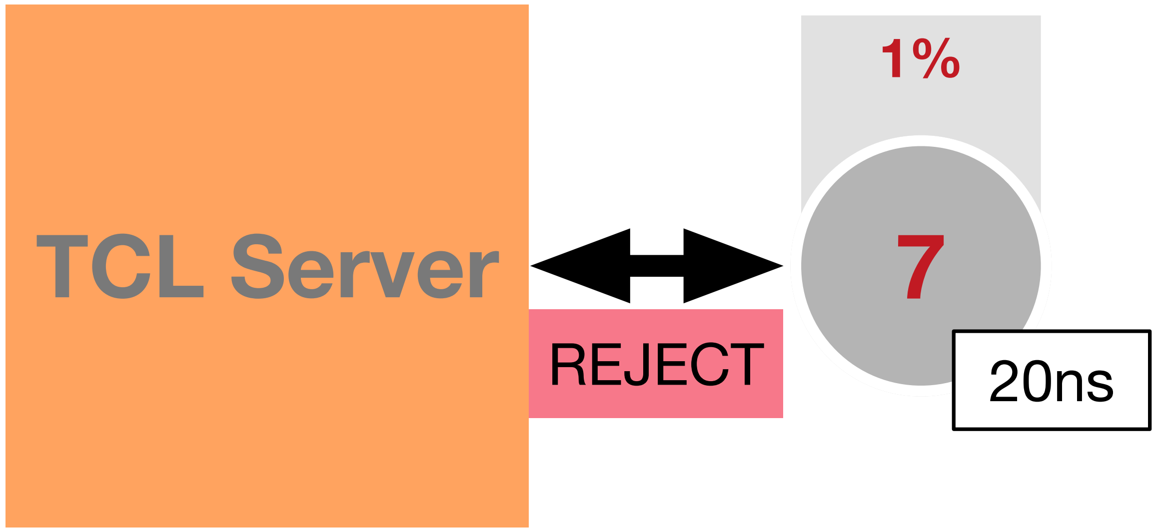
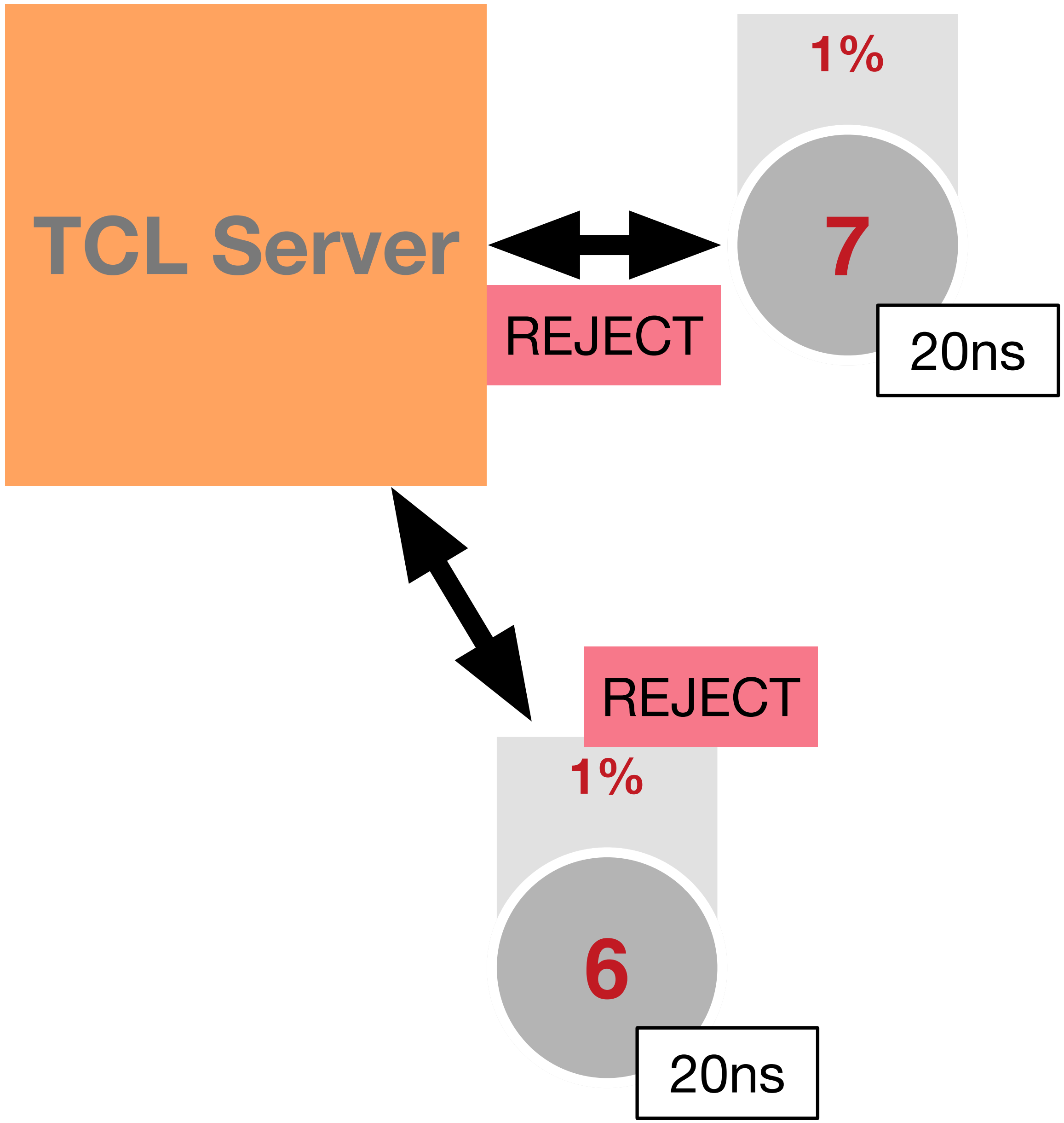
