

COMS31700 Design Verification: Coverage

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(Acknowledgement: Avi Ziv from the IBM Research Labs in Haifa has kindly permitted the re-use of some of his slides.)

Last Time

- Verification Cycle
- Verification Methodology &
- Verification Plan

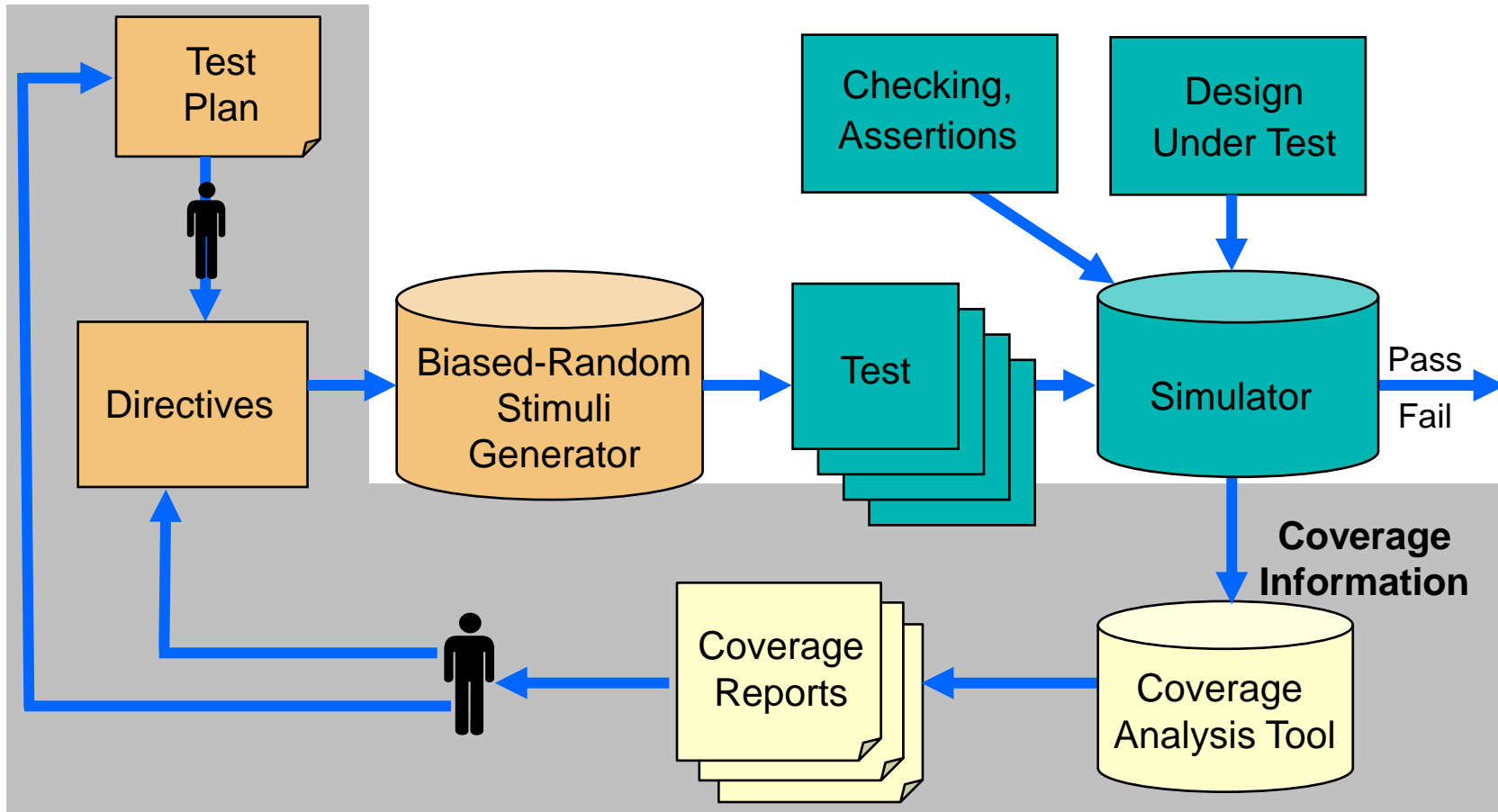
Previously: **Verification Tools**

Coverage is part of the Verification Tools.

Outline

- Introduction to coverage
- Code coverage models
- Structural coverage models
- Functional coverage
- Case study and lessons to learn
- Coverage analysis

Simulation-based Verification Environment



Why Coverage?

- Simulation is based on limited execution samples
 - Cannot run all possible scenarios, but
 - Need to know that all (important) areas of the DUV are verified
- Solution: Coverage measurement and analysis
- The main ideas behind coverage
 - Features (of the specification and implementation) are identified
 - Coverage models capture these features

Coverage Goals

- Measure the "quality" of a set of tests
 - NOTE: Coverage gives ability to see what **has not been** verified!
 - Coverage completeness does not imply functional correctness of the design! Why?
- Help create regression suites
 - Ensure that all parts of the DUV are covered by regression suite
- Provide a stopping criteria for unit testing
 - Why "only" for unit testing?
- Improve understanding of the design

Coverage Types

- Code coverage
- Structural coverage
- Functional coverage
- Other classifications
 - Implicit vs. explicit
 - Specification vs. implementation

Code Coverage - Basics

- Coverage models are based on the HDL code
 - Implicit, implementation coverage
- Coverage models are **syntactic**
 - Model definition is based on syntax and structure of the HDL
- **Generic models** – fit (almost) any programming language
 - Used in both software and hardware design

Code Coverage - Scope

Code coverage can answer the question:

“Is there a piece of code that has not been exercised?”

- Method used in software engineering for some time.
- Have you used gcov?

Main problem:

- **False positive answers can look identical to true positive answers.**

False positive: A bad design is thought to be good.

- **Useful for profiling:**
 - Run coverage on testbench to indicate what areas are executed most often.
 - **Gives insight on what to optimize!**
- Many types of code coverage report metrics/models.

Types of Code Coverage Models

- Control flow
 - Check that the control flow of the program has been fully exercised
- Data flow
 - Models that look at the flow of data in, and between, programs/modules
- Mutation
 - Models that check directly for common bugs by mutating the code and comparing results

Control Flow Models

- Routine (function entry)
 - Each function / procedure is called
- Function call
 - Each function is called from every possible location
- Function return
 - Each return statement is executed
- Statement (block)
 - Each statement in the code is executed
- Branch/Path
 - Each branch in branching statement is taken
 - `if`, `switch`, `case`, `when`, ...
- Expression/Condition
 - Each (sub-)expression in Boolean expression takes true and false values
- Loop
 - All possible number of iterations in (Bounded) loops are executed

Statement/Block Coverage

Measures which lines (statements) have been executed by the verification suite.

```
✓ if (parity==ODD || parity==EVEN) begin
❑ parity_bit = compute_parity(data,parity);
  end
✓ else begin
✓ parity_bit = 1'b0;
  end
✓ #(delay_time);
✓ if (stop_bits==2) begin
✓ end_bits = 2'b11;
✓ #(delay_time);
  end
```

What do we need to do to get statement coverage to 100%?

- Why has this never occurred?
- Is it a condition that can never occur? Was it simply forgotten?
- (Dead code can be “ok”!) WHY?

Path/Branch Coverage

Measures all possible ways to execute a sequence of statements.

- Are all **if/case** branches taken?
- How many execution paths?

```
✓ if (parity==ODD || parity==EVEN) begin
✓ parity_bit = compute_parity(data,parity);
end
✓ else begin
✓ parity_bit = 1'b0;
end
✓ #(delay_time);
✓ if (stop_bits==2) begin
✓ end_bits = 2'b11;
✓ #(delay_time);
end
```

□ □ ✓ ✓

Note: 100%
statement coverage
but only 75% path
coverage!

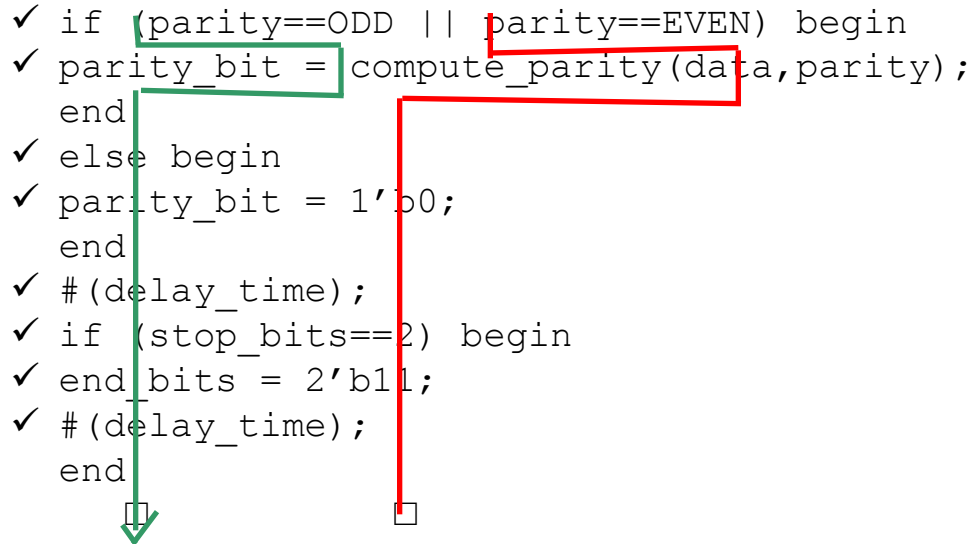
- **Dead code:** default branch on exhaustive **case**
- Don't measure coverage for code that was not meant to run! (tags)

Expression/Condition Coverage

Measures the various ways paths through the code are executed.

