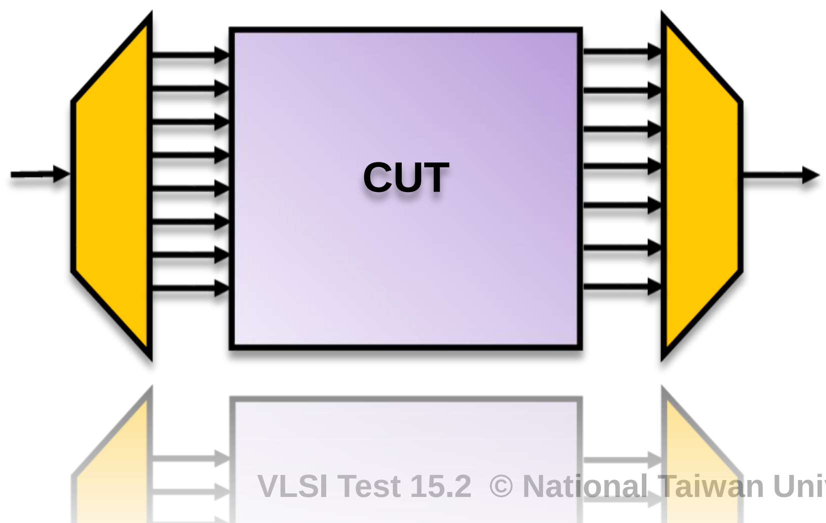
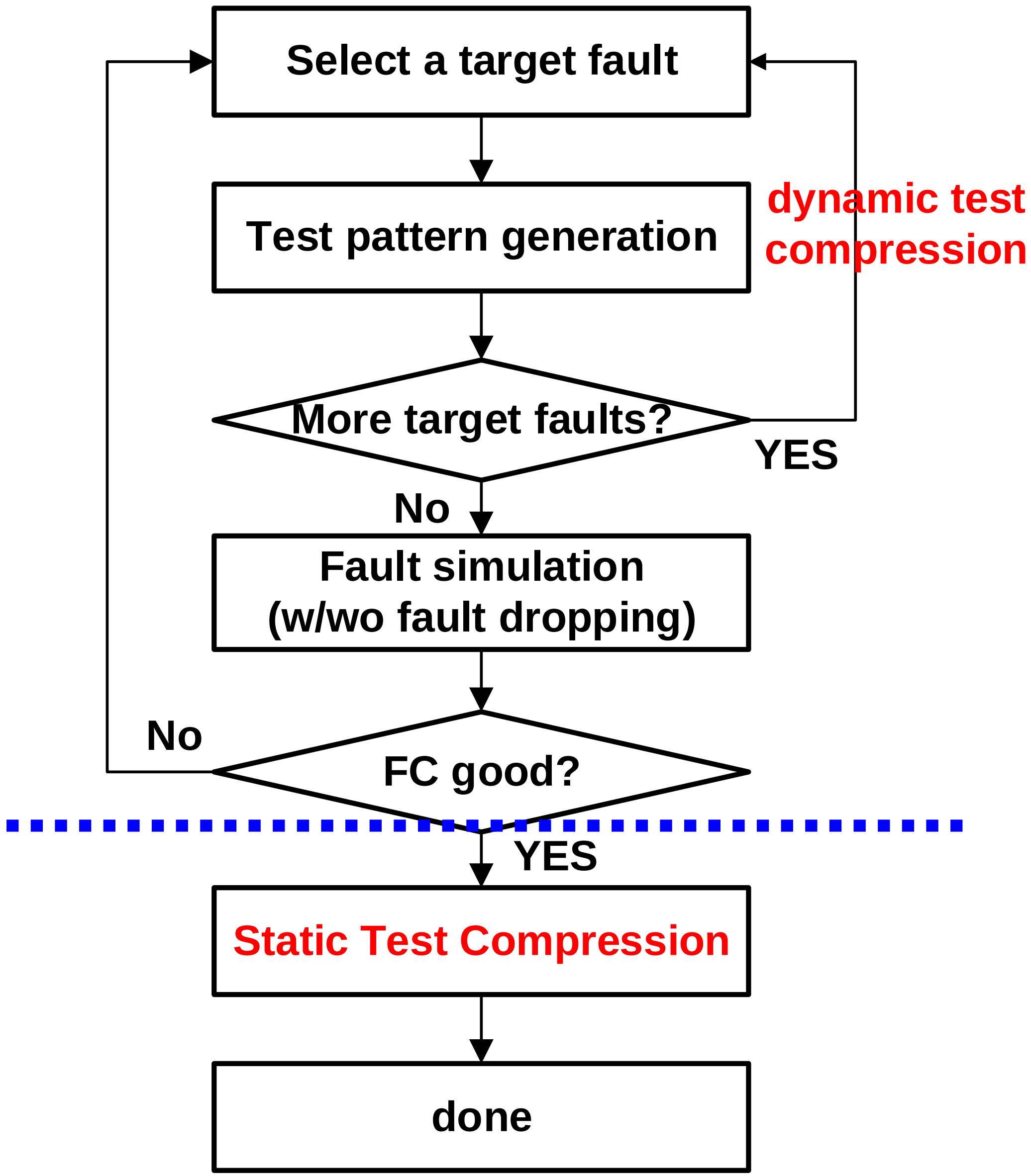
Test Compression

