COMS30026 Design Verification

Coverage

Part III: Coverage Analysis

Kerstin Eder

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

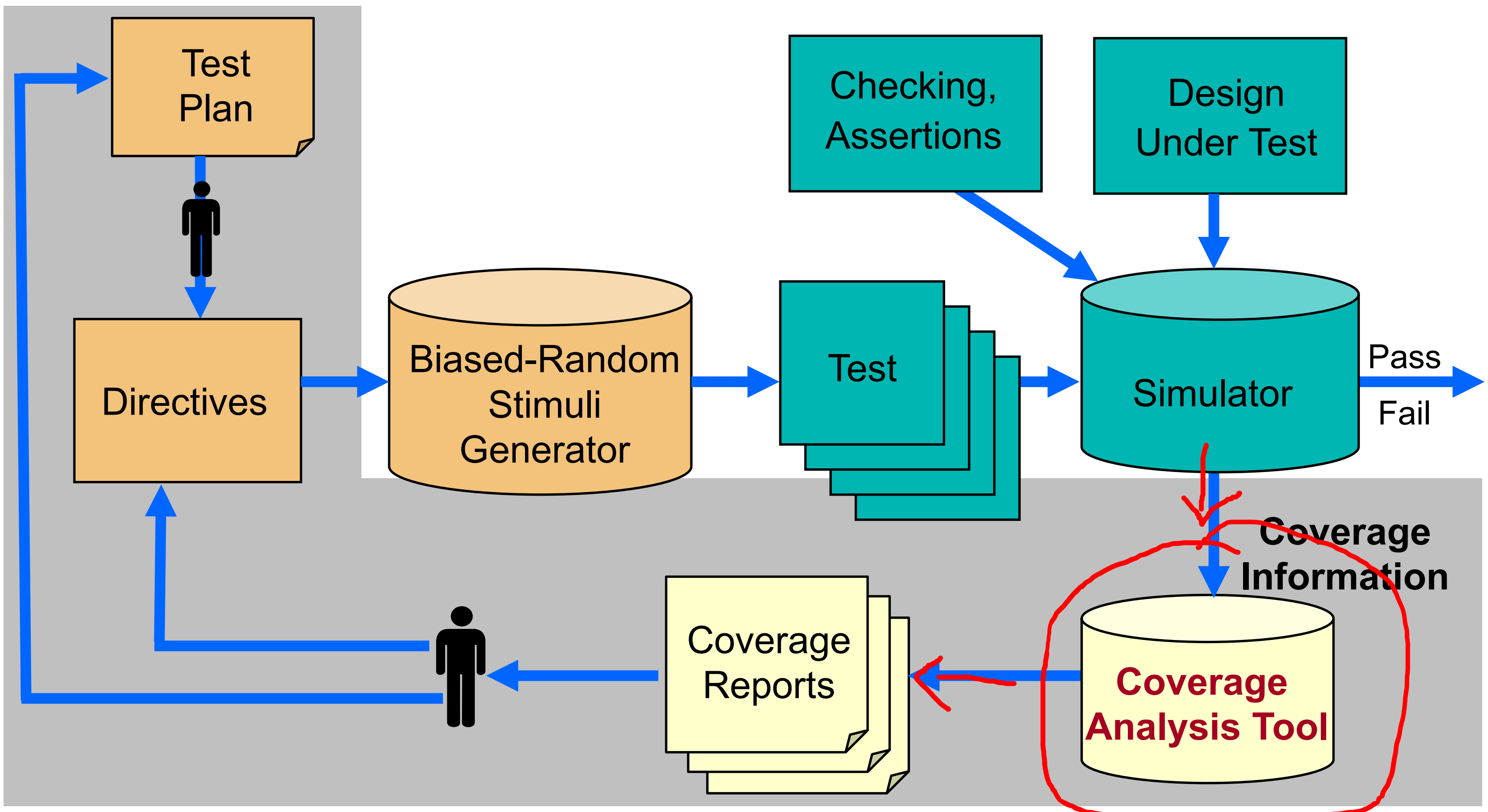
University of BRISTOL

Department of COMPUTER SCIENCE

Outline

- Introduction to coverage
- Part I: Coverage Types
  - – Code coverage models
  - – (Structural coverage models)
- Part II: Coverage Types (continued)
  - – Functional coverage models
- Part III: Coverage Analysis
- Previously: Verification Tools
  - – Coverage is part of the Verification Tools.

Coverage Analysis



Why Coverage Analysis

- The main goals of the coverage process are
  - Monitor the quality of the verification
  - Identify unverified and lightly verified areas
  - Help us understand verification progress

- 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

- Progress reports
  - Progress of coverage over time (more on this later)

Types of Coverage Reports

- Progress reports
  - Progress of coverage over time (more on this later)
- 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

Coverage Status Summary

- Provides a short summary of the coverage to date
- 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, i.e. how often it needs to be covered
  - …

Ints1	Inst2	Reg	Dep	goal	Tests covered	Times covered
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
FPdiv	FPsub	FPR	WW	3	1	1
Br	Sub.	CR	RR	3	12	11

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, i.e. how often it needs to be covered
  - …

Ints1	Inst2	Reg	Dep	goal	Tests covered	Times covered
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
FPdiv	FPsub	FPR	WW	3	1	1
Br	Sub.	CR	RR	3	12	11

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, i.e. how often it needs to be covered
  - …

Ints1
Add
Add
Sub.
Mul
Ldw
FPdiv
Br

Ints1	Inst2	Reg	Dep	goal	Tests covered	Times covered
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
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
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
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
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	And	GPR	None	3	3	9
FPdiv	FPsub	FPR	WW	3	1	1
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
FPdiv	FPsub	FPR	WW	3	1	1
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 moderately sized 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 inspect the coverage data using the appropriate level of detail
  - Allow to dynamically re-define the coverage model using different perspectives

Types of Coverage Views

- Views based on coverage data
  - Counts
  - Date stamps
- 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) -dimensional subspace
- Allow users to concentrate on a specific set of attributes
- May help investigate some of the things leading up to the bigger picture, and may inform test generation

