RunBasedReordering: A Novel Approach for Test Data Compression and Scan Power

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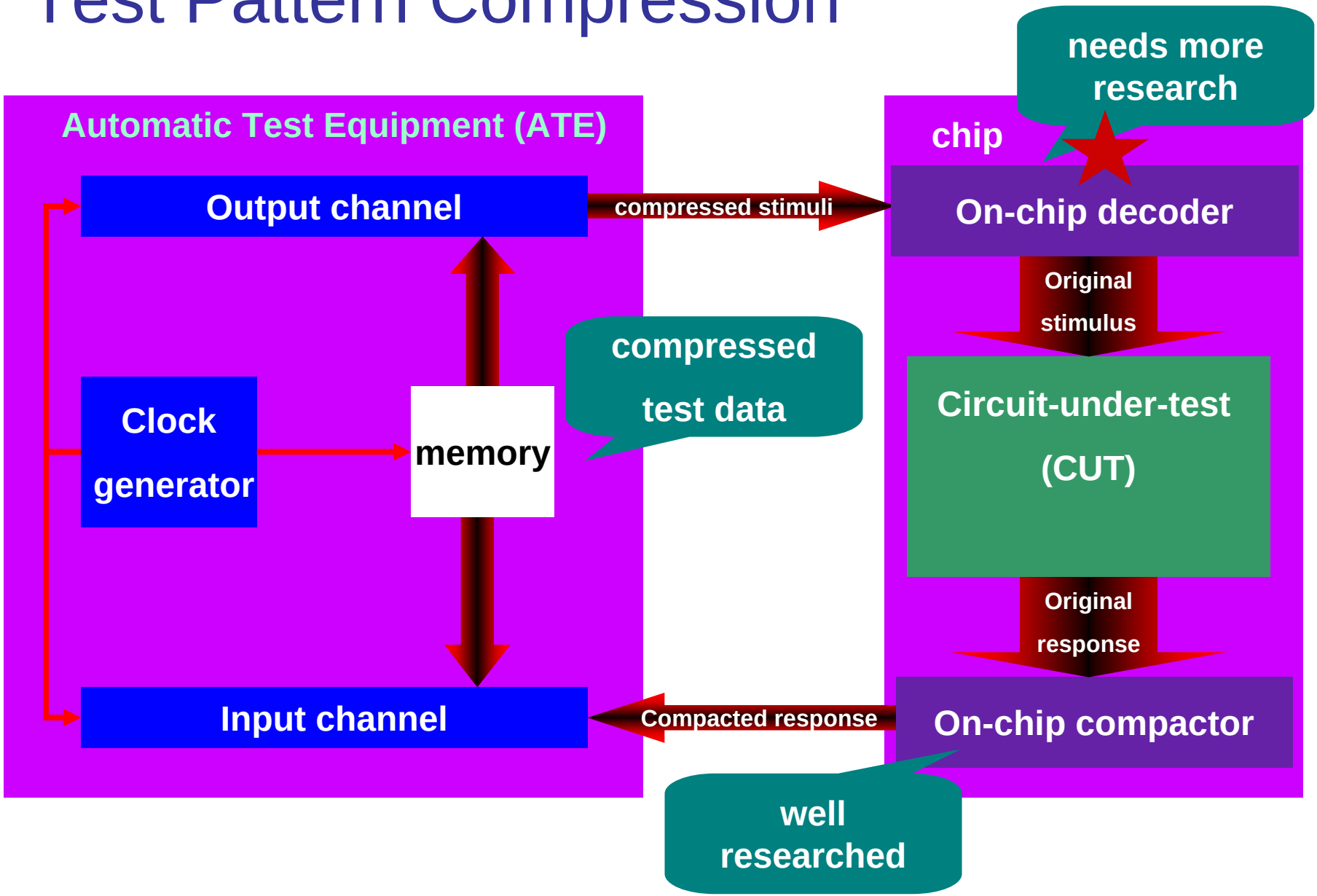
Background: Test Difficulties

- Large Test Data Size
  - 100~1000M bits
  - Automatic Test Equipment
    - small memory
    - cutting down patterns sacrifices fault coverage
- Long Test Time
  - Relative small number of pins
  - 1~2 $ for 1 minute
- High scan power
  - More flipping registers in test mode vs. work mode
  - Usually 2~3 times