- Introduction
- <u>Software Techniques</u>
  - Dynamic Test Compression (DTC)
  - <u>Static Test Compression (STC)</u>
- Hardware Techniques
  - Test Stimulus Compression
  - Test Response Compression
  - Industry Practices
- Conclusion



Review: STC vs. DTC

- *Dynamic test compression*
  - performed during TPG
  - more CPU time
  - more effective
- *Static test compression*
  - performed after TPG
  - less CPU time
  - less effective



Test Compression

- Introduction
- Software Techniques
  - Dynamic Test Compression
  - Static Test Compression
    - With fault dictionary
    - Without fault dictionary
      - Compatibility graph (X-unfilled)
      - Reverse order fault simulation (X-filled)

3 cases

- Hardware Techniques
  - Test Stimulus Compression
  - Test Response Compression
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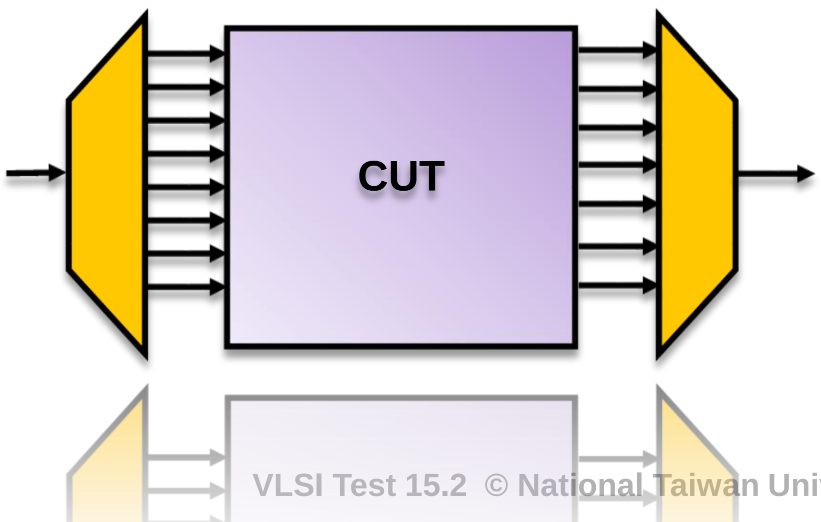

STC with Fault Dictionary

- Suppose we have a fault dictionary (without fault dropping)
- *Covering table*
  - Each row is a test pattern, each column is a fault
- Goal: Find minimum test set (select fewest test patterns)
  - Detect all faults
- Finding minimum test set is *minimum set covering problem*
  - NP-hard, but don't give up…

	f_1	f_2	f_3	f_4	f_5
t_1				X	
t_2		X	X		X
t_3		X		X	X
t_4	X			X	

Each row is a pattern
Each column is a fault
X= detection
(not don't care!)

Quine-McCluskey Method [McCluskey 56]

- First EDA algorithm for 2-level logic synthesis
- Fault that is detected only once is *essential fault*
  - Must select *essential patterns* that detect essential faults
- Example:
  - f_1, f_3 are essential faults; t_2, t_4 are essential patterns
  - Test set selected = {t_2, t_3, t_4} or {t_1, t_2, t_4}, minimum test length = 3

		f_1	f_2	f_3	f_4	f_5
	t_1		X		X	
√	t_2			X		X
√	t_3		X		X	X
√	t_4	X			X	

Each row is a pattern
Each column is a fault
X= detection

What if No Essential Faults?