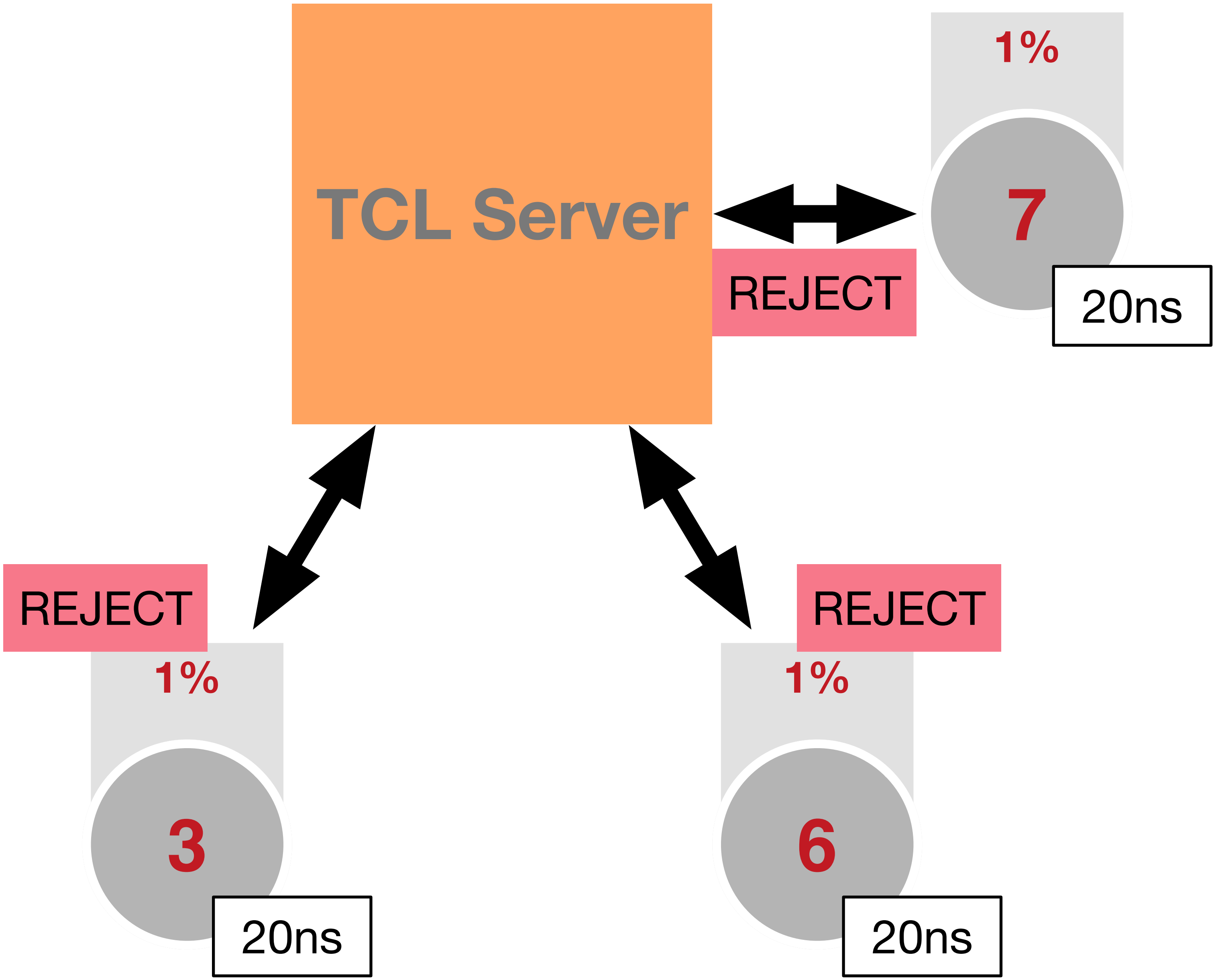