Instruction	Count
fadd	12321
fsub	10923
fmul	4232
fsqrt	13288
fabs	9835

Selection

- Select a subset of the values in the report
- 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
fadd	12321	127/136
fdiv	11729	101/136
fmadd	9725	107/136
fmsub	9328	111/136
fmul	4232	94/136
fres	10373	105/136
frsqrte	9792	23/36
fsqrt	13288	40/56
fsub	10923	122/136

Selection

- Select a subset of the values in the report
- 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

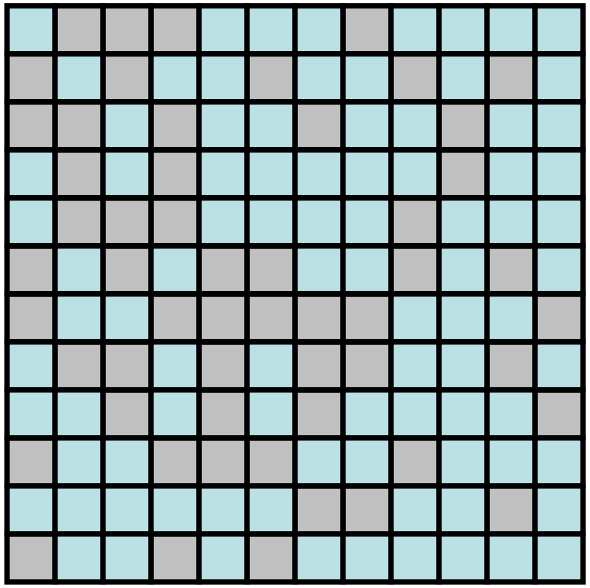
Instruction	Count	Density
fmadd	9725	107/136
fmsub	9328	111/136
frsqrte	9792	23/36
fsqrt	13288	40/56

Partitioning

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

Partitioning

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



Partitioning

- Provides a more **coarse-grained view** of the coverage data
- Partition 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, and which views to select
- Specifically, we often want to find large areas of uncovered tasks in the coverage model, ideally automatically
  - *Why are these important?*

Large Holes Example

- All combinations of two attributes, X and Y
  - Possible values 0 – 9 for both (10x10 = 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

Can you spot any patterns?

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

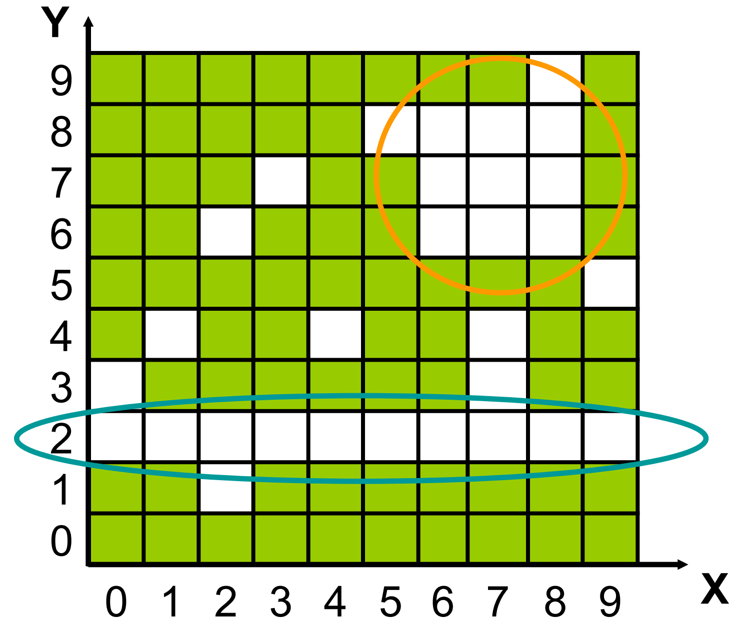
Uncovered Tasks

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



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

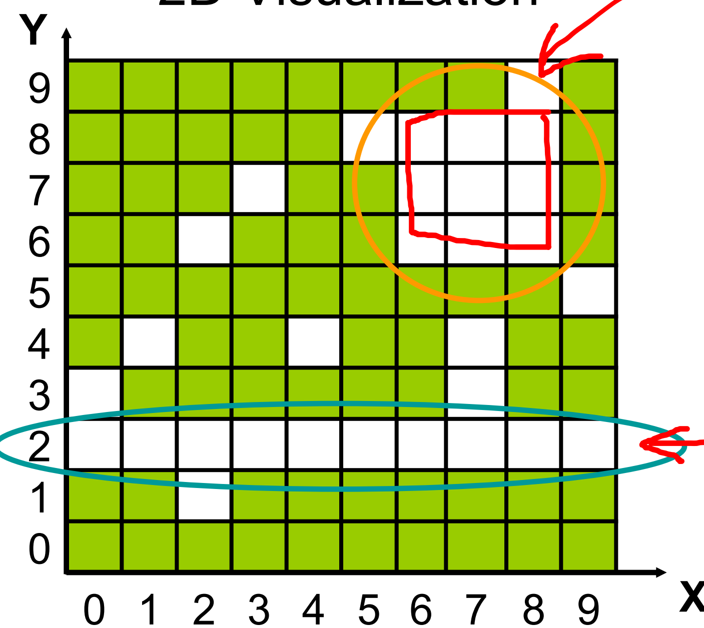
Uncovered Tasks

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
  - Like using Karnaugh maps
- Example coverage space, attributes X and Y each 0..9

Uncovered Tasks (X,Y)