- Where a branch condition is made up of a Boolean expression, want to know which of the subexpressions have been covered.

```
✓ if (parity==ODD || parity==EVEN) begin
✓ parity_bit = compute_parity(data,parity);
end
✓ else begin
✓ parity_bit = 1'b0;
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✓ #(delay_time);
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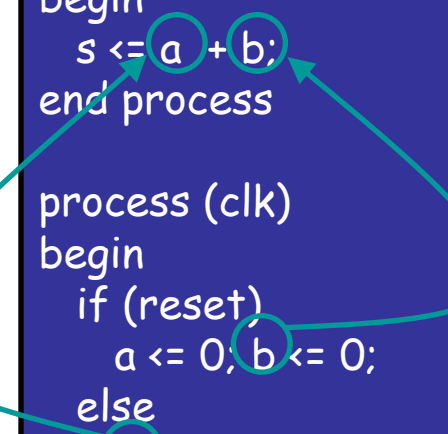


Note: Only 50%
expression
coverage!

- **Analysis:** Understand WHY part of an expression was not executed
- Reaching 100% expression coverage is extremely difficult.
(See also MC/DC coverage and use in certification!) ☺

Data Flow Models

- Coverage models that are based on flow of data during execution
- Each coverage task has two attributes
 - **Define** – where a value is assigned to a variable (signal, register, ...)
 - **Use** – where the value is being used
- Types of dataflow models
 - C-Use – Computational use
 - P-Use – Predicate use
 - All Uses – Both P and C-Uses