Quine-McCluskey Method (cont'd)

- 1. Remove redundant **equivalent row,** keep one row is enough
  - Row t_1 is equal to row t_2 because they have X in same columns
- 2. Remove **dominated row**
  - Row t_3 dominates row t_4 because
  - (1) row t_3 has X in all columns where row t_4 has X, and
  - (2) row t_3 has at least one X where row t_4 does not have X

	f_1	f_2	f_3	f_4	f_5	
t_1	X	X	X		X	
t_2	X	X	X		X	equivalent row
t_3		X	X	X	X	
t_4			X	X	X	dominated row
t_5	X			X	X	

Quine-McCluskey Method (cont'd)

- 3. Remove dominating column
  - Column f_5 dominates column f_4 (f_3, f_2, f_1 also) because
  - (1) column f_5 has X in all rows where column f_4 has X, and
  - (2) column f_5 has at least one X where column f_4 does not have X
- 4. Secondary essential
  - After steps 1~3, t_3 is now secondary essential pattern
- Minimum test set {t_1, t_3} or {t_3, t_5}, minimum test length =2

dominating column

		f_1	f_2	f_3	f_4	f_5
	t_1	X	X	X		X
√	t_3		X	X	X	X
	t_5	X				X

(cont'd from last page)

Quiz

Q1: Which are essential faults?
Q2: Which are dominated rows? Dominating columns?
Q3: What is minimum test length?

	f_1	f_2	f_3	f_4	f_5
t_1			X	X	X
t_2		X	X		X
t_3			X		
t_4	X				
t_5		X		X	X

QM Solves Many Cases in Polynomial Time

but not all…

FFT

- Mini-set covering is NP-hard
  - Q1: Show an special case where no rule of QM can be applied
  - Q2: What are you going to do with it?

	f_1	f_2	f_3	f_4
t_1	X	X		
t_2		X	X	
t_3			X	X
t_4	X			X

Alternative Solution, 01-ILP

- **Model STC as 01-Integer Linear Programming problem**

$$Objective:\ \min \sum_i t_i$$

$$s.t.\quad \sum_i d_{i,j} \times t_i \geq 1, \quad foreach\ fault\ j$$

  - **t_i=1 ,if test i is selected; t_i=0 otherwise**
  - **$d_{i,j}$=1 if test pattern t_i detects fault f_j**
- **Example: t_1=0, t_2=t_3=t_4=1**

	f_1	f_2	f_3	f_4	f_5
t_1		X			
t_2			X		X
t_3		X		X	X
t_4	X			X	

$$\begin{aligned}
&\min \quad t_1 + t_2 + t_3 + t_4 \\
&s.t. \\
&\quad t_4 \geq 1 \\
&\quad t_1 + t_3 \geq 1 \\
&\quad t_2 \geq 1 \\
&\quad t_3 + t_4 \geq 1 \\
&\quad t_2 + t_3 \geq 1
\end{aligned}$$

It is Well-solved… What Is Wrong?

- Q: What is practical issue of STC with dictionary?
  - A: Complete fault dictionary is very large, very slow

	f_1	f_2	f_3	f_4	f_5
t_1		X	X		
t_2	X	X	X		X
t_3			X		X
t_4	X			X	

Need STC without Dictionary

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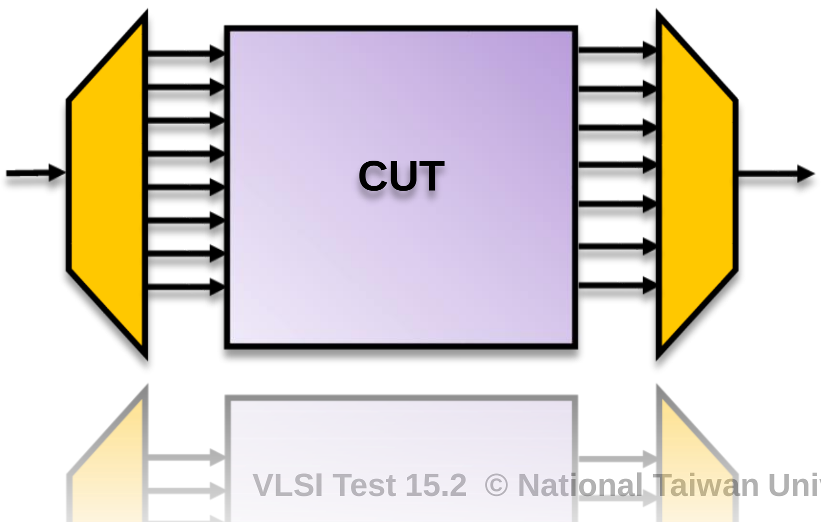


STC w/o Dictionary (X-unfilled)

- Suppose that we do NOT have dictionary
  - but we have don't care bits in test cubes
- Two test cubes are *compatible* iff no conflict in specified bits
- Compatible test cubes can be *merged* into one test cube
- Example
  - t_0 and t_1 are compatible, merged to 0xx10
  - Feasible solution:
    - 4 patterns: $\{t_0+t_1+t_2, t_3+t_6, t_4+t_5, t_7\}$
    - Any better solution?