TCL Server

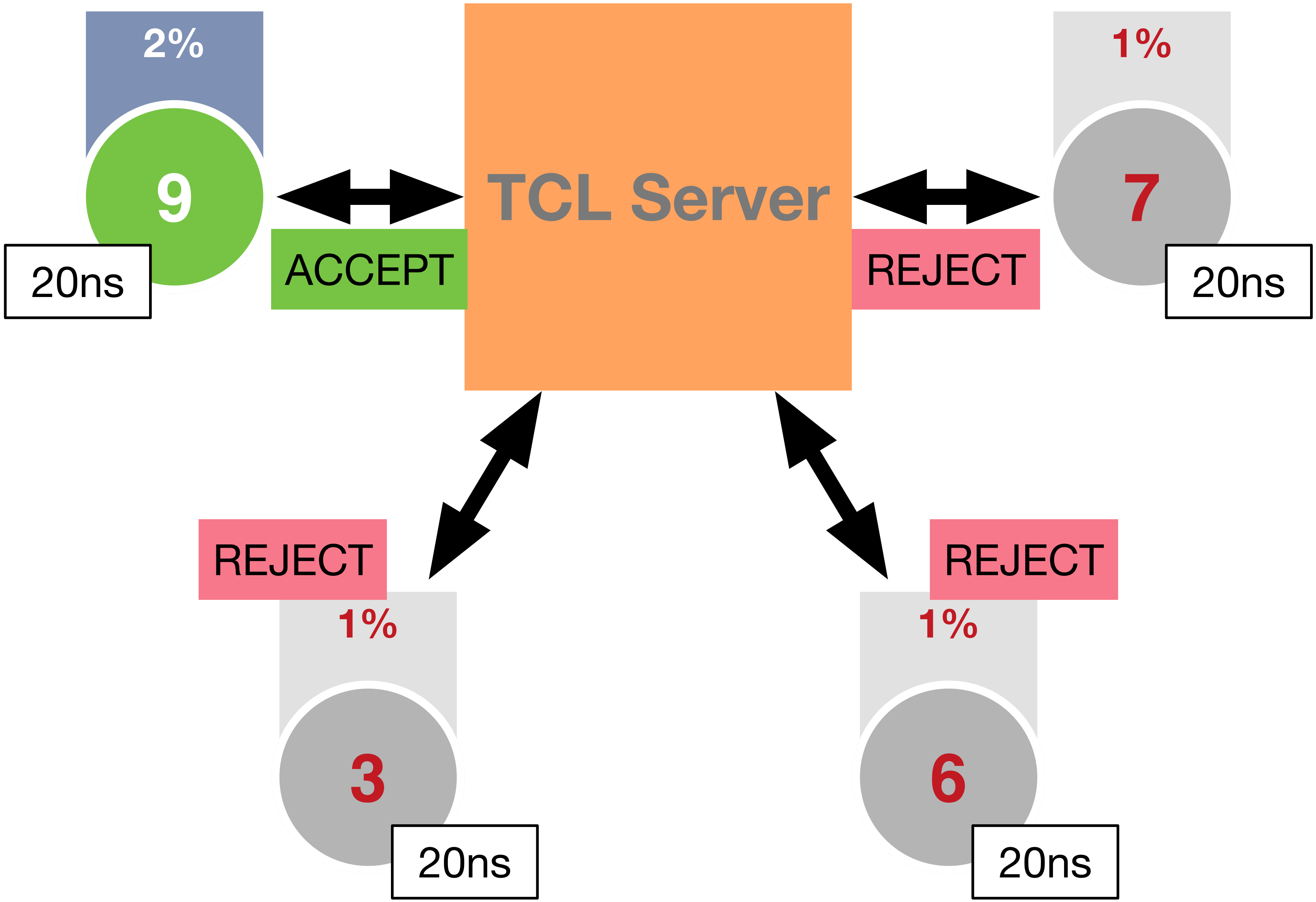


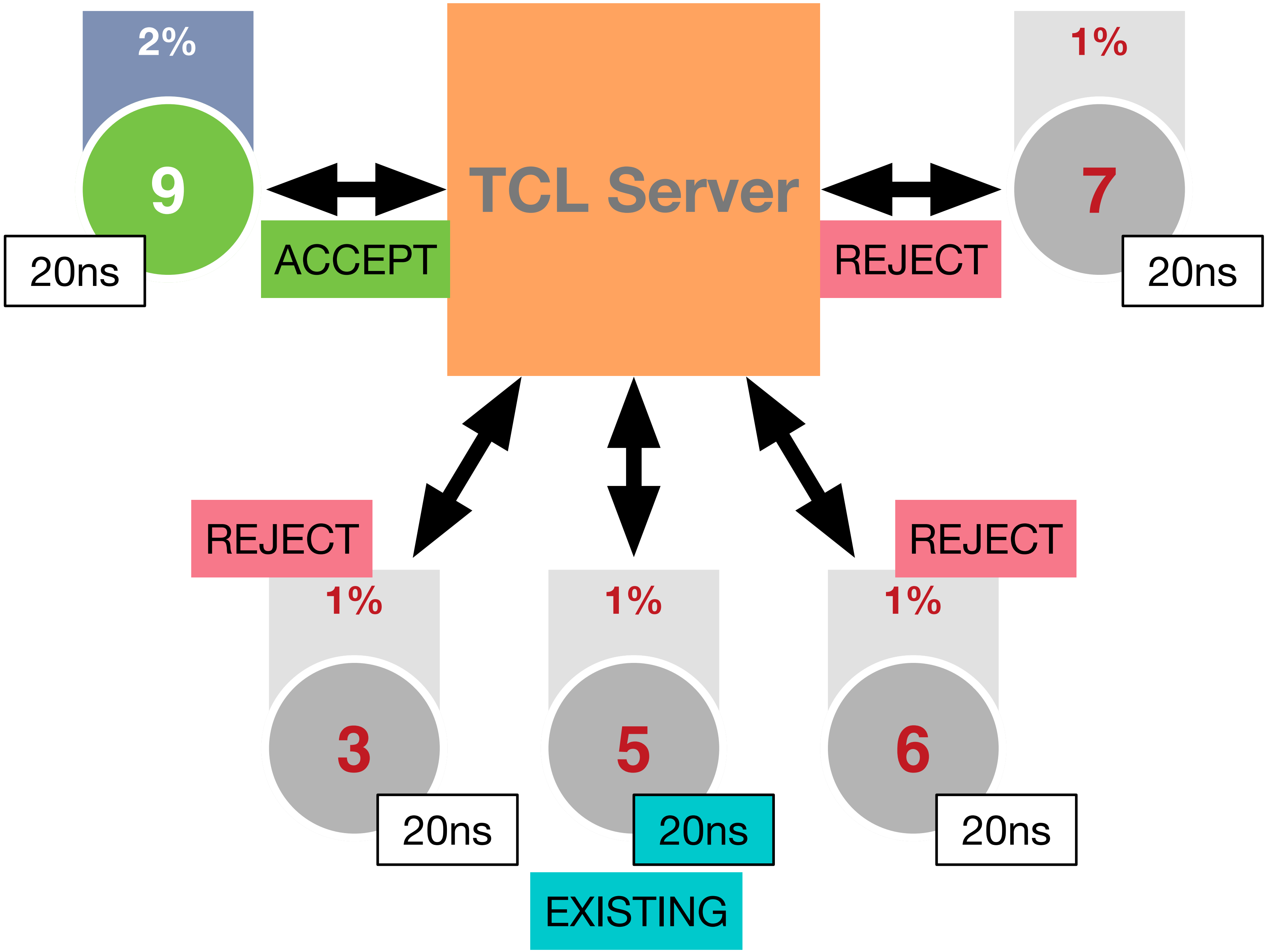
TCL Server
REJECT
1%
7
20ns


TCL Server
1%
7
REJECT
20ns
REJECT
1%
6
20ns



TCL Server
1%
7
REJECT
20ns
REJECT
1%
3
20ns
REJECT
1%
6
20ns


2%
9
20ns
ACCEPT
TCL Server
REJECT
1%
7
20ns
REJECT
1%
3
20ns
REJECT
1%
6
20ns


2%
9
20ns
ACCEPT
TCL Server
REJECT
1%
7
20ns
REJECT
1%
3
20ns
1%
5
20ns
EXISTING
REJECT
1%
6
20ns