```
process (a, b)
begin
  s <= a + b;
end process

process (clk)
begin
  if (reset)
    a <= 0; b <= 0;
  else
    a <= in1; b <= in2;
  end if
end process
```

Mutation Coverage

- Mutation coverage is designed to detect simple (typing) mistakes in the code
 - Wrong operator
 - + instead of –
 - >= instead of >
 - Wrong variable
 - Offset in loop boundaries
- A mutation is considered covered if we found a test that can distinguish between the mutation and the original
 - Strong mutation – the difference is visible in the primary outputs
 - Weak mutation – the difference is visible inside the DUV
- For more on Mutation Coverage see: *J Offutt and R.H. Untch. “Mutation 2000: Uniting the Orthogonal”*
- Commercial tools: Certitude by SpringSoft
<http://www.springsoft.com/products/functional-qualification/certitude>

Code Coverage Models for Hardware

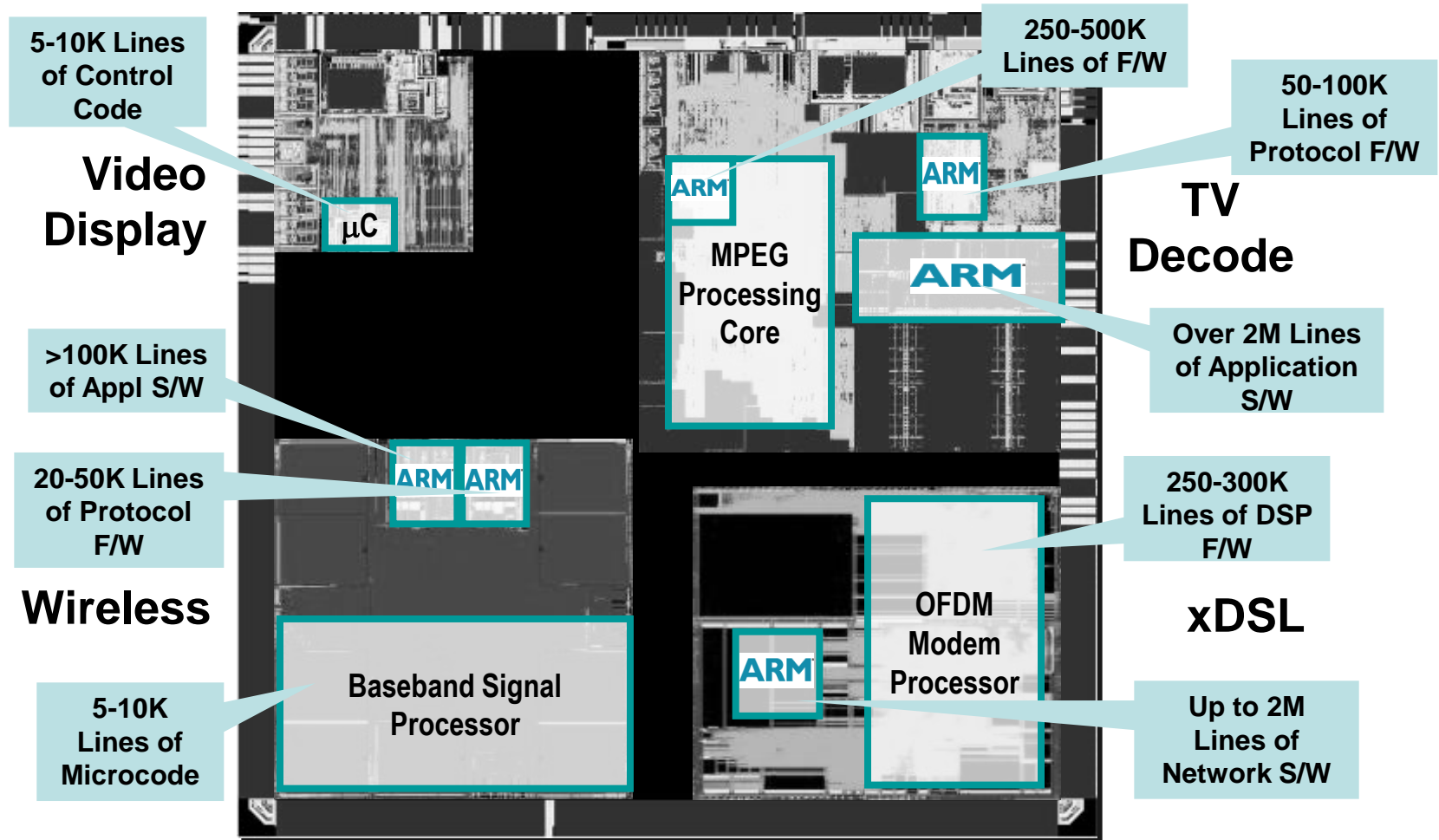
- Toggle coverage
 - Each (bit) signal changed its value from 0 to 1 and from 1 to 0
- All-values coverage
 - Each (multi-bit) signal got all possible values
 - Used only for signals with small number of values
 - For example, state variables of FSMs

Code Coverage Strategy

- Set **minimum % of code coverage** depending on available verification resources and importance of preventing post tape-out bugs.
 - A failure in low-level code may affect multiple high-level callers.
 - Hence, set a higher level of code coverage for unit testing than for system testing.
- **Generally, 90% or 95% goal for statement, branch or expression coverage.**
 - Some feel that less than 100% does not ensure quality.
 - Beware: Reaching full code coverage closure can cost a lot of effort!
 - This effort could be more wisely invested into other verification techniques.
- **Avoid setting a goal lower than 80%.**

Literature: *[J Barkley. Why Statement Coverage Is Not Enough. A practical strategy for coverage closure., TransEDA.]*

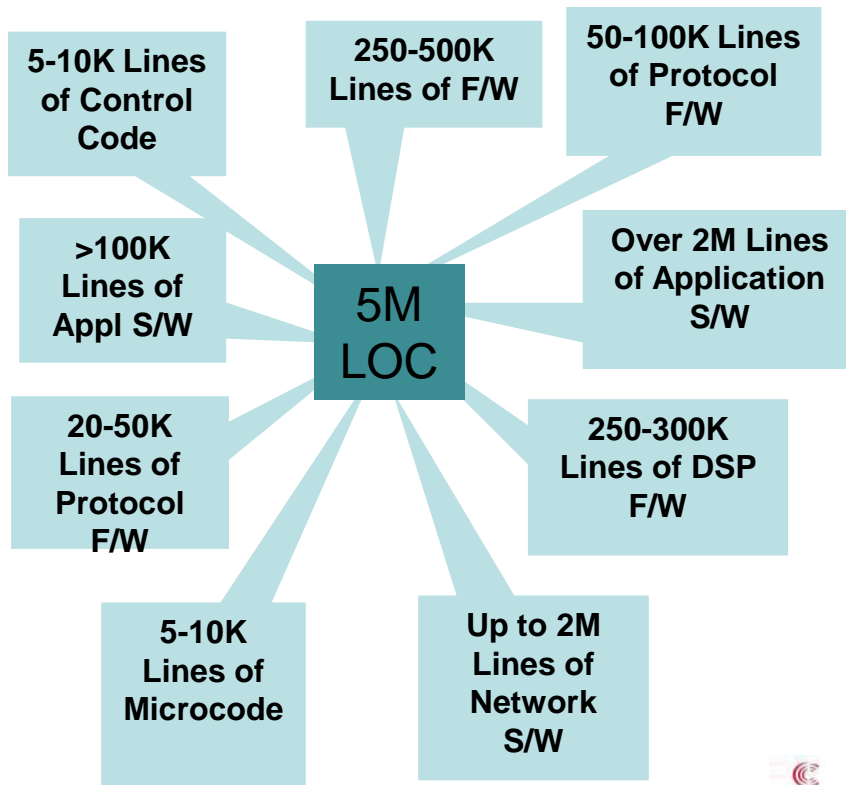
Increasing Design Complexity



Multiple Power Domains, Security, Virtualisation
Nearly five million lines of code to enable Media gateway

Increasing Design Complexity

LOC count:	10K
	100K
	50K
	10K
	500K
	100K
	2M
	300K
	2M
TOTAL:	<u><u>~5M LOC</u></u>



**At 95% coverage, this
leaves 250K LOC
not exercised during
verification!**

Modified Condition/Decision (MC/DC) Coverage

Tutorial on MC/DC Coverage: “*A Practical Tutorial on Modified Condition/Decision Coverage*” by Kelly Heyhurst et. al.

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20010057789_2001090482.pdf

- **Terminology:** Output of a Boolean expression is termed **decision**.
- **Decision coverage = branch coverage**
 - Requires that each decision toggles between true and false.
 - e.g. in `a || b` vectors TF and FF satisfy this requirement
- **Condition coverage**
 - Requires that each condition takes all possible values at least once, but does not require that the decision takes all possible outcomes at least once.
 - e.g. in `a || b` vectors TF and FT satisfy this requirement

Modified Condition/Decision (MC/DC) Coverage

- **Condition/Decision coverage**
 - Requires that each condition toggles and each decision toggles,
 - e.g. in `a || b` vectors TT and FF satisfy this requirement
- **Multiple Condition / Decision coverage**
 - Requires that all conditions and all decisions take all possible values.
 - Exhaustive expression coverage
 - e.g. in `a || b` vectors TT, TF, FT and FF satisfy this requirement
 - **Exponential growth in number of conditions.**

Modified Condition/Decision (MC/DC) Coverage

- **MC/DC Coverage** requires that each condition be shown to **independently** affect the outcome of the decision while fulfilment of the condition/decision coverage requirements.
 - e.g. in $a \mid \mid b$ vectors TF, FT and FF satisfy this requirement
- The independence requirement ensures that the effect of each condition is tested relative to the other conditions.
- A minimum of $(N + 1)$ test cases for a decision with N inputs is required for MC/DC in general.
- In some tools MC/DC coverage is referred to as **Focused Expression Coverage (fec)**.

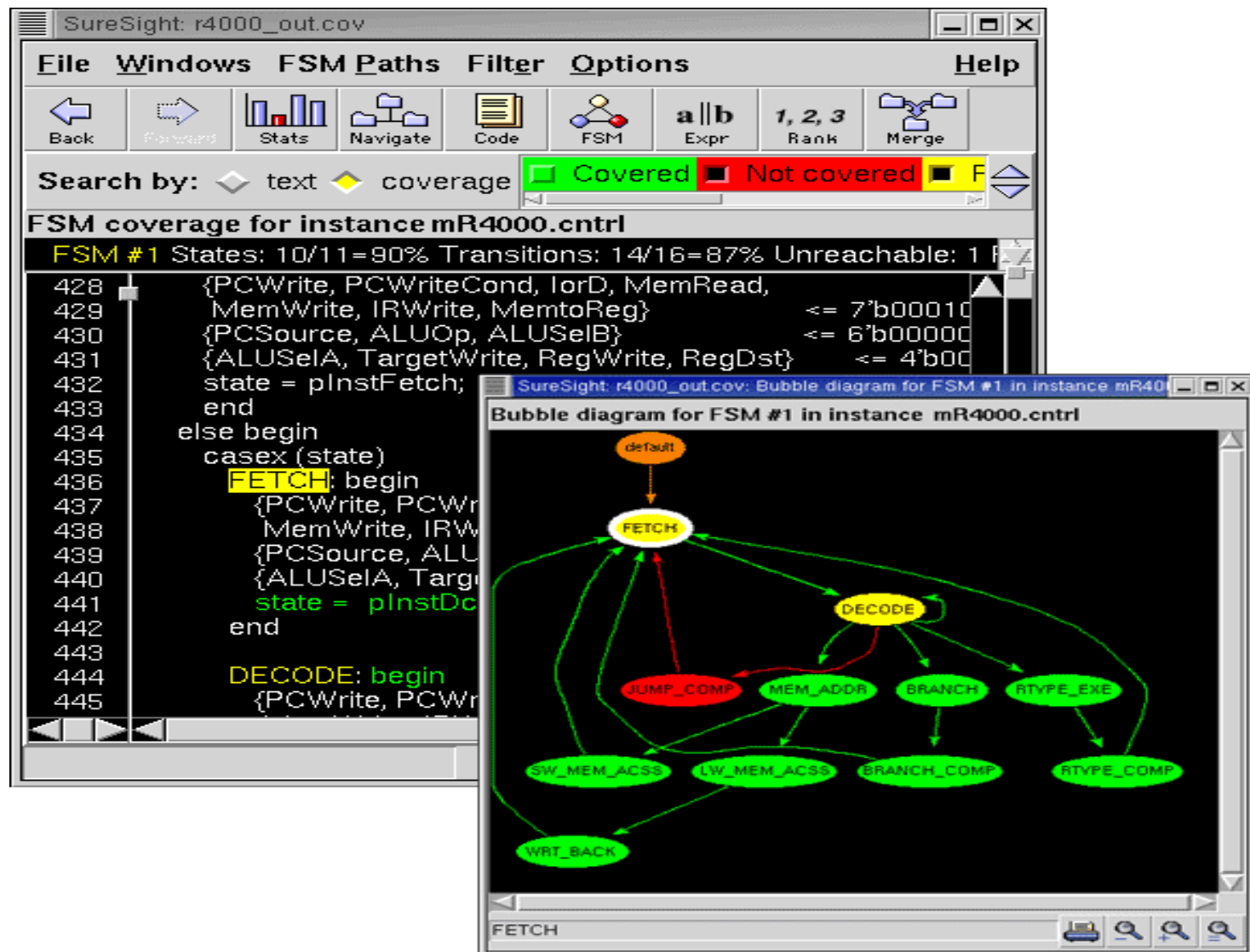
Structural Coverage

- Implicit coverage models that are based on **common structures in the code**
 - FSMs, Queues, Pipelines, ...
- The **structures are extracted automatically** from the design and pre-defined coverage models are applied to them
- Users may refine the models
 - Define illegal events

State-Machine Coverage

- State-machines are the essence of RTL design
- FSM coverage models are the most commonly used structural coverage models
- Types of coverage models
 - State
 - Transition (or arc)
 - Path

FSM Coverage Report



Code Coverage - Limitations

- Coverage questions not answered by code coverage tools
 - Did every instruction take every exception?
 - Did two instructions access the register at the same time?
 - How many times did cache miss take more than 10 cycles?
 - Does the implementation cover the functionality specified? [Need RBT!]
 - ...(and many more)
- Code coverage indicates how thoroughly the test suite exercises the source code!
 - Can be used to identify outstanding corner cases
- Code coverage lets you know if you are not done!
 - It does not indicate anything about the **functional correctness** of the code!