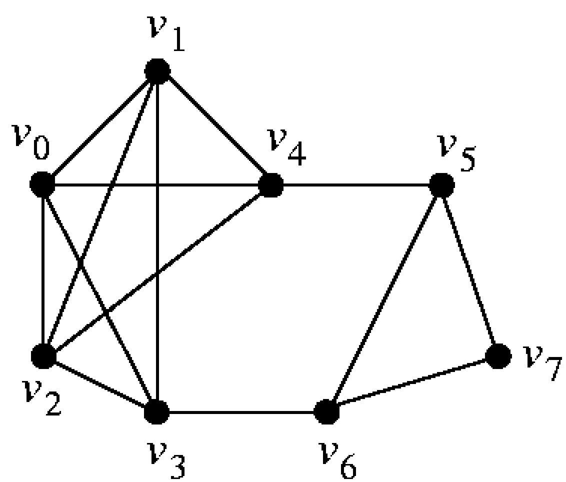
Any Algorithm to Solve This Problem?

t_0	0xx10
t_1	0xx1x
t_2	0x01x
t_3	01xx0
t_4	x0xx0
t_5	1xxxx
t_6	x1x00
t_7	11xx0

x = don't cares

Compatibility Graph

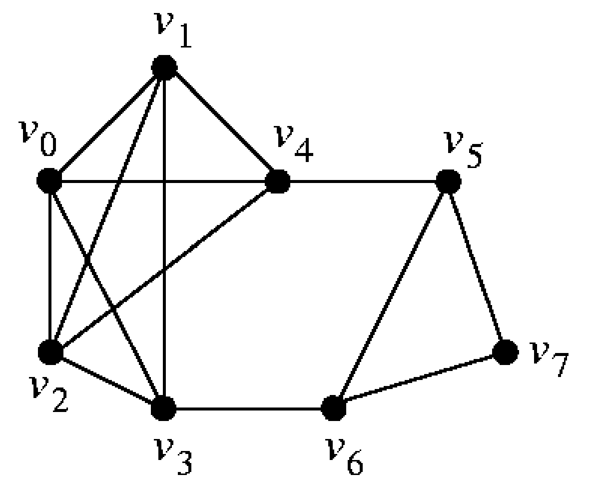
- ***Compatibility graph G(V, E)***
  - Vertex v_i represents a test cube t_i
  - Edge e_{ij} between v_i and v_j means two test cubes are compatible
  - Adjacent vertices can be merged into one
- Example
  - t_0 and t_1 are adjacent, can be merged



t_0	0xx10
t_1	0xx1x
t_2	0x01x
t_3	01xx0
t_4	x0xx0
t_5	1xxxx
t_6	x1x00
t_7	11xx0

Clique

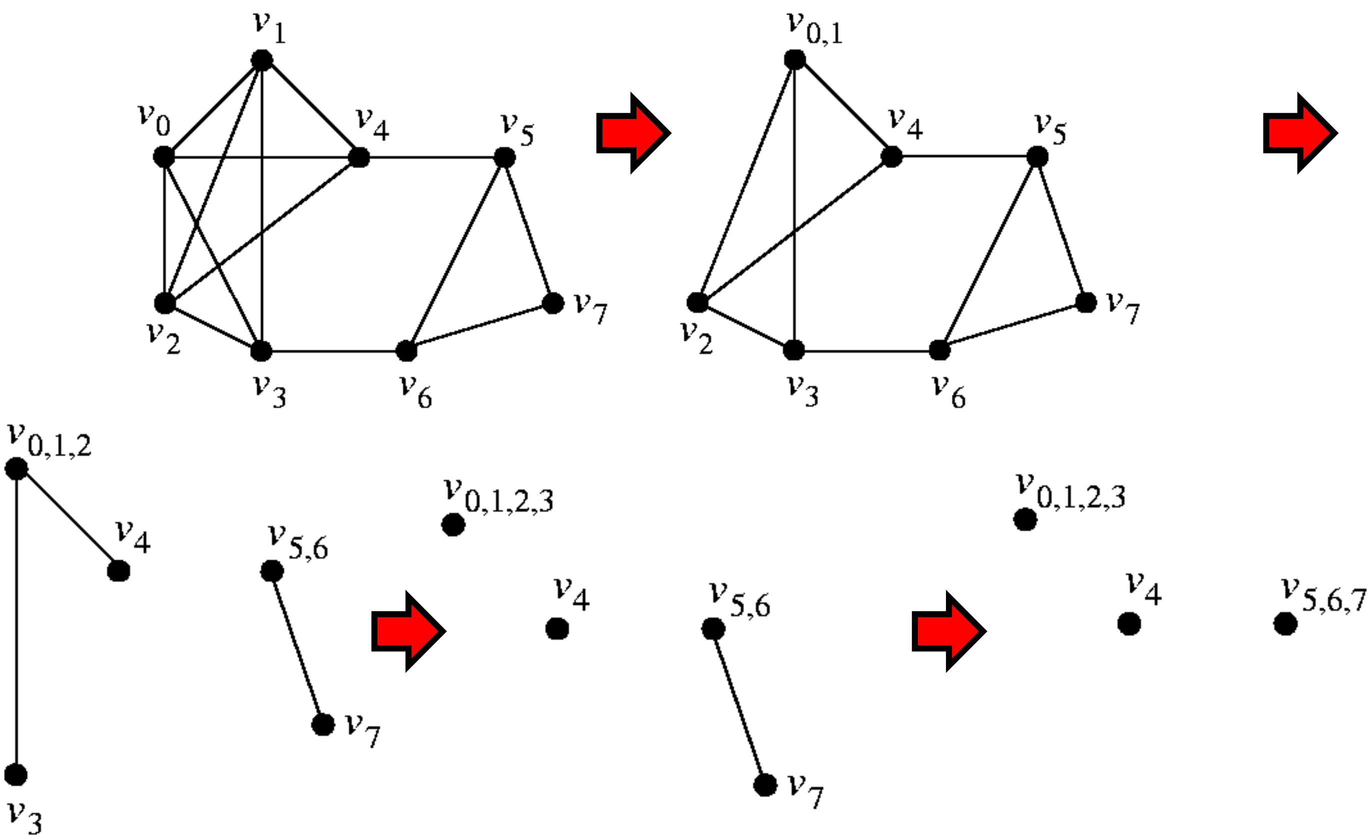
- *Clique* is a subset of vertices such that
  - Each pair of vertices are connected
  - Clique is a *complete subgraph*
- *Minimum clique partition problem*
  - Partition graph into minimum number of cliques
- Example:
  - $\{v_0, v_1, v_2, v_3\}$ $\{v_5, v_6, v_7\}$ are cliques
  - minimum clique partition
    - $\{v_0, v_1, v_2, v_3\}\{v_4\}\{v_5, v_6, v_7\}$
    - 3 partitions