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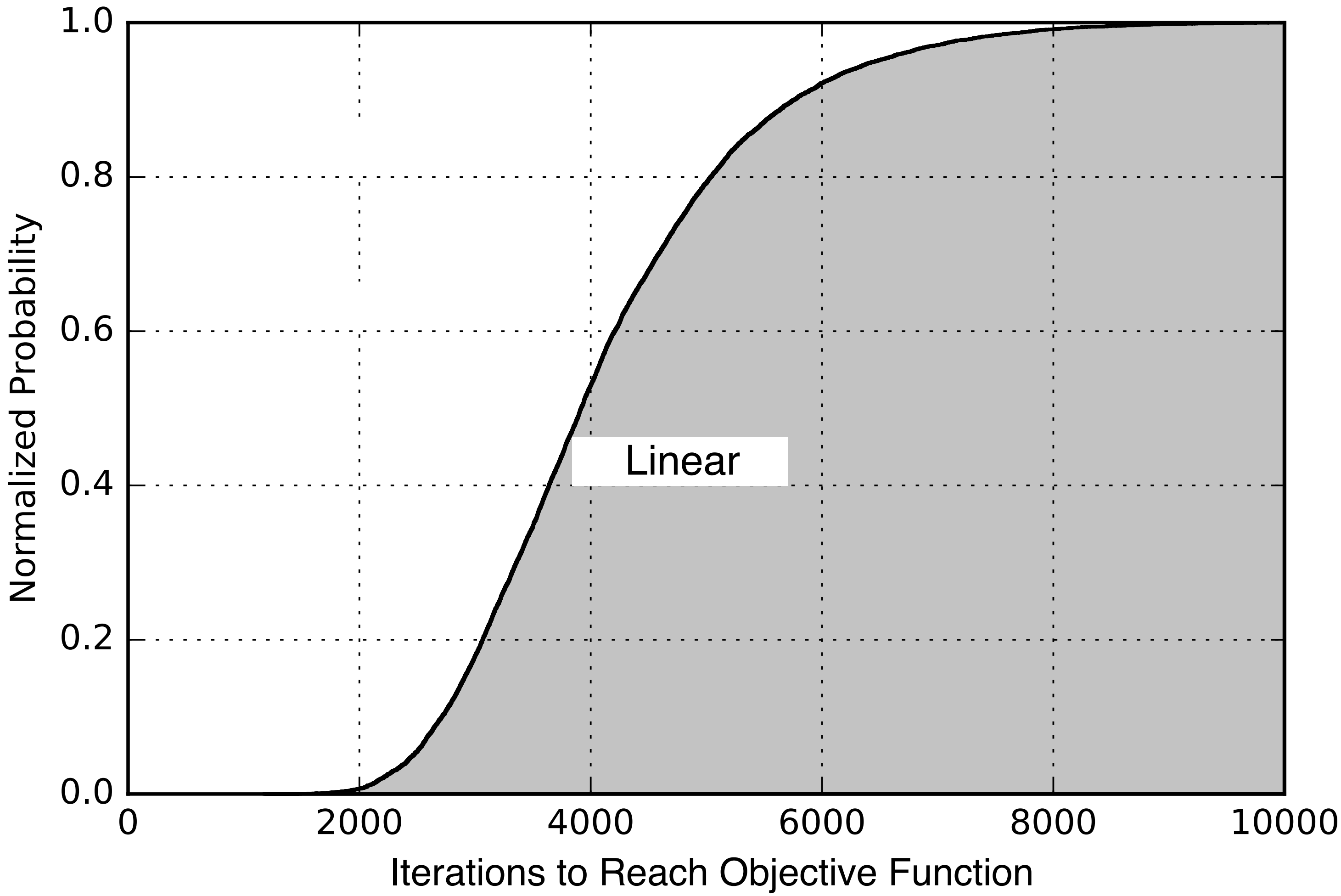