- **100% code coverage does not mean very much.** ☹
- Need another form of coverage!

Functional Coverage

- It is important to cover the **functionality** of the DUV.
 - Most functional requirements can't easily be mapped into lines of code!
- **Functional coverage models** are designed to assure that various aspects of the functionality of the design are verified properly, they link the requirements/specification with the implementation
- Functional coverage models are specific to a given design or family of designs
- Models cover
 - The inputs and the outputs
 - Internal states or microarchitectural features
 - Scenarios
 - Parallel properties
 - Bug Models

Functional Coverage Model Types

- **Discrete set of coverage tasks**
 - Set of unrelated or loosely related coverage tasks often derived from the requirements/specification
 - Often used for corner cases
 - Driving data when a FIFO is full
 - Reading from an empty FIFO
 - In many cases, there is a close link between functional coverage tasks and **assertions**
- **Structured coverage models**
 - The coverage tasks are defined in a structure that defines relations between the coverage tasks
 - Allow definition of **similarity and distance** between tasks
 - Most commonly used model types
 - **Cross-product**
 - Trees
 - Hybrid structures

Cross-Product Coverage Model

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

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

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

Example: Cross-Product Coverage Model 1

Design: switch/cache unit

[G Nativ, S Mittermaier, S Ur and A Ziv. *Cost Evaluation of Coverage Directed Test Generation for the IBM Mainframe. In Proceedings of the 2001 International Test Conference, pages 793-802, October 2001.*]

Motivation: Interactions of core processor unit **command-response** sequences can create complex and potentially unexpected conditions causing contention within the **pipes** in the switch/cache unit when many **core processors** (CPs) are active.

All conditions must be tested to gain confidence in design correctness.

Attributes relevant to command-response events:

- Commands - CPs to switch/cache [31]
- Responses - switch/cache to CPs [16]
- Pipes in each switch/cache [2]
- CPs in the system [8]
- (Command generators per CP chip [2])

How big is the coverage space, i.e. how many coverage tasks?

Example: Cross-Product Coverage Model 2

Size of coverage space:

- Coverage space is formed by **cross-product (or, more formally, the Cartesian product) over all attribute value domains.**
- Size of cross-product is product of domain sizes:
 - $31 \times 16 \times 2 \times 8 \times 2 = 15872$
- Hence, there are 15872 coverage tasks.

Example coverage task:

(Command=20, Response=01, Pipe=1, CP=5, CG=0)

Are all of these tasks reachable/legal?

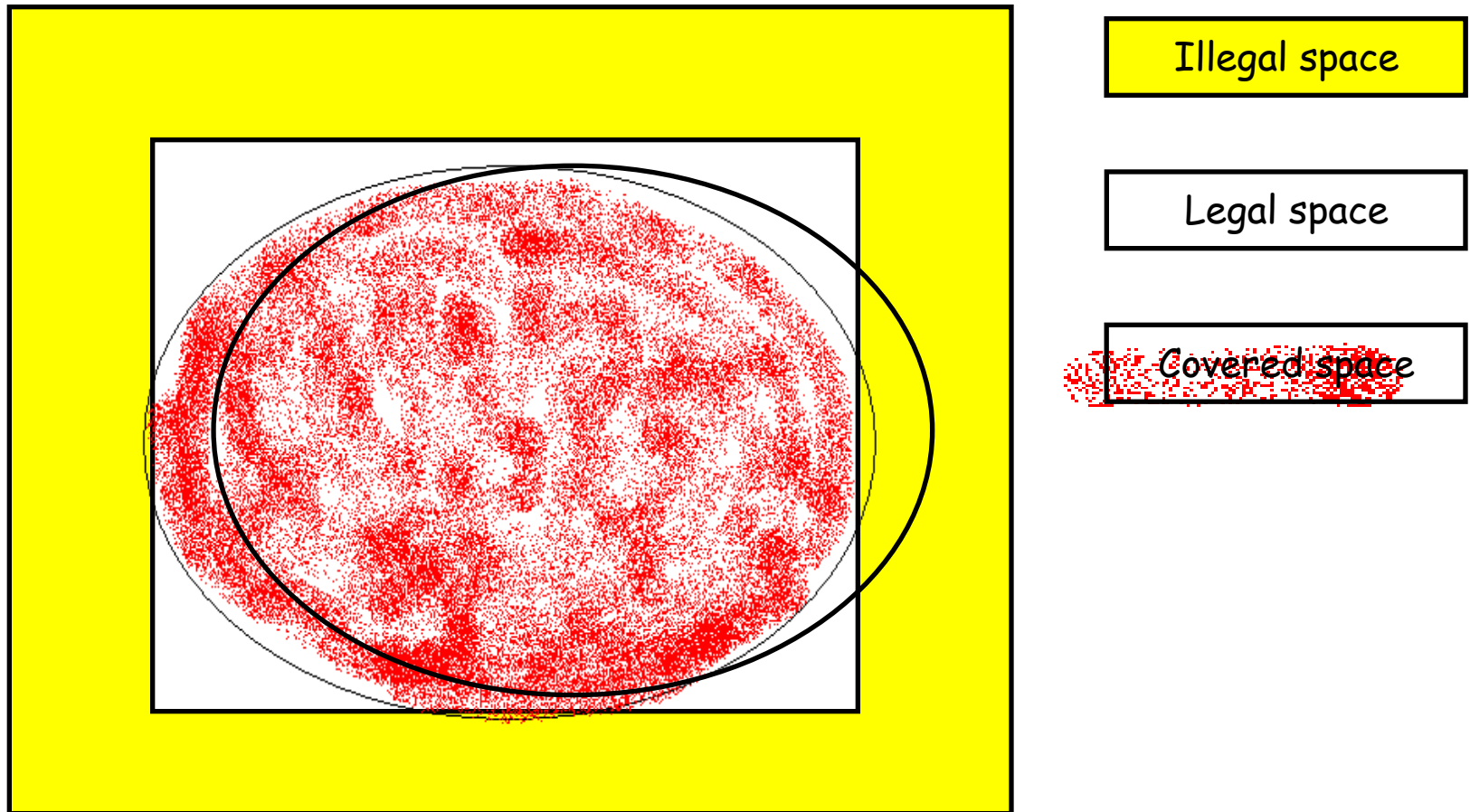
- Restrictions on the coverage model are:
 - possible responses for each command
 - unimplemented command/response combinations
 - some commands are only executed in pipe 1
- After applying restrictions, there are 1968 legal coverage tasks left.
- **Make sure you identify & apply restrictions before you start!**

Defining the Legal and Interesting Spaces

In Practice:

- Boundaries between legal and illegal coverage spaces are often not well understood
- The design and verification team create initial spaces based on their understanding of the design
- Coverage feedback modifies the space definition
- **Sub-models** are used to economically check and refine the spaces
 - Easy to define as these are sub-crosses!
- Interesting spaces tend to **change often** due to shift in focus in the verification process

Legal Spaces Are Self-correcting



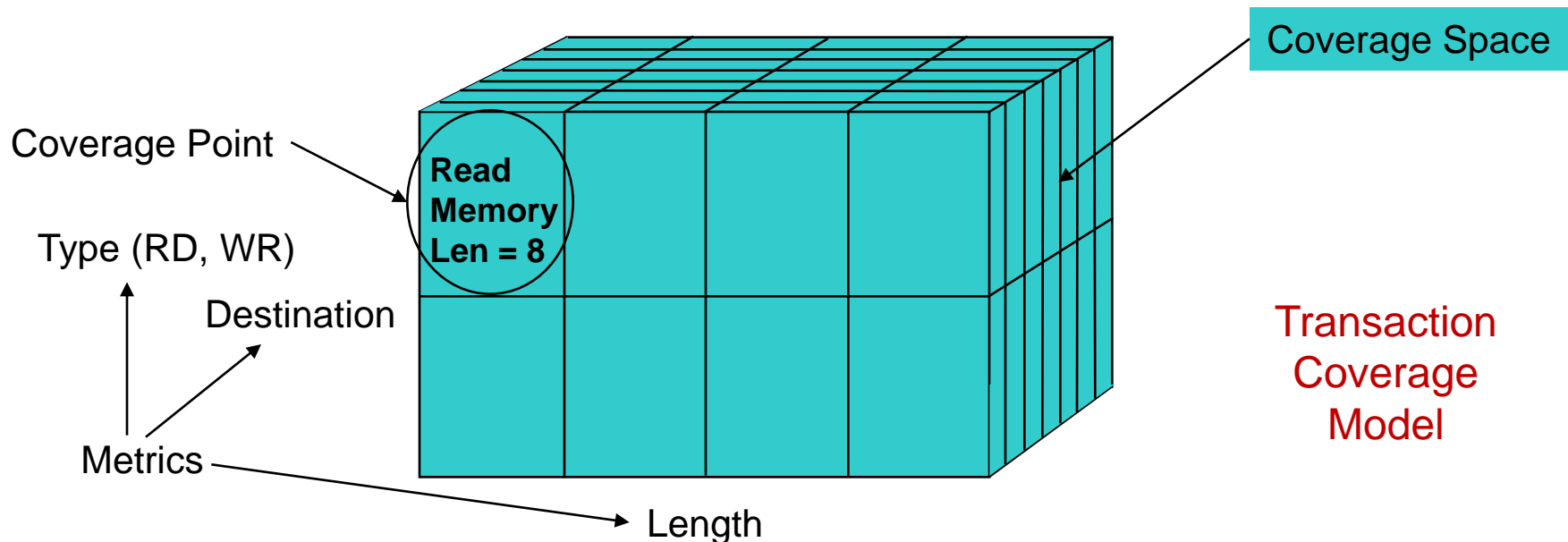
Cross-Product Coverage more formally

- Functional cross-product coverage models can be defined using **multi-dimensional coverage spaces**.
- A **functional coverage space** C_m is defined as the Cartesian product over m signal domains $D_0; \dots; D_{m-1}$.
 - $C_m = D_0 \times \dots \times D_{m-1}$
- Let $\|D_k\| = d_k$ denote the **size of domain** D_k .
- The functional coverage space C_m contains $\|C_m\| = \|D_0\| * \dots * \|D_{m-1}\| = d$ distinct **coverage points** $p_0; \dots; p_{d-1}$.
- A **coverage point** p_i with $i \in \{0; \dots; d-1\}$ is characterized by an **m -tuple of values** $p_i = (v_0; \dots; v_{m-1})$, where $p_i[k] = v_k$ and each $v_k \in D_k$, for $k \in \{0; \dots; m-1\}$.

Formalization facilitates automation of coverage analysis e.g. identification of coverage gaps.

Coverage Terminology

- **coverage model** *n. 1. A set of legal and interesting coverage points in the coverage space.*
- **coverage point** *n. 1. A point within a multi-dimensional coverage space. 2. An event of interest that can be observed during simulation.*



Cross-Product Models In e

Verification Languages such as e support cross-product coverage models:

- The **story** is hidden in the **event**
- The **attributes** and their **values** are defined in the **coverage items**
- **Legal and interesting space** are defined using the **illegal** and **ignore** constructs
 - Restrictions can be defined on the coverage items and the cross itself