- MCP is NP-hard problem
  - Can be solved by Tseng-Siewiorek
    - Greedy algorithm, does NOT guaranteed optimal solution

Tseng-Siewiorek Idea

- Select two **adjacent vertices** of maximum ***common neighbors***
- Merge two vertices into a ***supervertex***
  - *e.g.*, merge v_0 v_1 → $v_{0,1}$ supervertices
- Iteratively merge vertices until no more edge



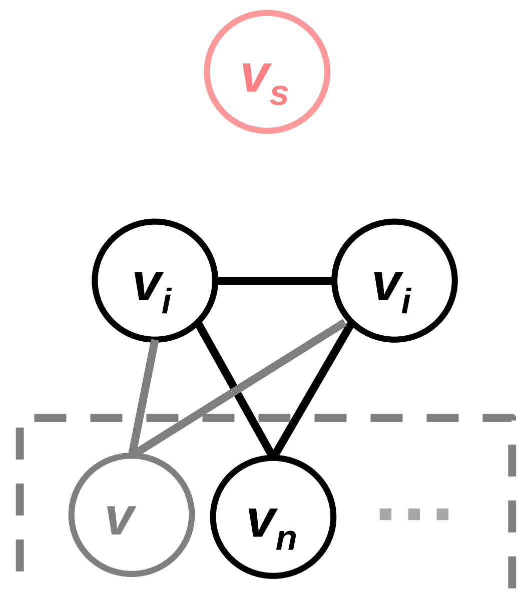
$t_{0,1,2,3}$	01010
t_4	x0xx0
$t_{5,6,7}$	11x00

Tseng-Siewiorek Algorithm (1)

G_c^k = compatibility graph in K_{th} iteration
V_c^k = set of vertices in G_c^k
E_c^k = set of edges in G_c^k

$k \leftarrow 0;$
$G_c^k(V_c^k, E_c^k) \leftarrow G_c(V_c, E_c);$
$\textbf{while}\left(E_c^k \neq \emptyset\right)\ \{$
  $find\ \left(v_i, v_j\right) \in E_c^k\ with$ largest set of common neibors;
  $\mathrm{N} \leftarrow set\ of\ common\ neibors\ of\ v_i\ and\ v_j;$
  $s \leftarrow i \cup j;$
  $V_c^{k+1} \leftarrow V_c^k \cup \{v_s\} \backslash \{v_i, v_j\};$ \ means remove
  $E_c^{k+1} \leftarrow \emptyset;$
  $\textbf{for each}\ (v_m, v_n) \in E_c^k$ build new edges
    $\textbf{if}(v_m \neq v_i \wedge v_m \neq v_j \wedge v_n \neq v_i \wedge v_n \neq v_j)$
      $E_c^{k+1} \leftarrow E_c^{k+1} \cup \{(v_m, v_n)\};$
  $\textbf{for each}\ v_n \in N$
    $E_c^{k+1} \leftarrow E_c^{k+1} \cup \{(v_n, v_s)\};$
  $k \leftarrow k+1;$
$\}$