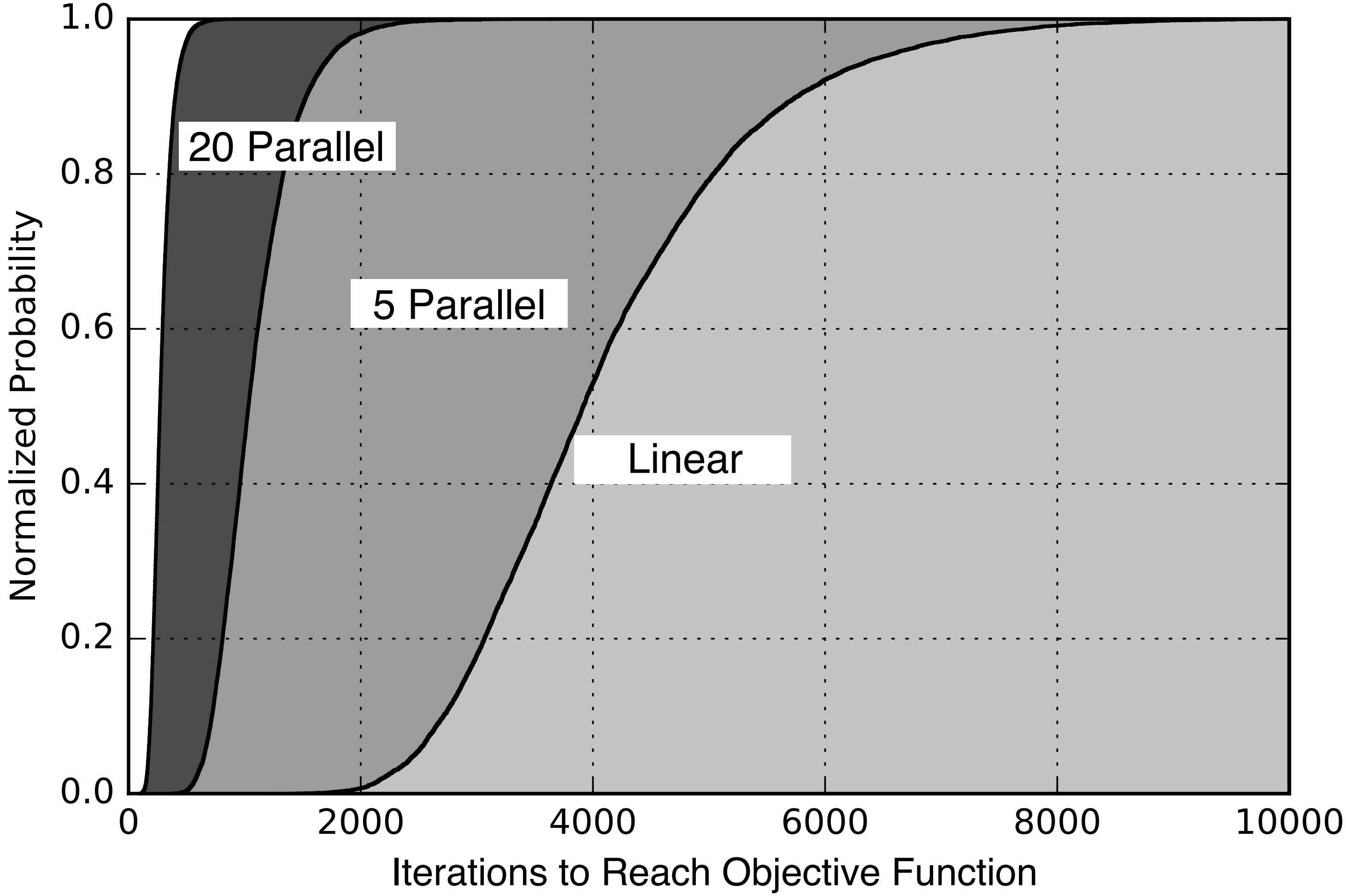
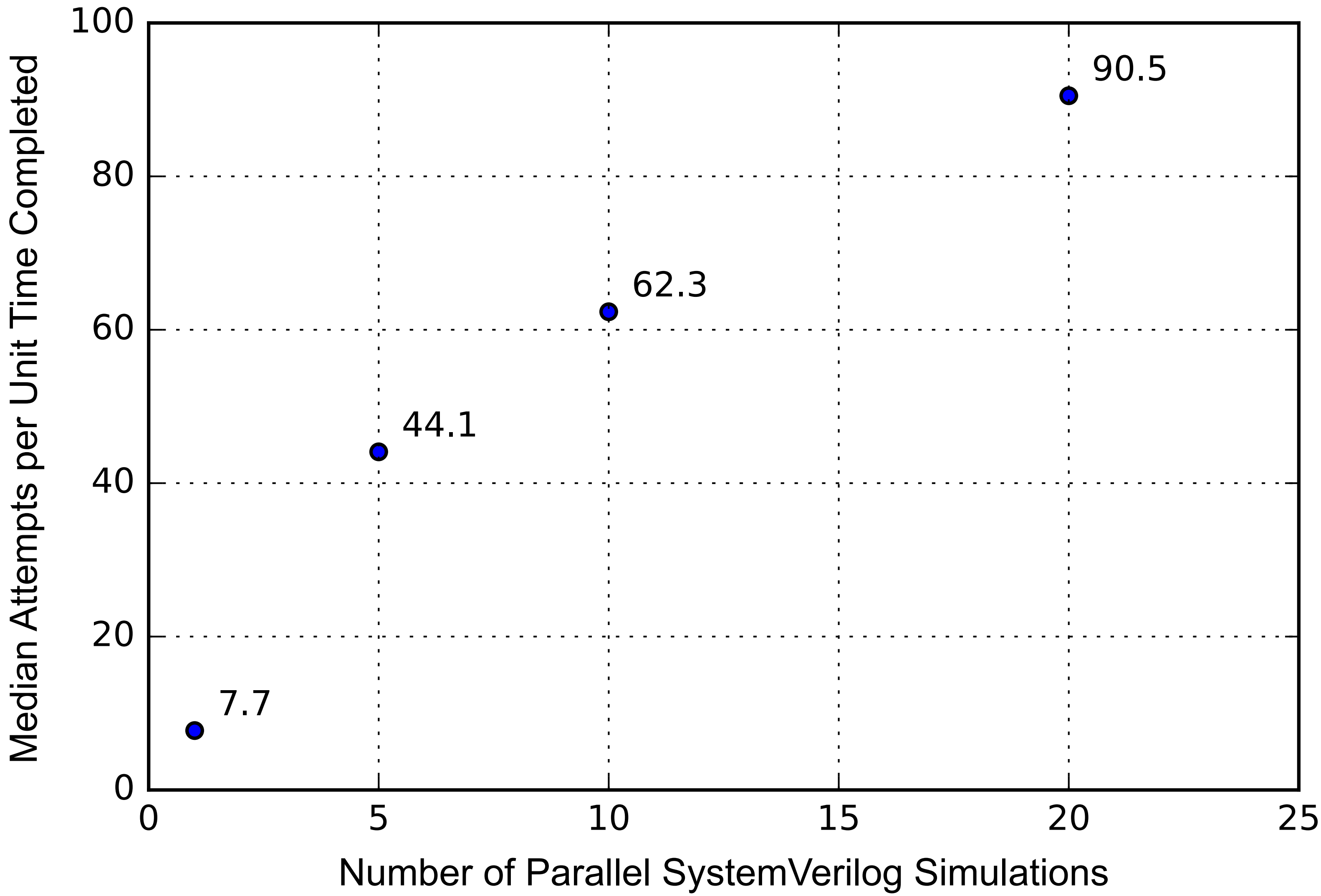
Iterations Required width=5