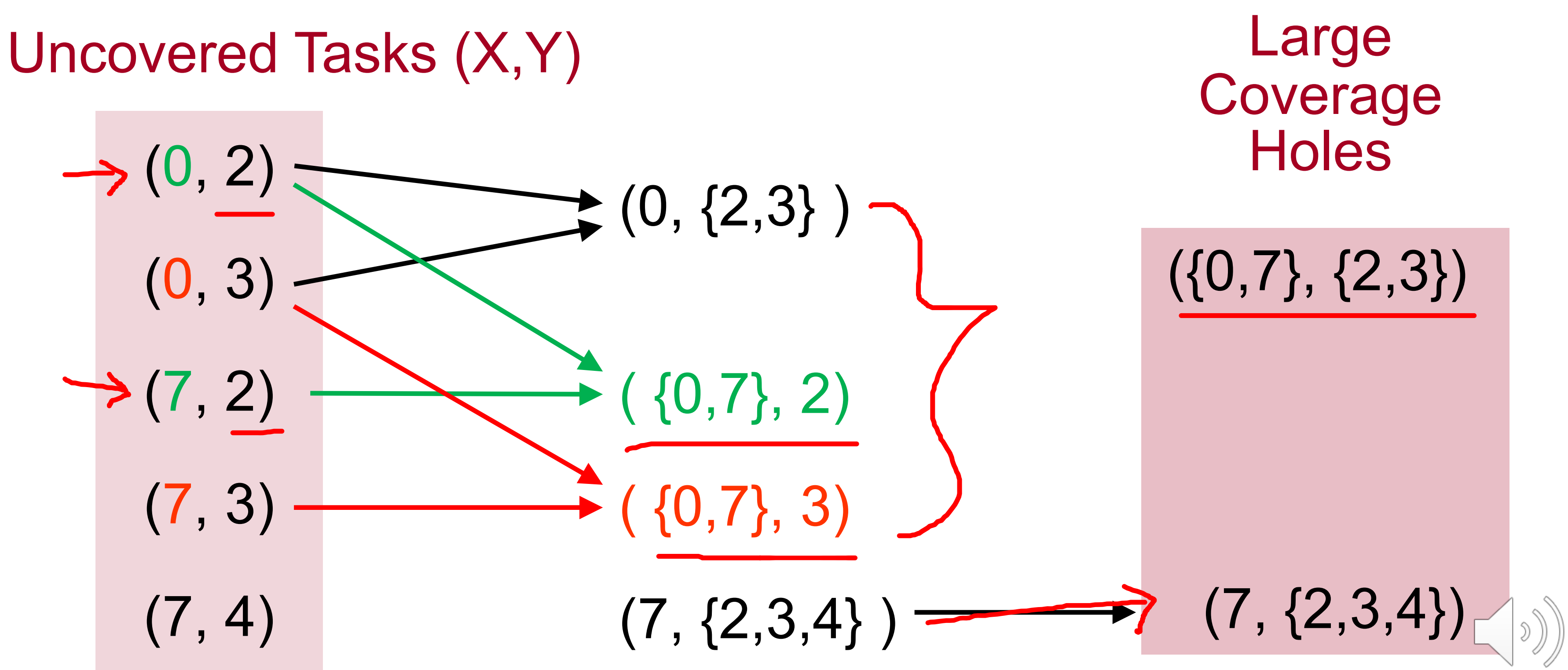
(0, 2)
(0, 3)
(7, 2)
(7, 3)
(7, 4)

(0, {2,3})

(7, {2,3,4})

Aggregated Holes

- Combine uncovered tasks with common values in some attributes
  - Like using Karnaugh maps
- Example coverage space, attributes X and Y each 0..9

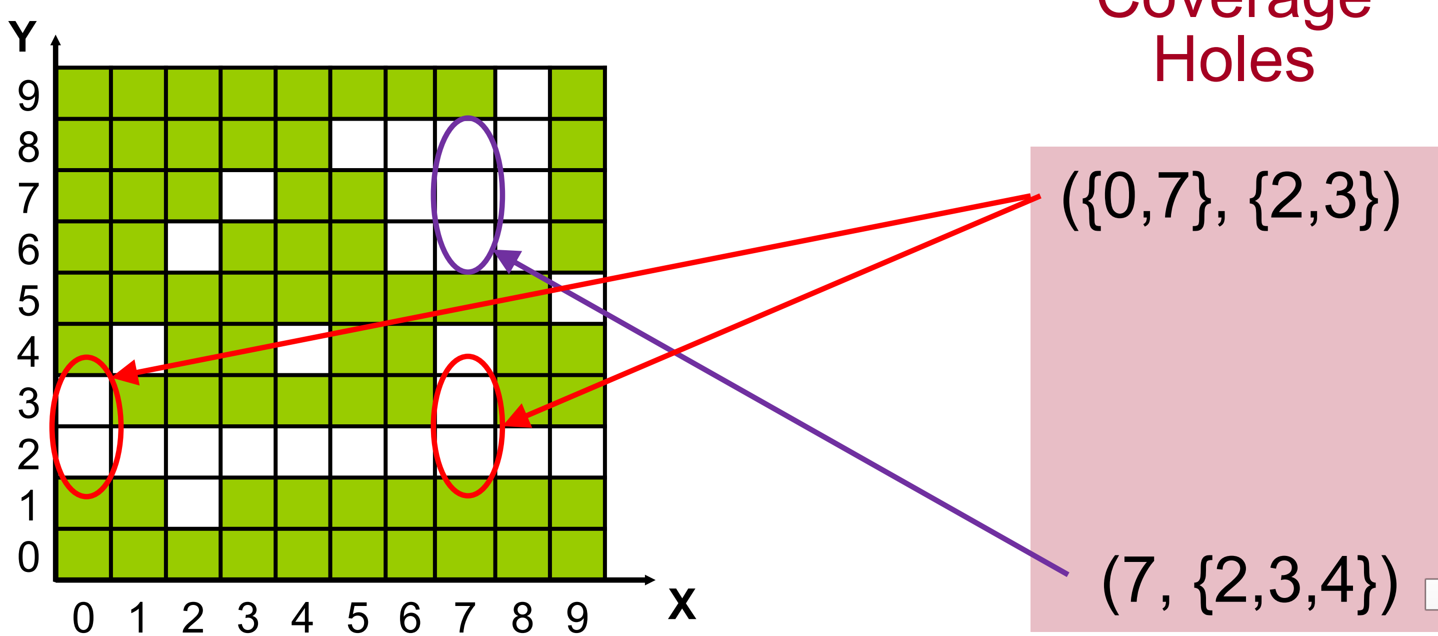


Aggregated Holes

- Combine uncovered tasks with common values in some attributes
  - Like using Karnaugh maps
- Example coverage space, attributes X and Y each 0..9

2D Visualization

Large Coverage Holes



Projected Holes

- Find holes that are complete subspaces of the functional cross-product coverage space
- Coverage holes are in the form $(q_1, q_2, \ldots, q_n)$
  - q_i is either a single value or a wildcard (*)
- The dimension of a coverage hole is the number of wildcards in the tuple
- **Example:** (fadd, add, *, WW) has dimension 1

"There has not been an instruction sequence where fadd is followed by add with a WW dependency for any of the registers."