v_s=supervertex of v_i and v_j



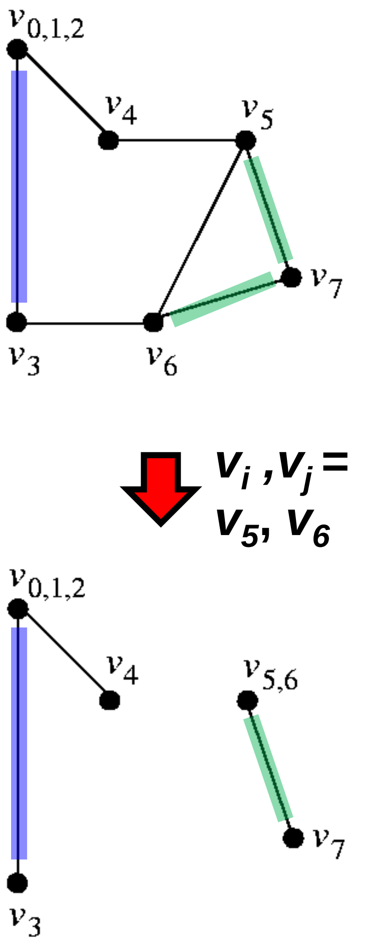
N={common neighbors}

Tseng-Siewiorek Algorithm (2)

$k \leftarrow 0;$
$G_c^k(V_c^k, E_c^k) \leftarrow G_c(V_c, E_c);$
$\boldsymbol{while}(E_c^k \neq \emptyset)$ {
  $find\ (v_i, v_j) \in E_c^k\ with$ largest set of common neibors;
  $\mathbb{N} \leftarrow set\ of\ common\ neibors\ of\ v_i\ and\ v_j;$
  $s \leftarrow i \cup j;$
  $V_c^{k+1} \leftarrow V_c^k \cup \{v_s\} \backslash \{v_i, v_j\};$
  $E_c^{k+1} \leftarrow \emptyset;$
  $\boldsymbol{for\ each}\ (v_m, v_n) \in E_c^k$
    $\boldsymbol{if}(v_m \neq v_i \wedge v_m \neq v_j \wedge v_n \neq v_i \wedge v_n \neq v_j)$
      $E_c^{k+1} \leftarrow E_c^{k+1} \cup \{(v_m, v_n)\};$
  $\boldsymbol{for\ each}\ v_n \in N$
    $E_c^{k+1} \leftarrow E_c^{k+1} \cup \{(v_n, v_s)\};$
  $k \leftarrow k + 1;$
}

keep edges touch neither v_i nor v_j
e.g. **edge (v_{012}, v_3)**

new edge between N and v_s
e.g. **edge (v_5, v_7)**



Quiz

Q1: Draw compatibility graph
Q2: What is minimum test length using T-S algorithm?

t_0	0xx10
t_1	x1x10
t_2	0x11x
t_3	00x11

FFT

- Q: What is practical problem with this method?
  - Practically, there are many don't cares in test cubes
  - X-unfilled test generation is slower and length is longer
    - than X-filled test generation

t_0	0xx10xxxxxx1
t_1	0xx1xxxxxxxx
t_2	0x01xxx1xxxx
t_3	01xx0xxxxxxx
t_4	X0xx0xxxxx0x
t_5	1xxxxxxxxxxx
t_6	x1x00xxxx1xx
t_7	11xx0xxxxxx0

t_0	011101100011
t_1	010111000000
t_2	010011010101

Need STC with X-filled

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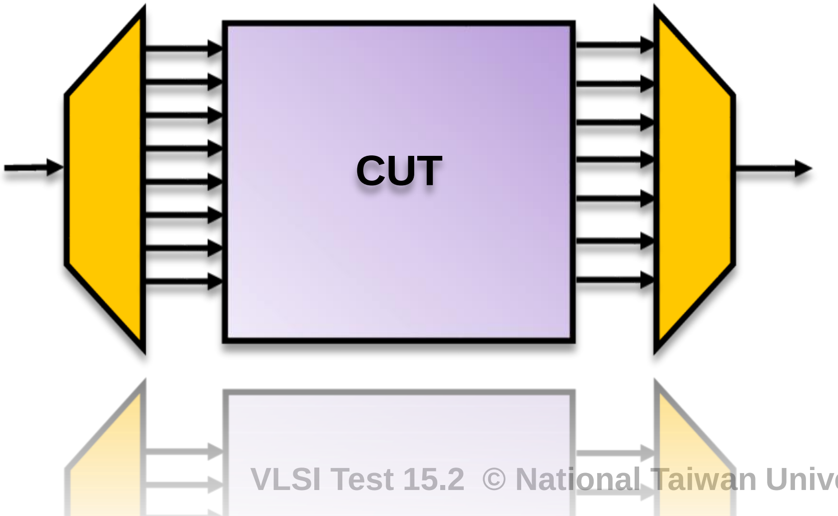