Iterations Required width=5



Parallel Potential



- **Bernard Lowe**: It's the code you added, sir. It has some, uh...

Robert Ford: "Mistakes" is the word you're too embarrassed to use. You ought not to be. You're a product of a trillion of them. Evolution forged the entirety of sentient life on this planet using only one tool: the mistake.

- Westworld, Season 1 ep. 3, HBO, 2016

Results

- ✅ Faster Automated Coverage Closure
- ✅ Efficient Final Stimulus Solution
- *TBD* Proposed Higher Quality of Coverage

Compare to Formal

- Formal can’t use classes
  - No **UVM**
  - No concept of **seed**
  - Verification IP and Environments Restricted to **Synthesizable**

Compare to Graph

- Graph Based Stimulus
- Objective Function versus Graph
  - Defined **Stimulus** (Graph)
  - Defined **Objective** (Proposal)
- Different approaches to generating desired stimulus
  - *Both can be complementary*

make

```
> make help
clean                     Cleans up work area
help                      Help Text
server                    Starts up a TCL branching server
shutdown                  shutdown the the TCL server
status                    Status from the TCL server
synopsys                  Runs a Synopsys Build and does ...
synopsys_reload           Builds and Reloads a simulation from file
...

  Examples
    > make synopsys WIDTH=3
    > make -j5 sim_synopsys_parallel SERVER=127.0.0.1 PARALLEL_SIMS=5
    > make status
    > make sim_synopsys_reload
```

Limitations

- Improve Probability not Solve Probability
- Simulator Checkpointing Must Be Comprehensive
  - DPI Calls, external C Programs
- Log File is Jumbled on First Run
  - Fixed by running resultant “replicate” file

Limitations

Choice of Interval	`+interval_time=x`
Choice of Start Time	`+start_time=x`
Objective Max Target	`+max_objective=x`
Max Attempts	`+max_attempts=x`

Future Work

- Porting the TCL to other Simulators
- Dynamic Intervals
  - Simulated Annealing
  - Murphy VII has ideas beyond the simple set Interval time used here
- Configuration Space Problem

Conclusion

- Inspiration from Tom Murphy VII paper
  - Nintendo AI
- Goals
  - ✅ Faster Automated Coverage Closure
  - ✅ Efficient Final Stimulus Solution
  - *TBD* Proposed Higher Quality of Coverage

Questions

Shy Audience Questions

- Compare this method with the current method of gathering coverage.
- How can you gather configuration coverage with this method?
- Is you paper better than this presentation because ... well, you know.