Projected Holes

Terminology:

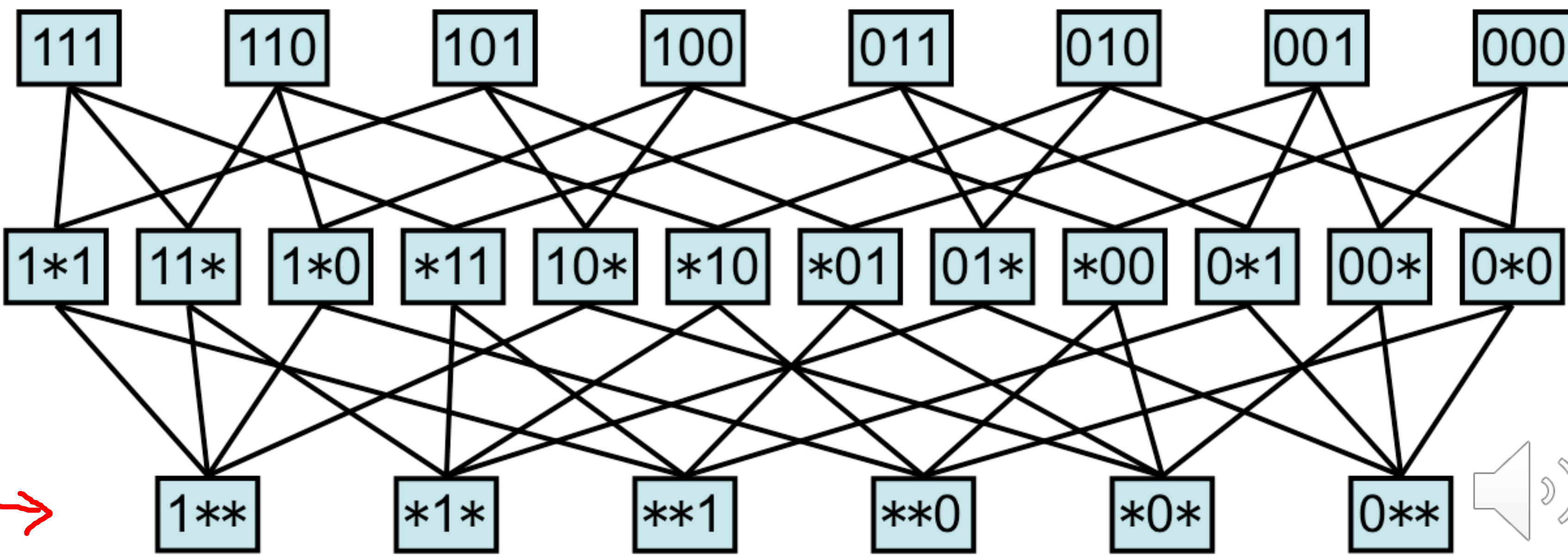
- Coverage hole p is an ancestor of coverage hole q if all the tasks in q are also in p.

  (fadd, *, *, WW) is an ancestor of (fadd, add, *, WW)

- Holes with higher dimensions usually represent larger subspaces.
- The higher the dimension the higher the priority for coverage closure.