STC with X-filled (1)

- ***Reverse-order fault simulation***
  - Fault simulate X-filled patterns in reverse order of ATPG
    - Delete redundant test patterns
  - Example:
    - First simulate t_4, and then t_3, t_2, t_1
    - Delete t_1. Choose test set $\{t_4, t_3, t_2\}$
  - Advantage: Simple, no dictionary needed. Most popular STC

ATPG order ↓

	f_1	f_2	f_3	f_4	f_5
t_1		X			
t_2			X		X
t_3		X		X	X
t_4	X			X	

Fault sim. order ↑

- Q: Why ATPG generated redundant t_1 at beginning?

STC with X-filled (2)

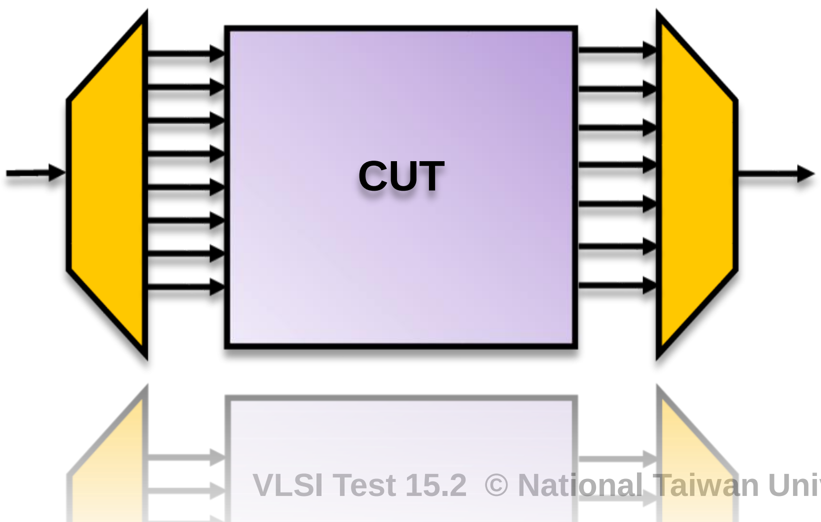
- *Random-order fault simulation*
  - Fault simulate test patterns in random order
  - Example:
    - First simulate t_4, and then t_2 , t_1, t_3
    - Choose test set {t_4, t_1, t_2}