```
struct instruction {  
    opcode: [NOP, ADD, SUB,  
            AND, XOR];  
    operand1 : byte;  
  
    event stimulus;  
  
    cover stimulus is {  
        item opcode;  
        item operand1;  
        cross opcode, operand1  
            using ignore = (opcode == NOP);  
    };  
};
```

Summary: Functional Coverage

Determines whether the **functionality** of the DUV was verified.

- Functional coverage models are **user-defined**.
 - (specification driven)
 - This is a skill. It needs (lots of) experience!
 - Focus on **control signals**. WHY?
- **Strengths:**
 - High expressiveness: cross-correlation and multi-cycle scenarios.
 - Objective measure of progress against verification plan.
 - Can identify coverage holes by crossing existing items.
 - Results are easy to interpret.
- **Weaknesses:**
 - Only as good as the coverage metrics.
 - To implement the metrics, engineering effort is required and a lot of expertise.

Summary: Code Coverage

Determines if all the **implementation** was verified.

- Models are implicitly defined by the source code.
 - (implementation driven)
 - statement, path, expression, toggle, etc.
- **Strengths:**
 - Reveals unexercised parts of design.
 - May reveal gaps in functional verification plan.
 - No manual effort is required to implement the metrics. (Comes for free!)
- **Weaknesses:**
 - No cross correlations.
 - Can't see multi-cycle/concurrent scenarios.
 - Manual effort required to interpret results.

Summary: Coverage Models

- Do we need both code and functional coverage? YES!

Functional Coverage	Code Coverage	Interpretation
Low	Low	There is verification work to do.
Low	High	Multi-cycle scenarios, corner cases, cross-correlations still to be covered.
High	Low	Verification plan and/or functional coverage metrics inadequate. Check for “dead” code.
High	High	High confidence in quality.

- Coverage models complement each other!
- No single coverage model is complete on its own.

Case Studies

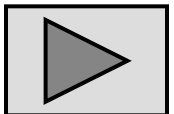
The Coverage Process in Practice

Examples:

- Verifying interdependency in a PowerPC processor
- Pipeline of Branch unit in S/390 system

(Thanks to Avi Ziv from IBM Research Labs in Haifa for sharing these.)

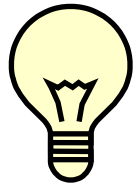
Coverage Analysis



Coverage Closure
(now part of the
“Closing the Cycle” lecture)

Example 1: Interdependency in a PowerPC Processor

- Interdependencies between instructions in the pipeline of a processor create interesting testing scenarios



- They activate many **microarchitectural mechanisms**, such as forwarding and stalling
- Studies have shown that they are the **source of many bugs** in processor designs
- Functionality at this level is often related to increasing **processor performance**

First Approach – Black Box Model

- The motivation (story):

Verify all dependency types of a resource (register) relating to all instructions

- The **semantics** of the coverage tasks:

A coverage task is a quadruplet (I_i, I_k, R, DT) , where Instruction I_i is followed by Instruction I_k , and both share Resource R with Dependency Type DT

- The attributes:

- I_i, I_k - Instruction: add, sub, ...
- R - Register (resource): G1, G2, ...
- DT - Dependency Type:
 - WW, WR, RW, RR and ???

First Approach – Black Box Model

- The motivation (story):

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- The attributes:

- I_i, I_k - Instruction: add, sub, ...
- R - Register (resource): G1, G2, ...
- DT - Dependency Type:
 - WW, WR, RW, RR and None

More Semantics

- The semantics provided so far is too coarse
 - What if I_i is the first instruction in the test and I_k is the 1000 instruction?
- Need to refine the semantics to improve probability of hitting interesting events
- Additional semantics
 - The distance between the instructions is no more than 5