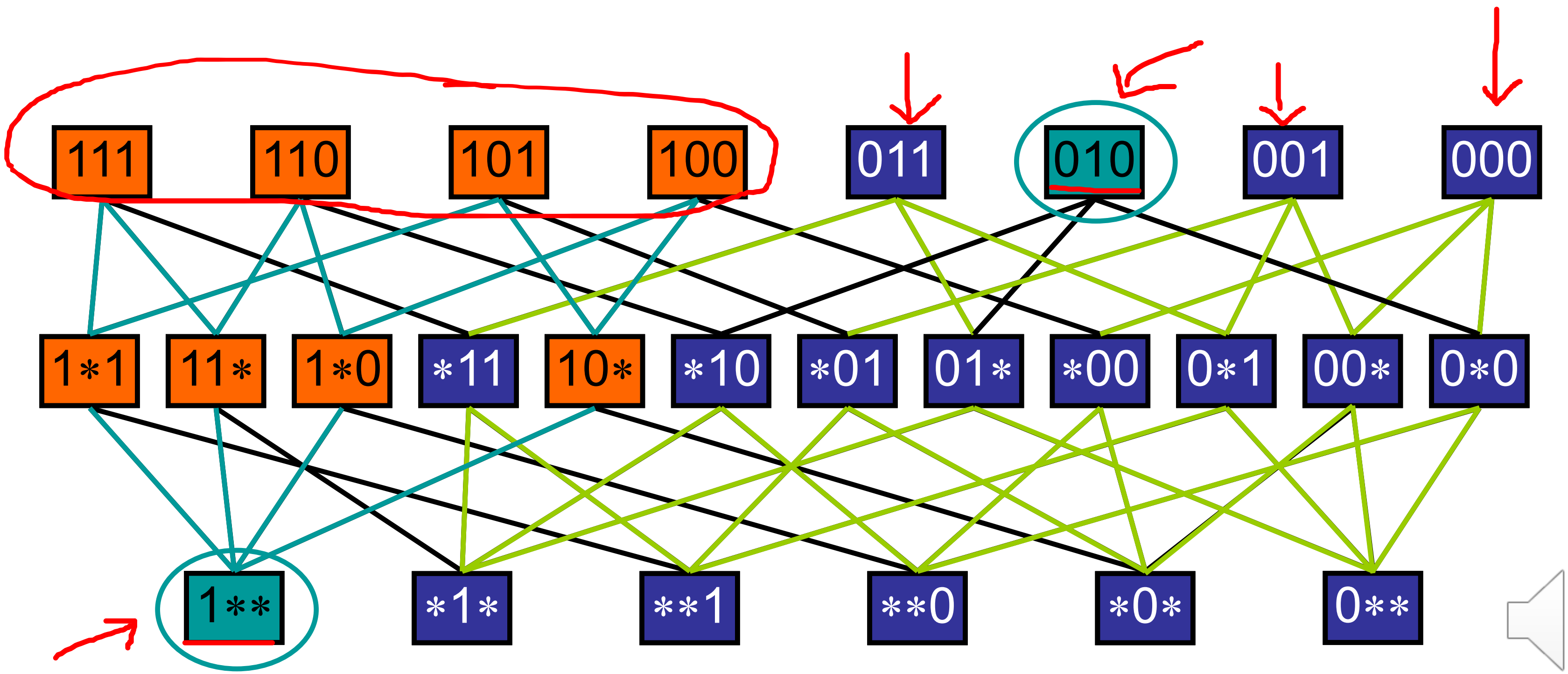
Projected Holes Algorithm

- Build layered network of all subspaces
  - First layer: All coverage tasks individually listed.
  - Second layer: Projections applied to single elements (medium sized holes if not covered)
  - Third layer: Projections applied to two elements (largest holes if not covered)



Projected Holes Algorithm

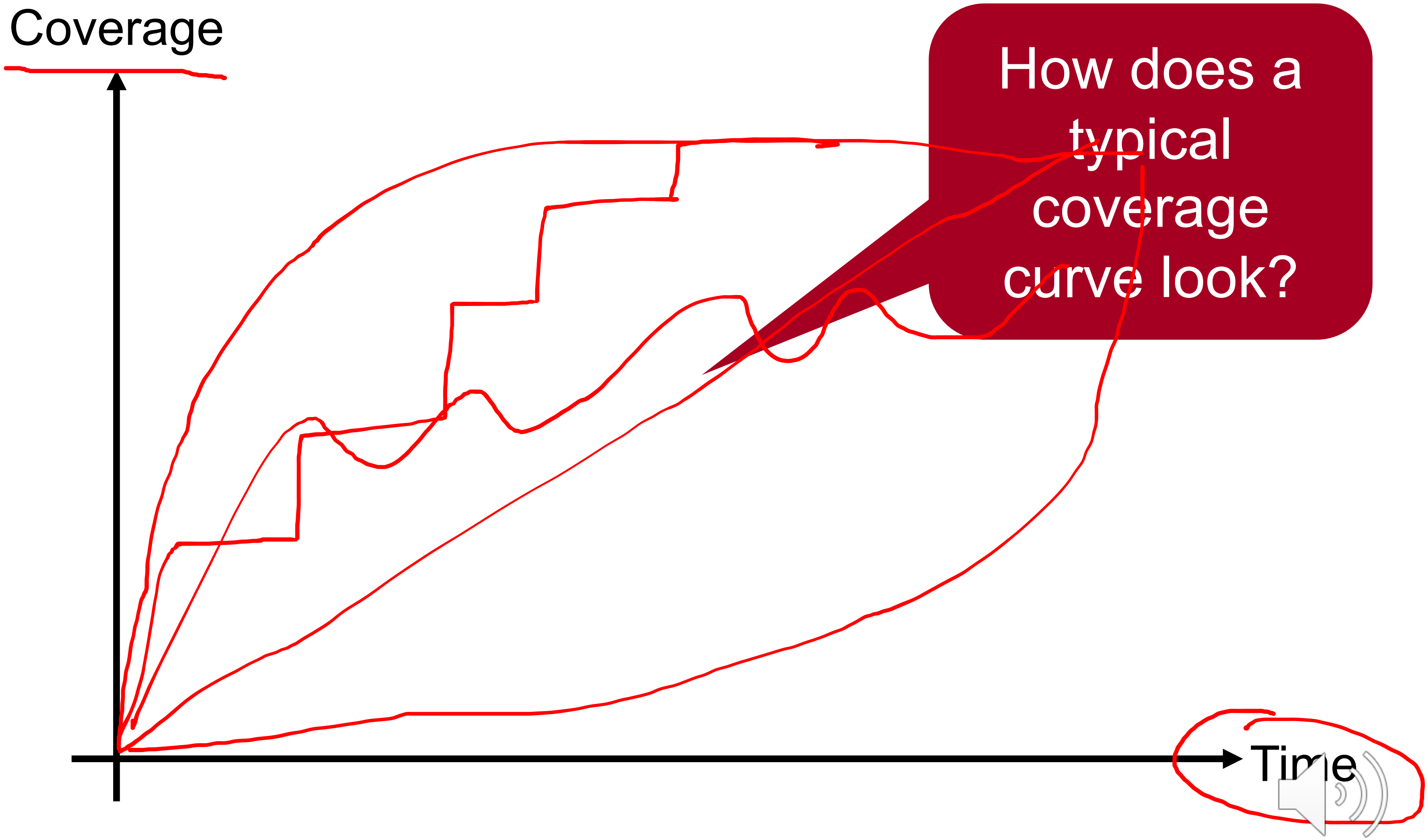
- Build layered network of all subspaces
- Recursively mark the ancestors of **covered tasks**
- Loop from the bottom
  - Report unmarked nodes as holes
  - Recursively mark descendants