	f_1	f_2	f_3	f_4	f_5
t_1		X			
t_2			X		X
t_3		X		X	X
t_4	X			X	

Too Many Orders to Try

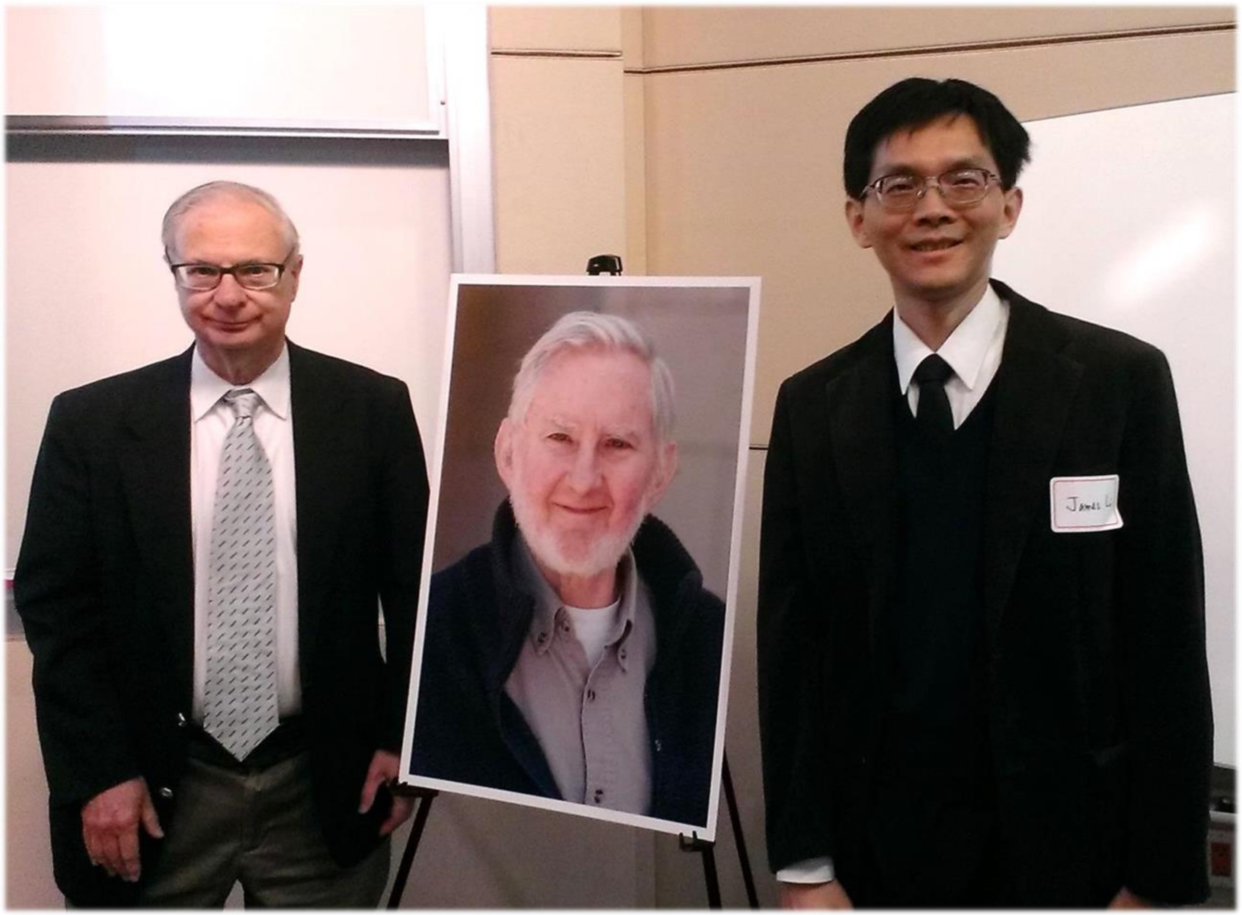
Summary

- Static test compression
  - With fault dictionary
    - Minimum set-covering problem
      - Quine-McCluskey or 01-ILP
    - Too large dictionary
  - Without fault dictionary
    - Compatibility graph (X-unfilled)
      - T-S Algorithm
    - Reverse order fault simulation (X-filled)
      - Most popular solution



Three Authors Together

- Prof. Siewiorek, Prof. McCluskey, Prof. James Li
- 2016 Stanford University



FFT1

$k \leftarrow 0;$

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$\quad find\ \left(v_i, v_j\right) \in E_c^k\ with$ largest set of common neibors;

$\quad \mathbb{N} \leftarrow set\ of\ common\ neibors\ of\ v_i\ and\ v_j;$

$\quad s \leftarrow i \cup j;$

$\quad V_c^{k+1} \leftarrow V_c^k \cup \{v_s\} \backslash \{v_i, v_j\};$

$\quad E_c^{k+1} \leftarrow \emptyset;$

$\quad \boldsymbol{for\ each}\ (v_m, v_n) \in E_c^k$

$\qquad \boldsymbol{if}(v_m \neq v_i \wedge v_m \neq v_j \wedge v_n \neq v_i \wedge v_n \neq v_j)$

$\qquad\quad E_c^{k+1} \leftarrow E_c^{k+1} \cup \{(v_m, v_n)\};$

$\quad \boldsymbol{for\ each}\ v_n \in N$

$\qquad E_c^{k+1} \leftarrow E_c^{k+1} \cup \{(v_n, v_s)\};$

$\quad k \leftarrow k + 1;$

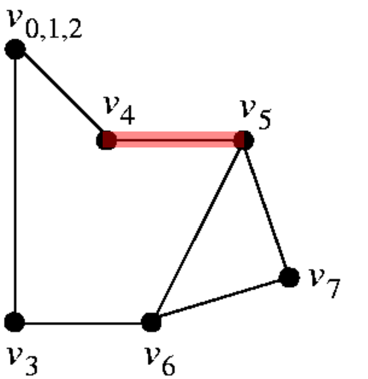
$\}$

keep edges touch neither v_i nor v_j

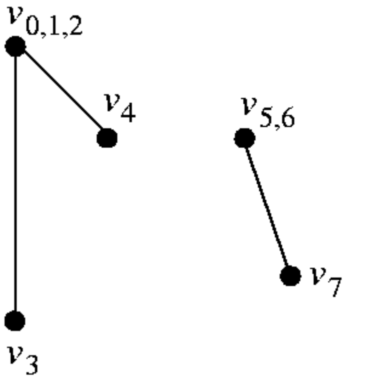
***e.g.* edge (v_{012}, v_3)**

new edges between N and v_s

***e.g.* edge (v_5, v_7)**



v_i, v_j = v_5, v_6



Why Edge (v_4,v_5) Removed?

FFT2

- **MCP is NP-hard**
- **Show an example when TS-algorithm fails to find an optimal solution**