 - The first instruction is at least the 6th

The Legal Space

- Not all combinations are valid
 - Not all instructions read from registers
 - Not all instructions write to registers
 - Fixed point instructions cannot share FP (floating point) registers
 - ... and more

Space and Model Size

- PowerPC has

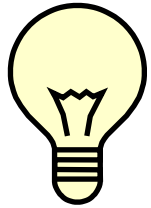
- ~400 instructions

- (actually this is an old number, current PowerPC has close to 1000 instructions)

- ~100 registers

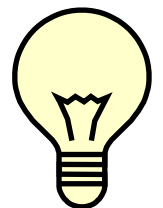
- Coverage space size is $400 \times 400 \times 100 \times 5 = 80,000,000$ tasks

- Even after all restrictions are applied, the model size is still 200,000 tasks



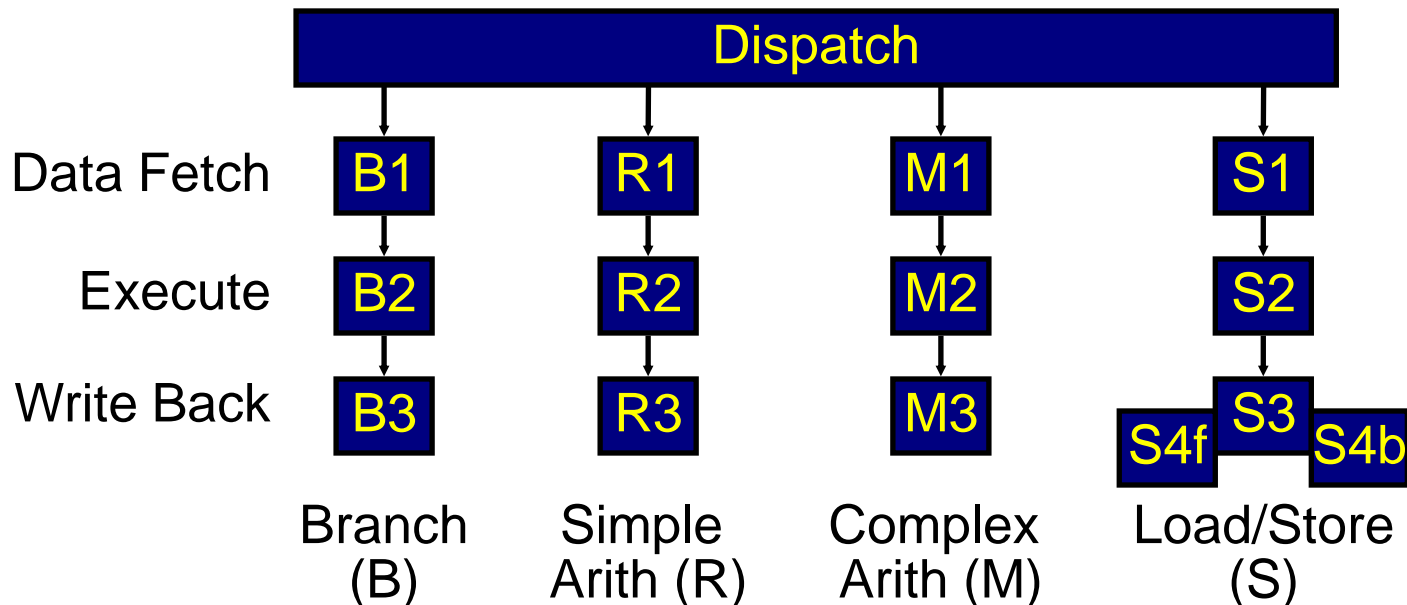
Coverage Results

- A random test generator was used to generate tests that achieved 100% coverage
- Testing the generated tests against the forwarding and stalling mechanisms of a specific processor showed that many such mechanisms were not activated by the tests



Grey Box Model

- Microarchitectural model for a specific Processor
 - Multithreaded
 - In-order execution
 - Up to four instructions dispatched per cycle



Model Details

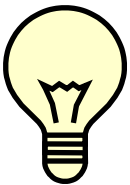
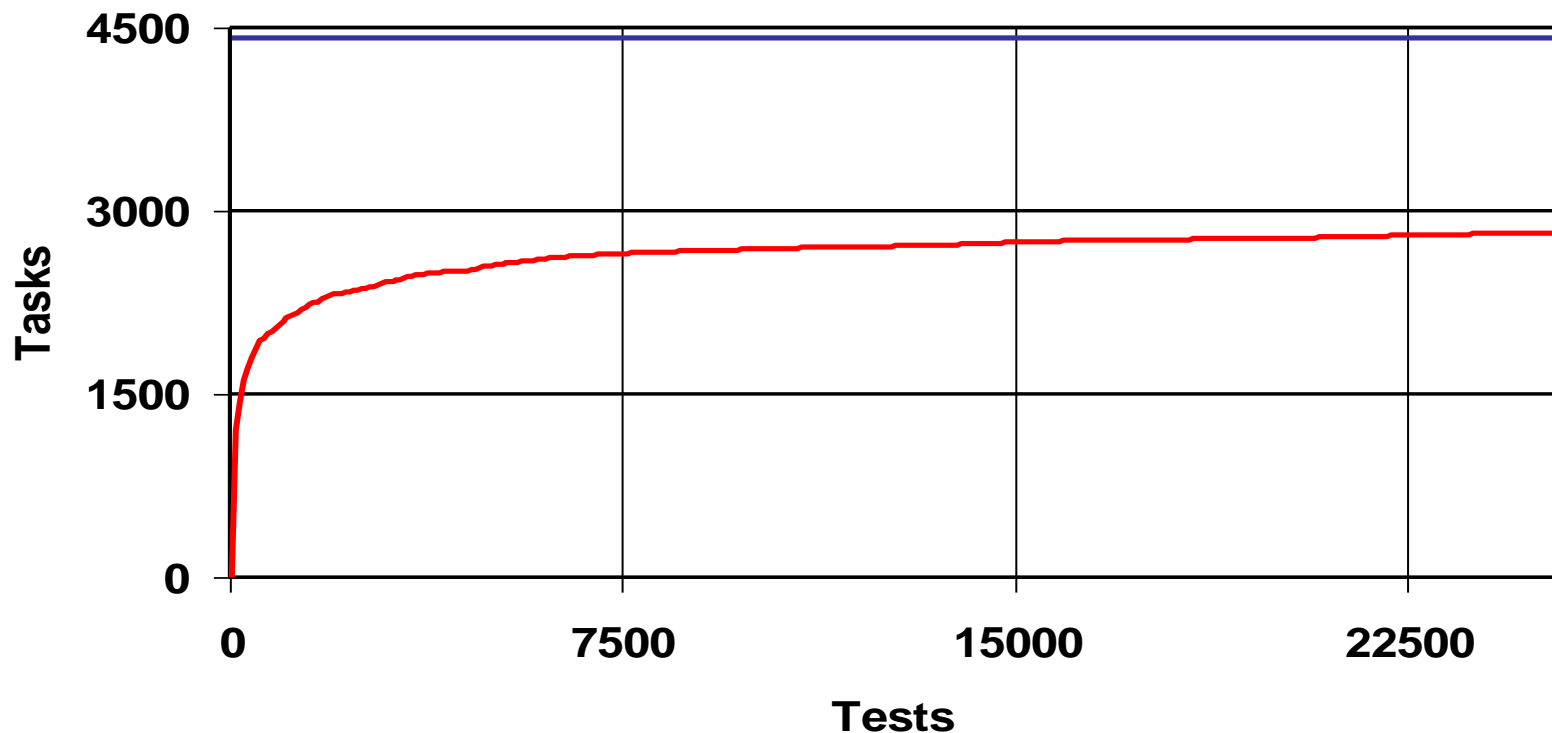
- Model contains 7 attributes
 - Type, pipe and stage of first instruction (I1 ,P1 ,S1)
 - Same attributes for second instruction (I2, P2, S2)
 - Type of dependency between the instructions
 - RR, RW, WR, WW, None
- Grouping is done in a similar way to the architectural model
- Many restrictions exist
 - I1 is simple fixed point \rightarrow P1 is R or M
 - P1 is not S \rightarrow S1 is 1, 2, or 3
- After restrictions, 4418 tasks are legal

Coverage Measurement

- Make sure that you measure what you really want and what really happens
- Use simpler environment and models to **test and debug the measurement system**
 - Hierarchy of models
 - All instructions
 - All pipe stages
 - Controlled simulation

Analysis of Interdependency Model

- After 25,000 tests 2810 / 4418 tasks were covered (64%)



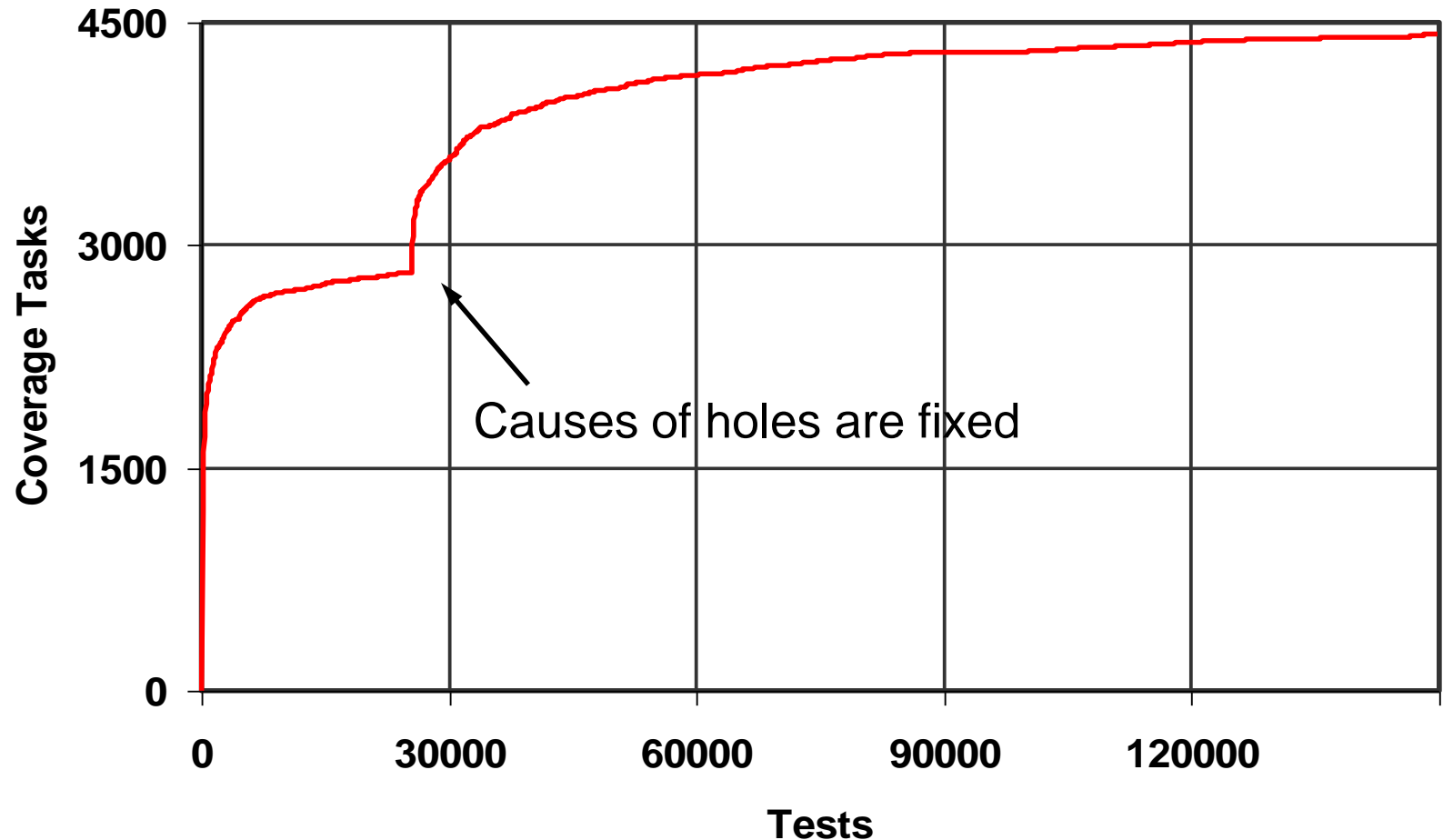
Analysis of Interdependency Model

- Hole analysis detected two major areas that are lightly covered



- Stages S4f and S4b that are specific to thread switching are almost always empty
 - Reason: not enough thread switches during tests
- The address-base register in the store-and-update instruction is not shared with other registers in the test
 - Reason: bug in the test generator that didn't consider the register as a modified register

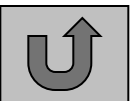
Coverage Progress



Architecture vs. Microarchitecture

- Architecture
 - No implementation details
 - Easy to share between designs
 - Temporal model

- Microarchitecture
 - Pipe implementation knowledge is needed
 - Access to microarchitectural mechanisms is needed
 - White box or at least grey box
 - More for observability than for controllability (Why?)
 - Snapshot model



Example 2: S/390 Branch Unit

- Unit handles branch prediction and execution of branch instructions
- Contains
 - Nine stage complex pipe
 - More than one instruction at the same time in some stages
 - Instructions can enter the pipe at two places
 - Branch history tables
 - and more
- 2 PY spent on verification
- Done by experts with experience with similar designs
- About 100,000 tests per day

Coverage Models for Branch Unit

- Several models defined



- Access to branch tables
- Flow of a branch in the pipe
- State of the pipe

- State of the pipe model

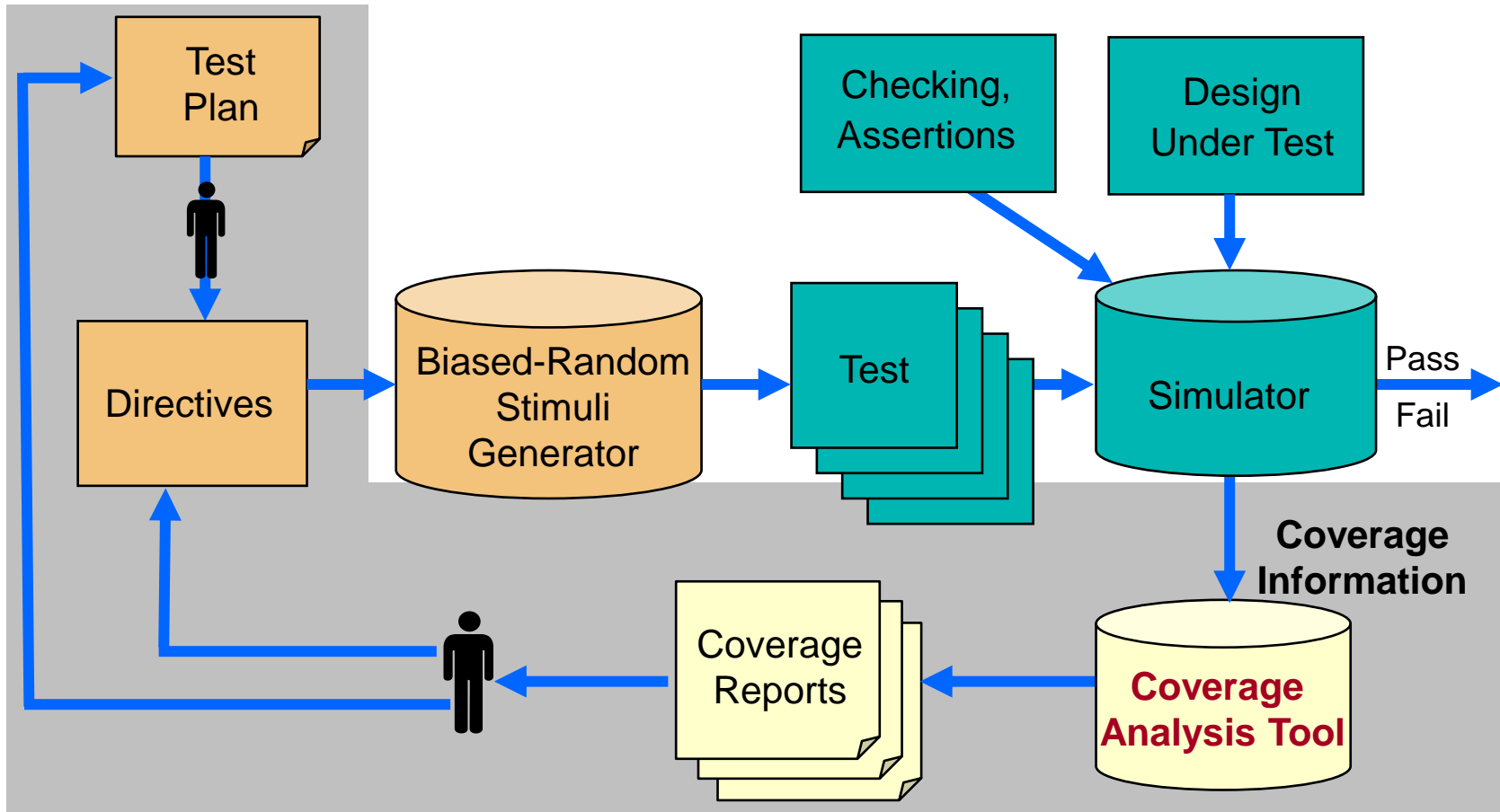


- Attributes contain
 - Location and type of each branch in the pipe in a given cycle
 - Reset signal
- Model size:
 - Without restrictions ~ 15,000,000
 - With restrictions ~ 1400



Coverage Analysis

Coverage Analysis



Why Coverage Analysis

- The main goals of the coverage process are