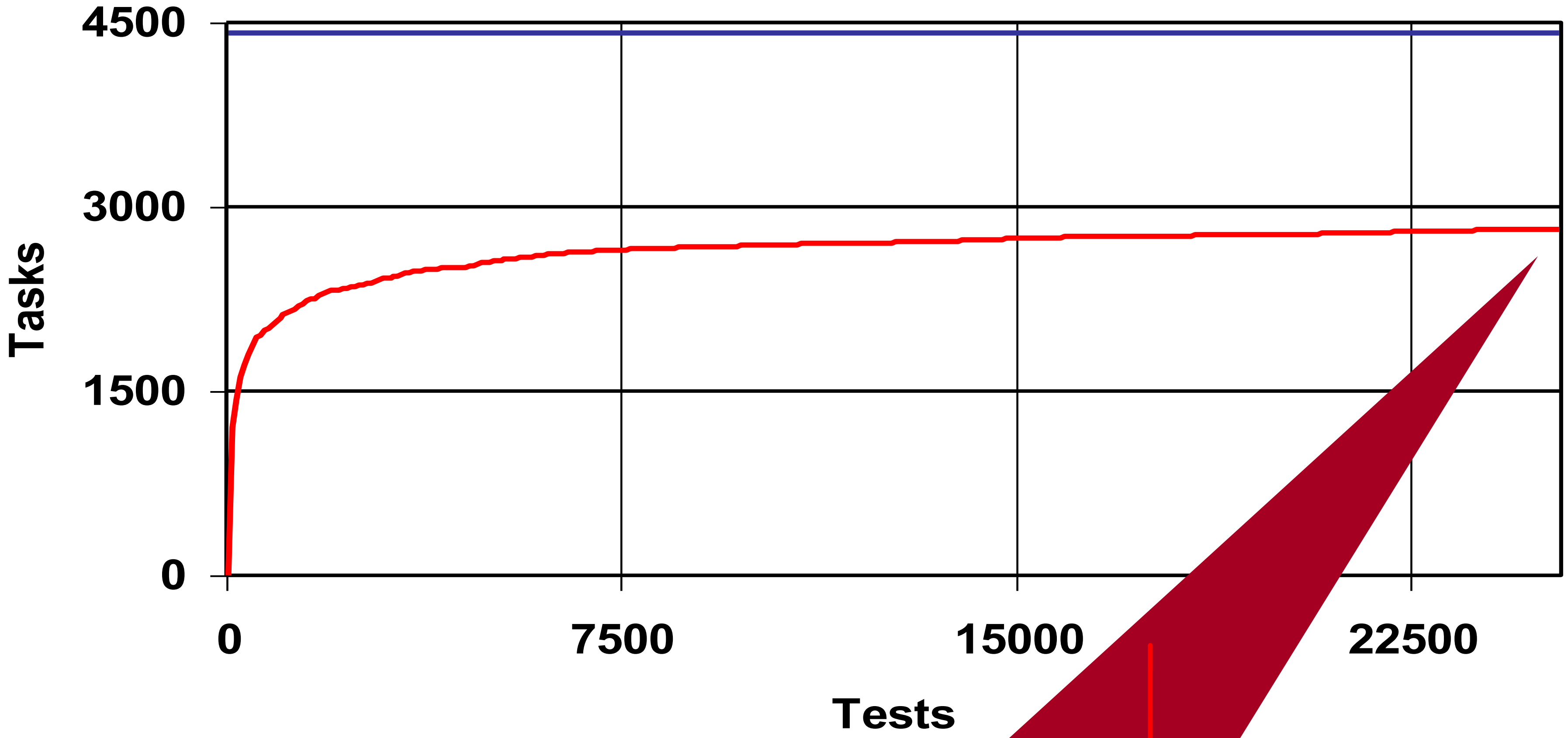
Coverage Progress

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

Coverage Progress

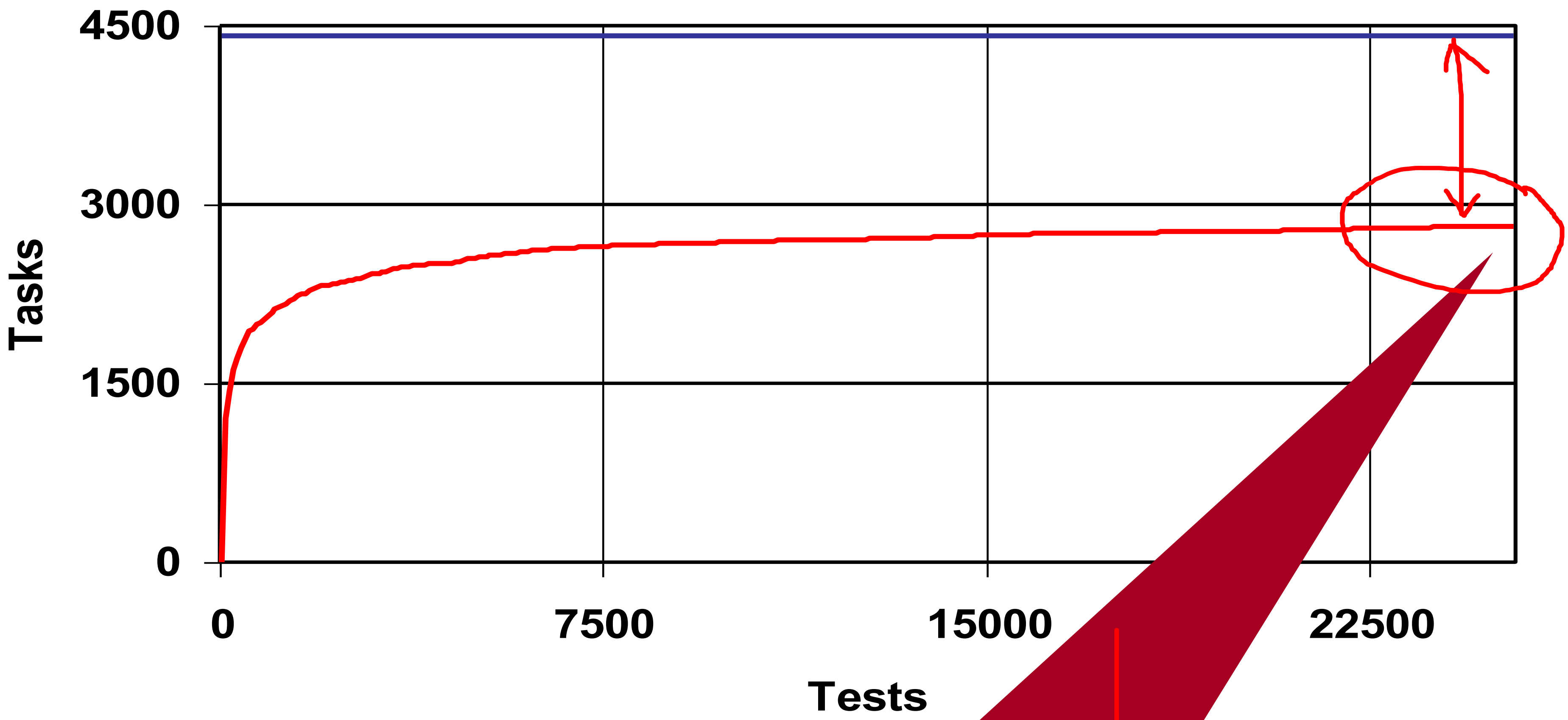