Backup Slides

Dynamic Re-Seeds

- SystemVerilog RNG (Random Number Generator)
  - `.randomize()`
  - `.srandom(int)`

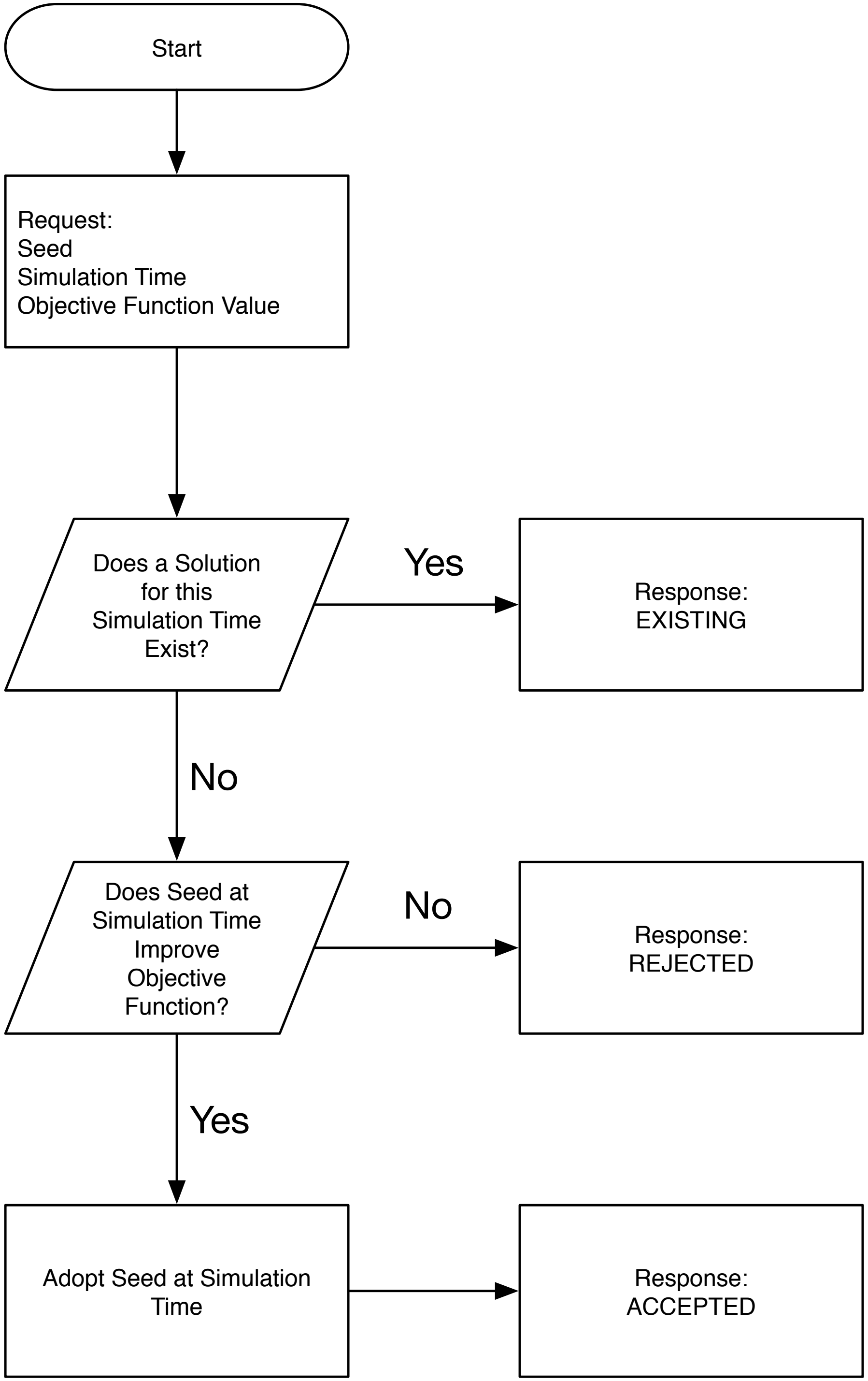
```
static function void set_seed(int unsigned s);
   this.srandom(s);
endfunction
```

Dynamic Re-Seeds

```
function void pre_randomize();

    if (ms_enable) begin
        ms_run();
    end

endfunction
```

UVM Dynamic Re-Seeds

```
function void ms_run();

...

    type_id              = get_type_name();
    type_id2             = {uvm_instance_scope(), type_id};

    if (uvm_pkg::uvm_random_seed_table_lookup.exists(inst_id))

...

    reseed();

endfunction
```


Start
Request:
Seed
Simulation Time
Objective Function Value
Does a Solution for this Simulation Time Exist?
Yes
Response:
EXISTING
No
Does Seed at Simulation Time Improve Objective Function?
No
Response:
REJECTED
Yes
Adopt Seed at Simulation Time
Response:
ACCEPTED

UVM reseed

reseed

```
function void reseed ()
```

Calls *srandom* on the object to reseed the object using the UVM seeding mechanism, which sets the seed based on type name and instance name instead of based on instance position in a thread.