 - Monitor the quality of the verification process
 - Identify unverified and lightly verified areas
 - Help understanding of the verification process
- **Coverage analysis** helps closing the loop from coverage measurement to the verification plan and test generation

Coverage Analysis Goals

- **Conflicting goals for coverage analysis:**
 - Want to collect as much data as possible
 - Not to miss important events
 - User needs concise and informative reports
 - Not to get drawn into too much detail
- Different types of users require different types of information
- **Goal:** provide concise and informative reports that address the specific needs of the report user

Types of Coverage Reports

- Status reports
 - Coverage status summary
 - Detailed status reports of covered and uncovered tasks
 - Reports can be adapted to specific user needs
 - Allow interactive navigation between reports to explore coverage state
- Progress reports
 - Progress of coverage over time

Coverage Status Summary

- Provides a short summary of the coverage state
- Provides the overall state of the coverage model (or models)
- Useful for
 - Status meetings and status reports
 - A quick glance at the coverage state

Size of coverage space:	1539648
Number of tasks:	4200
Number of tasks covered:	1273
Percent tasks covered:	30.39524
Number of holes:	2927
Number of illegal tasks:	9
Number of traces measured:	16254
Number of cycles measured:	94231273

Detailed Status Report

- Provides details on each task in the coverage model
 - Covered or not
 - How many times covered
 - In how many tests covered
 - First and last time covered
 - Coverage goals
 - ...

	Inst1	Inst2	Reg	Dep	goal	Tests covered	Times covered
Ints1	Add	Mul	GPR	RR	3	1	2
	Add	Stw	G0	RW	3	13	21
	Add	Mul	GPR	RR	3	1	2
	Add	Stw	G0	RW	3	13	21
	Sub.	Add.	CR	WR	3	2	3
Add	Mul	Div	GPR	WW	3	0	0
	Ldw	And	GPR	None	3	3	9
	Add	Mul	GPR	RR	3	1	2
	Add	Stw	G0	RW	3	13	21
	Sub.	Add.	CR	WR	3	2	3
Add	Mul	Div	GPR	WW	3	0	0
	Ldw	And	GPR	None	3	3	9
	FPdiv	FPsub	FPR	WW	3	1	1
	Br	Sub.	CR	RR	3	12	11
	FPdiv	FPsub	FPR	WW	3	1	1
Sub.	Br	Sub.	CR	RR	3	12	11
	Sub.	Add.	CR	WR	3	2	3
	Mul	Div	GPR	WW	3	0	0
	Add	Mul	GPR	RR	3	1	2
	Add	Stw	G0	RW	3	13	21
Mul	Sub.	Add.	CR	WR	3	2	3
	Mul	Div	GPR	WW	3	0	0
	Ldw	And	GPR	None	3	3	9
	FPdiv	FPsub	FPR	WW	3	1	1
	Br	Sub.	CR	RR	3	12	11
Ldw	Ldw	And	GPR	None	3	3	9
	FPdiv	FPsub	FPR	WW	3	1	1
	Br	Sub.	CR	RR	3	12	11
	Ldw	And	GPR	None	3	3	9
	FPdiv	FPsub	FPR	WW	3	1	1
FPdiv	Add	Mul	GPR	RR	3	1	2
	Add	Stw	G0	RW	3	13	21
	Sub.	Add.	CR	WR	3	2	3
	Mul	Div	GPR	WW	3	0	0
	Ldw	And	GPR	None	3	3	9
Br	FPdiv	FPsub	FPR	WW	3	1	1
	Br	Sub.	CR	RR	3	12	11
	Br	Sub.	CR	RR	3	12	11
	Br	Sub.	CR	RR	3	12	11
	Br	Sub.	CR	RR	3	12	11

Detailed Status Reports

- Detailed status reports can provide too much detail even for a moderate coverage model
 - Hard to focus on the areas in the coverage model we are currently interested in
 - Hard to understand the meaning of the coverage information
 - Are we missing something important?
- Solution: **Views into the coverage data**
 - Allow the user to focus on the current area of interest and look at the coverage data with the appropriate level of detail
 - Dynamically define the coverage model

Types of Coverage Views

- Views based on coverage data
 - Counts
 - Dates
- Views based on coverage definition
 - Projection
 - Selection
 - Partitioning
- Other filtering mechanisms

All the above options can be combined

Projection

- Project the n dimensional coverage space onto an m ($< n$) subspace
- Allow users to concentrate on a specific set of attributes
- Help in understanding some of things leading up to the big picture

Instruction	Count	Density
fadd	12321	127/136
fsub	10923	122/136
fmul	4232	94/136
fsqrt	13288	40/56
fabs	9835	38/40

Selection

- Selects a subset of the values of an attribute
- Allows the report to concentrate on a specific area in the coverage model