Coverage Progress Example



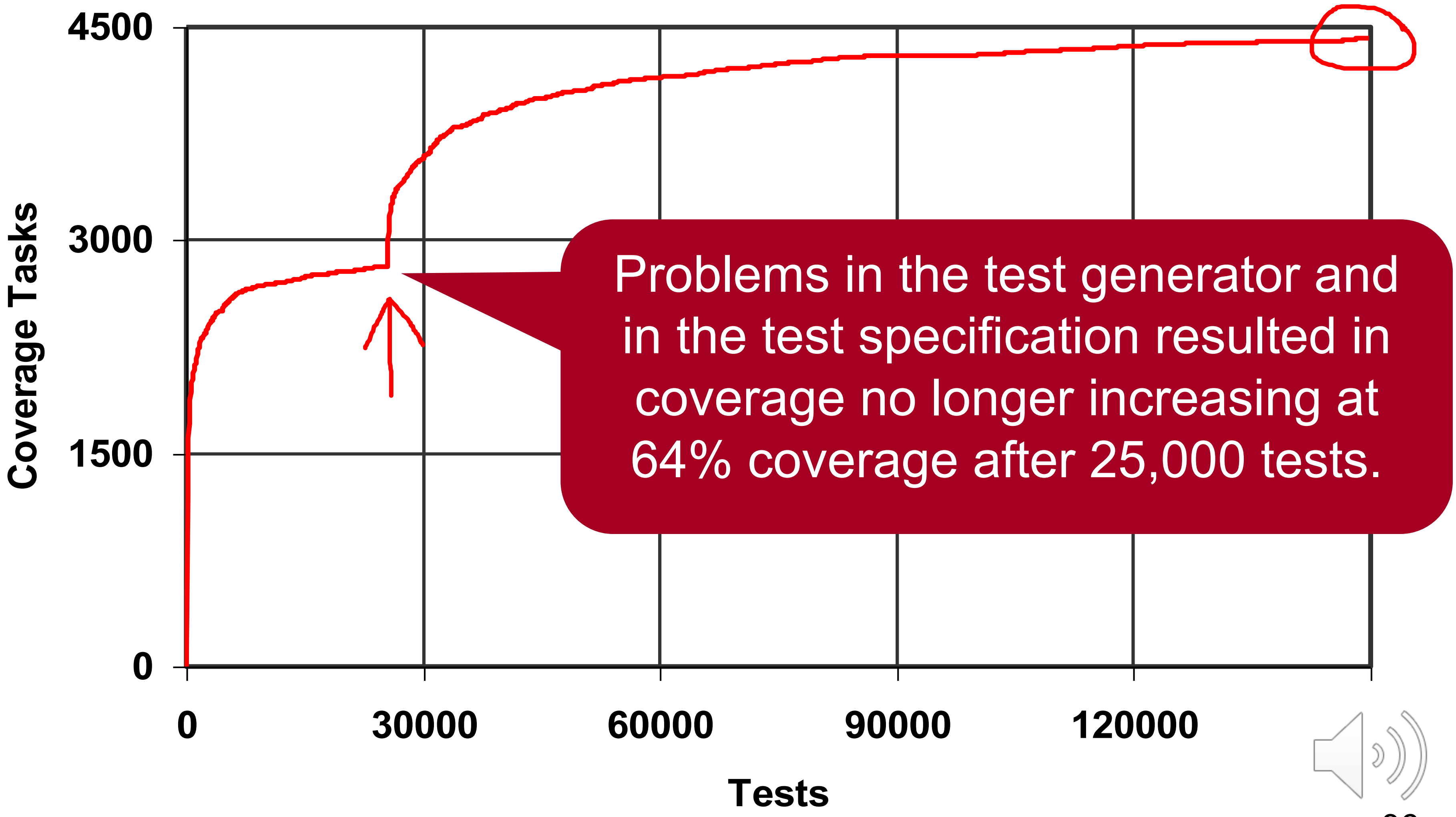
After 25,000 tests 2810 / 4418 tasks were covered, a total of 64%.

Coverage Progress Example



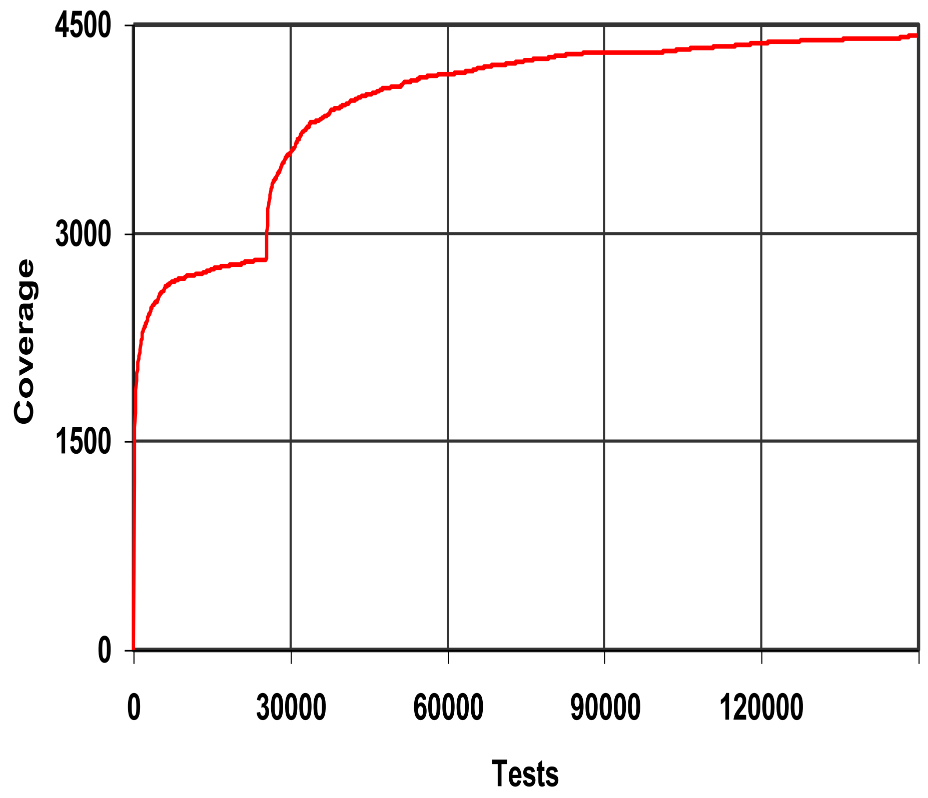
After 25,000 tests 2810 / 4418 tasks were covered, a total of 64%.

Coverage Progress Example



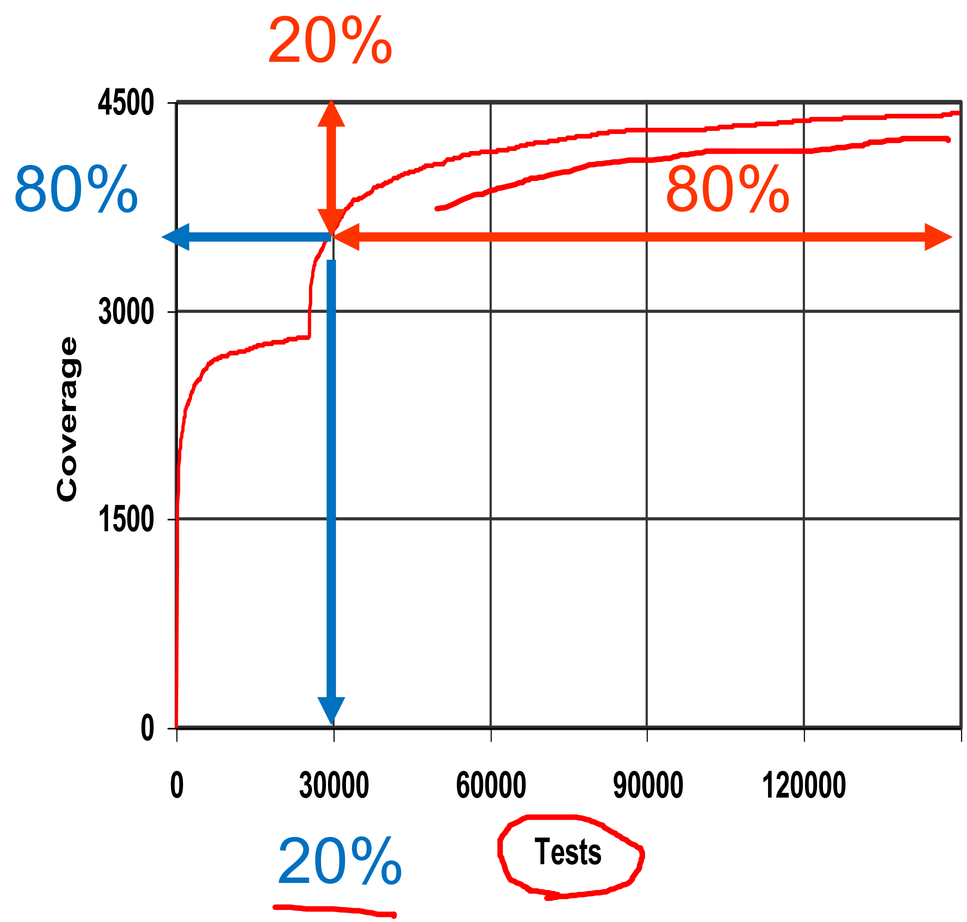
Progress Report Usage

- Progress report can provide a lot of information
  - How well we are progressing overall
  - What is the current progress rate?
  - Are there any changes in the coverage progress rate?
  - What is the expected maximal coverage?



Progress Report Usage

- Progress report can provide a lot of information
  - How well we are progressing overall
  - What is the current progress rate?
  - Are there any changes in the coverage progress rate?
  - What is the expected maximal coverage?
  - **When can we expect to reach our coverage target, i.e. maximal coverage?**



Using Coverage – What can go wrong?

- Low coverage goals
- Collecting coverage without analyzing and interpreting the results
- Some coverage models are ill-suited to deal with common problems
  - For example, missing code won't be possible to identify using code coverage
    - Need a requirements-based methodology to overcome this!
- Generating simple tests just to cover specific uncovered tasks
  - There is merit in generating tests outside the coverage!

WHY?

“Coverage is a measure of effort, not achievement.”

*** *Discuss* ***

Summary: Coverage

- Coverage is an important verification tool.
  - Code coverage: statement, path, expression
    - Structural coverage: FSM
  - Functional coverage models
  - (Assertion coverage as discussed during the lecture on Assertion-based Verification.)
- Coverage analysis techniques
- In practice, several coverage models are typically used in combination.
  - Code coverage alone does not mean very much!
- For a verification methodology to be effective and efficient, it should be **coverage driven**.