- Clears the report from data that is not of interest at the time

Instruction	Count	Density
fmadd	9725	107/136
fmsub	9328	111/136
frsq rte	9792	23/36
fsqrt	13288	40/56

Partitioning

- Provides a more coarse-grained view of the coverage data
- Partitions values of given attributes into non-overlapping sets
 - Example: Instruction types -> Arith, Branch, Load, Store, etc

4/12	9/12	9/12
5/12	10/12	8/12
7/12	3/12	9/12
8/12	7/12	10/12

Automatic Coverage Analysis

- Detailed status reports do not always reveal interesting information hidden in the coverage data
 - You need to know where to look
 - You need to know which questions to ask the coverage tool
- Specifically, it is hard to find large areas of uncovered tasks in the coverage model

Large Holes Example

- All combinations of two attributes, X and Y
 - Possible values 0 – 9 for both (100 coverage tasks)
- After a period of testing, 70% coverage is achieved

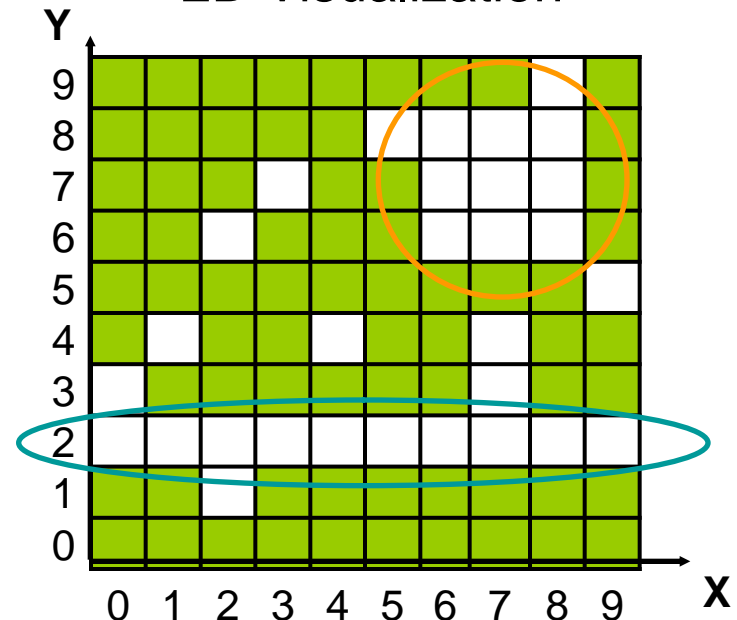
Uncovered Tasks

X	Y
0	2
0	3
1	2
1	4
2	1
2	2
2	6
3	2
3	7
4	2

X	Y
4	4
5	2
5	8
6	2
6	6
6	7
6	8
7	2
7	3
7	4

X	Y
7	6
7	7
7	8
8	2
8	6
8	7
8	8
8	9
9	2
9	9

2D Visualization

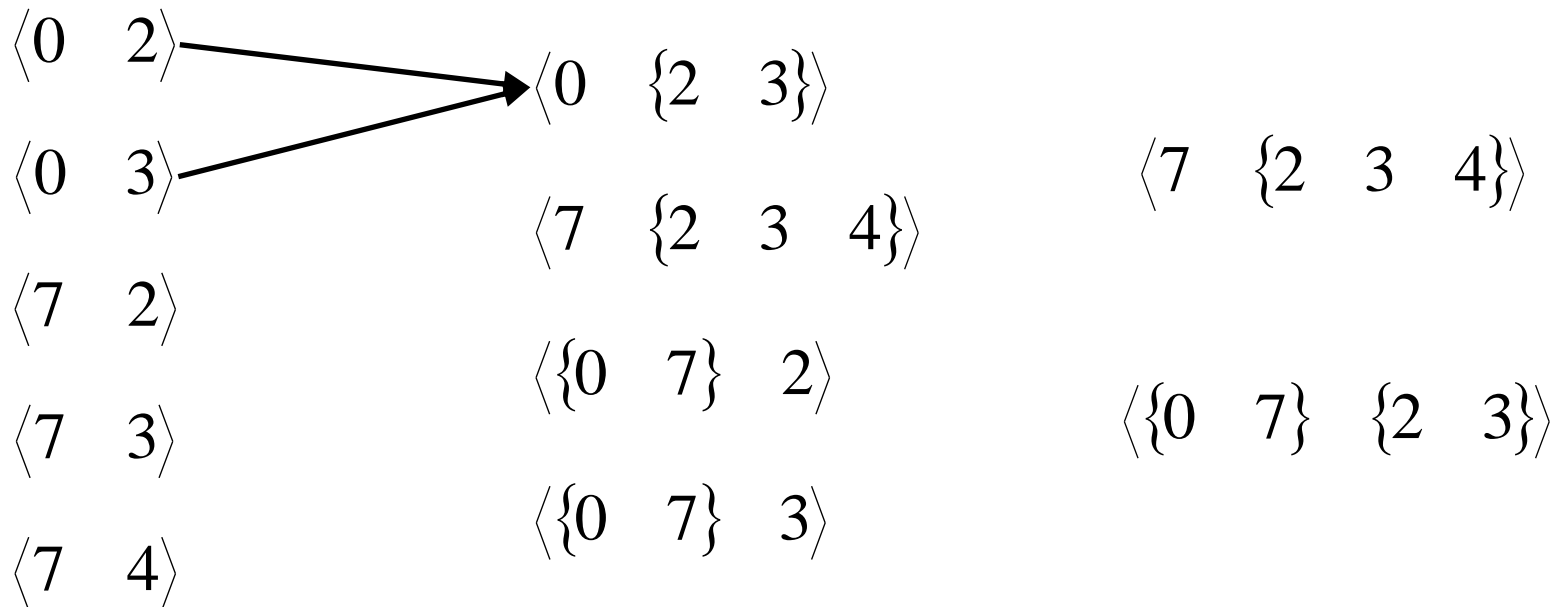


Hole Analysis Algorithms

- Try to find large areas in the coverage space that are not covered
- Use basic techniques to combine sets of uncovered events into large meaningful holes
- Two basic algorithms
 - Aggregation
 - Projected holes

Aggregated Holes

- Combine uncovered tasks with common values in some attributes
- Similar to Karnaugh maps

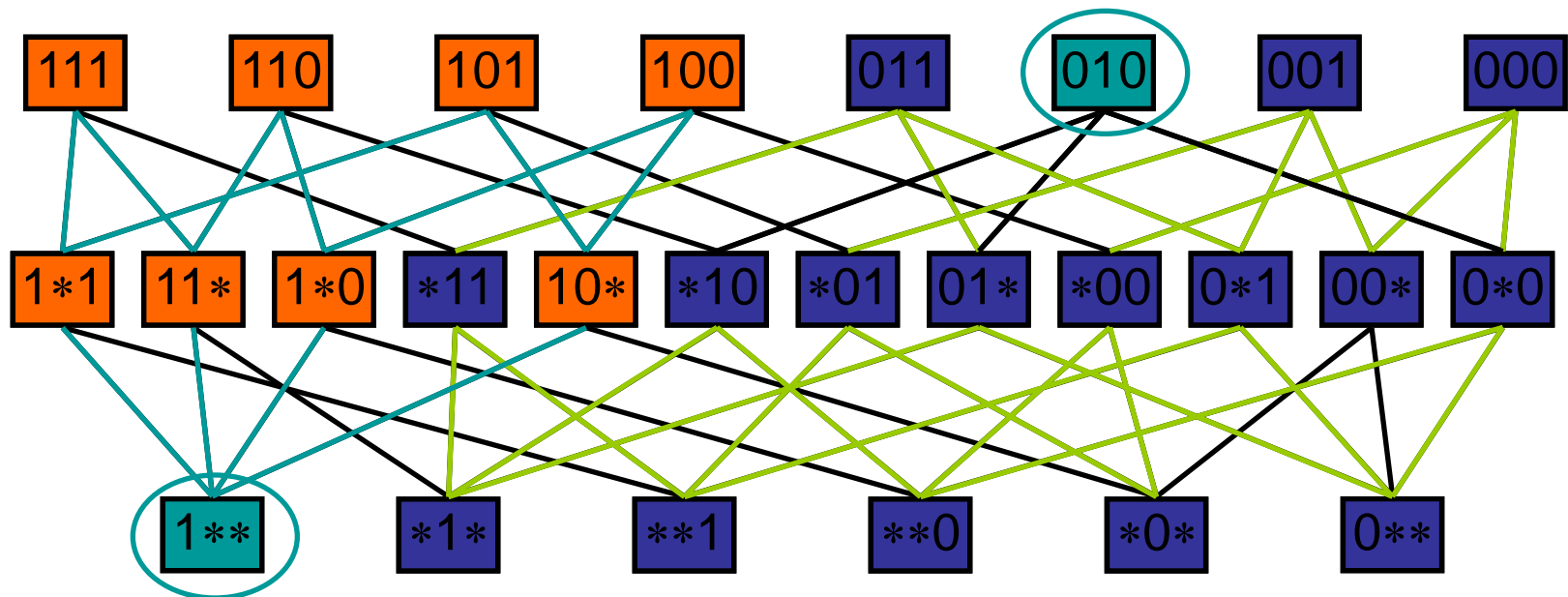


Projected Holes

- Find holes that are **complete subspaces** of the coverage space
- Holes are in the form $\langle q_1, q_2, \dots, q_n \rangle$
 - q_i is either a single value or a wildcard (*)
 - Hole dimension is the number of wildcards
 - Example: $\langle \text{fadd}, \text{add}, *, \text{WW} \rangle$ has dimension 1
- Hole p is an ancestor of q if all the tasks in q are in p
 - $\langle \text{fadd}, *, *, \text{WW} \rangle$ is ancestor of $\langle \text{fadd}, \text{add}, *, \text{WW} \rangle$
- Holes with higher dimensions usually represent larger subspaces and are more important

Projected Holes Algorithm

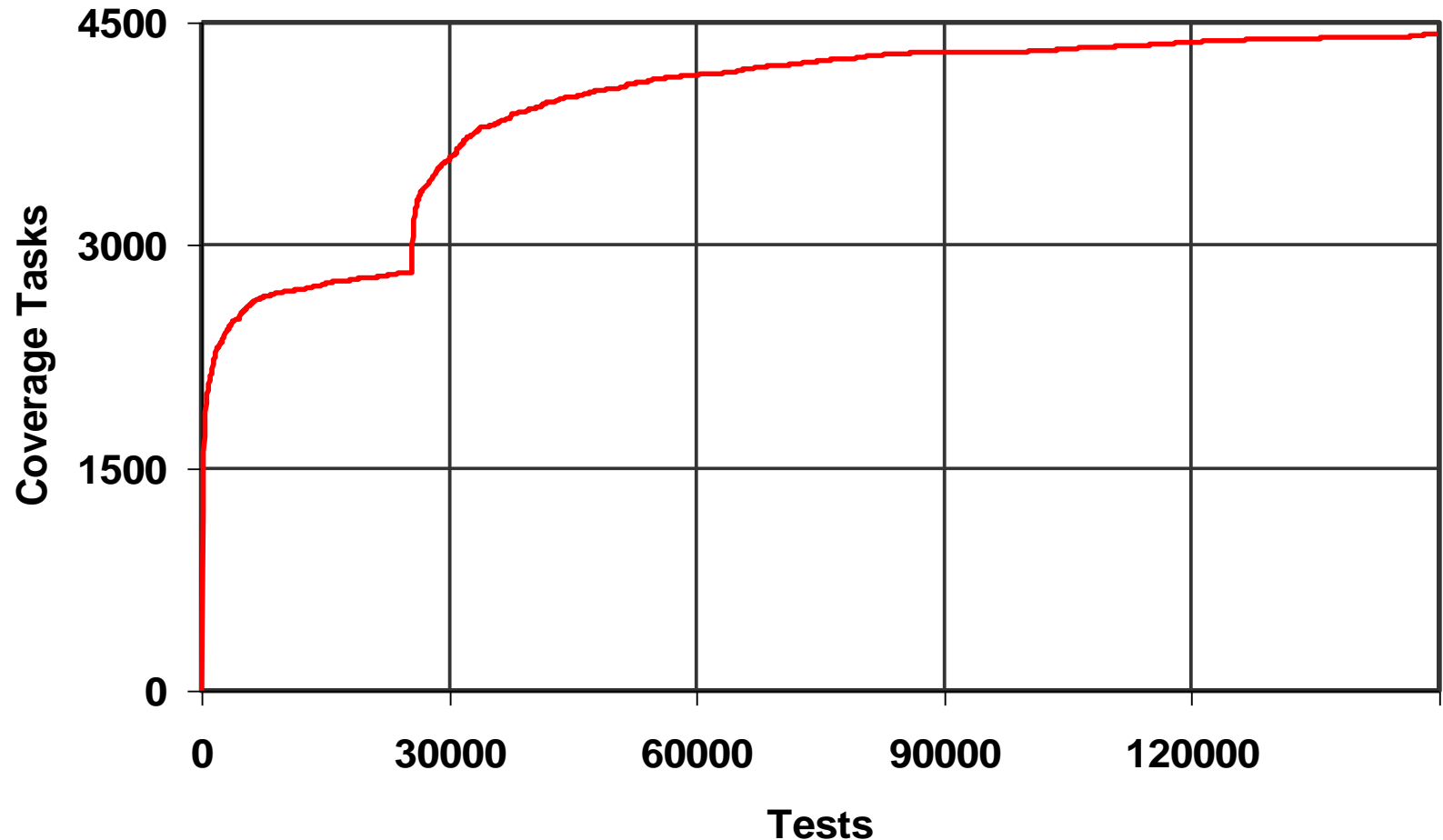
- Build layered network of all subspaces
- Recursively mark ancestors of covered tasks
- Loop from the bottom
 - Report unmarked nodes as holes
 - Recursively mark descendents



Coverage Progress

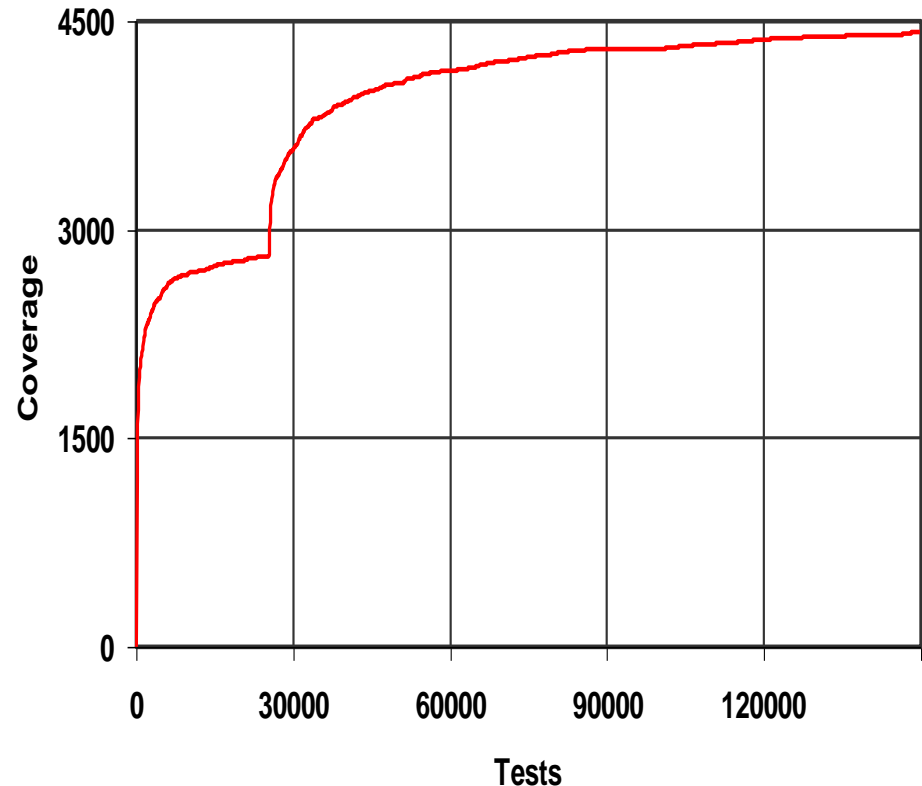
- Shows the progress of coverage over time
- Time can be measured by
 - Wall clock (or calendar) time
 - Number of tests
 - Number of simulation cycles
- Can be used on the entire coverage model or specific views of it

Coverage Progress Example



Progress Report Usage

- Progress report can provide a lot of information
 - How well we are progressing overall
 - What is the current progress rate
 - Are we experiencing changes in the progress rate
 - What is the expected maximal coverage
 - When it would be reached



Using Coverage – What can go wrong?

- Low coverage goals
- Some coverage models are ill-suited to deal with common problems
 - Missing code
 - Use Requirements-based Methodology to overcome this!
- Generating simple tests just to cover specific uncovered tasks
 - There is merit in generating tests outside the coverage!
- Collecting coverage without analyzing and interpreting the results

WHY?

Summary: Coverage

- Coverage is an important verification tool.
 - **Code** coverage: statement, path, expression
 - **Structural** coverage: FSM
 - **Functional** coverage models: story, attributes, values, restrictions
 - (**Assertion** coverage will be introduced during the lecture on Assertion-based Verification.)
- **Combination** of coverage models required in practice.
 - Code coverage alone does not mean anything!
- Verification Methodology should be **coverage driven**.