Test Pattern Compression



Compression Methods

- Run length
  - conventional run-length
  - Golomb
  - EFDR: Extended Frequency Directed Run-length
- LFSR based
  - linear expansion
- Dictionary based
  - on-chip memory
  - index instead of data
- Selective Coding
  - encode specified bits
- Hybrid

EFDR Encoding

- Run
  - a sequence of 0s or 1s ended by their complement: 00001, 1110
  - test set: a sequence of runs
- EFDR codes
  - run type (1-bit)
  - group prefix:
    run length based grouping
  - group tail:
    length encoding within group

Group	Run Length	Group Prefix	Tail	Code Word Runs of 0's	Code Word Runs of 1's
A1	1	0	0	000	100
	2		1	001	101
A2	3	10	00	01000	11000
	4		01	01001	11001
	5		10	01010	11010
	6		11	01011	11011
A3	7	110	000	0110000	1110000
	8		001	0110001	1110001
	9		010	0110010	1110010
	10		011	0110011	1110011
	11		100	0110100	1110100
	12		101	0110101	1110101
	13		110	0110110	1110110
	14		111	0110111	1110111

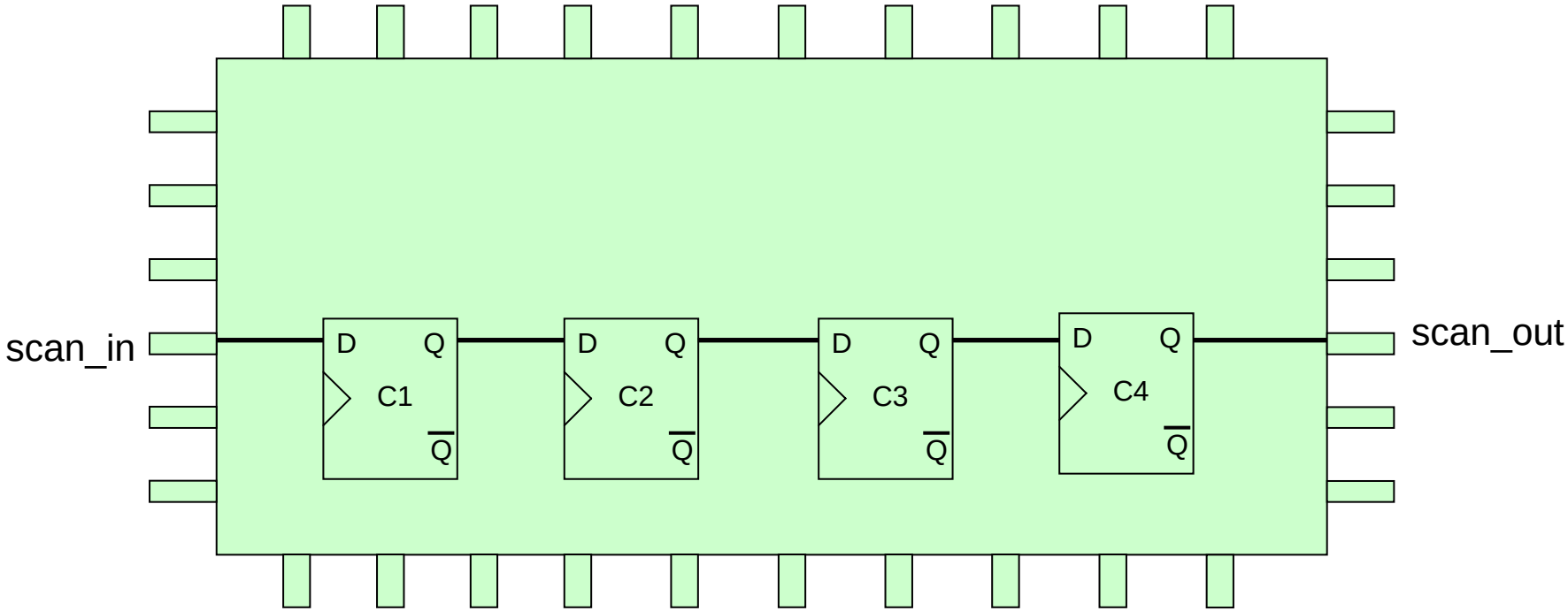
TD = 0000001111110001

Runs:(0)6(1)5(0)2

TE = 0101111010001

Scan Chain Reordering

- Idea: reduce the number of runs in the test data
  - exchange pattern bits without changing the pattern's functionality



test pattern: 0101

Scan Chain Reordering

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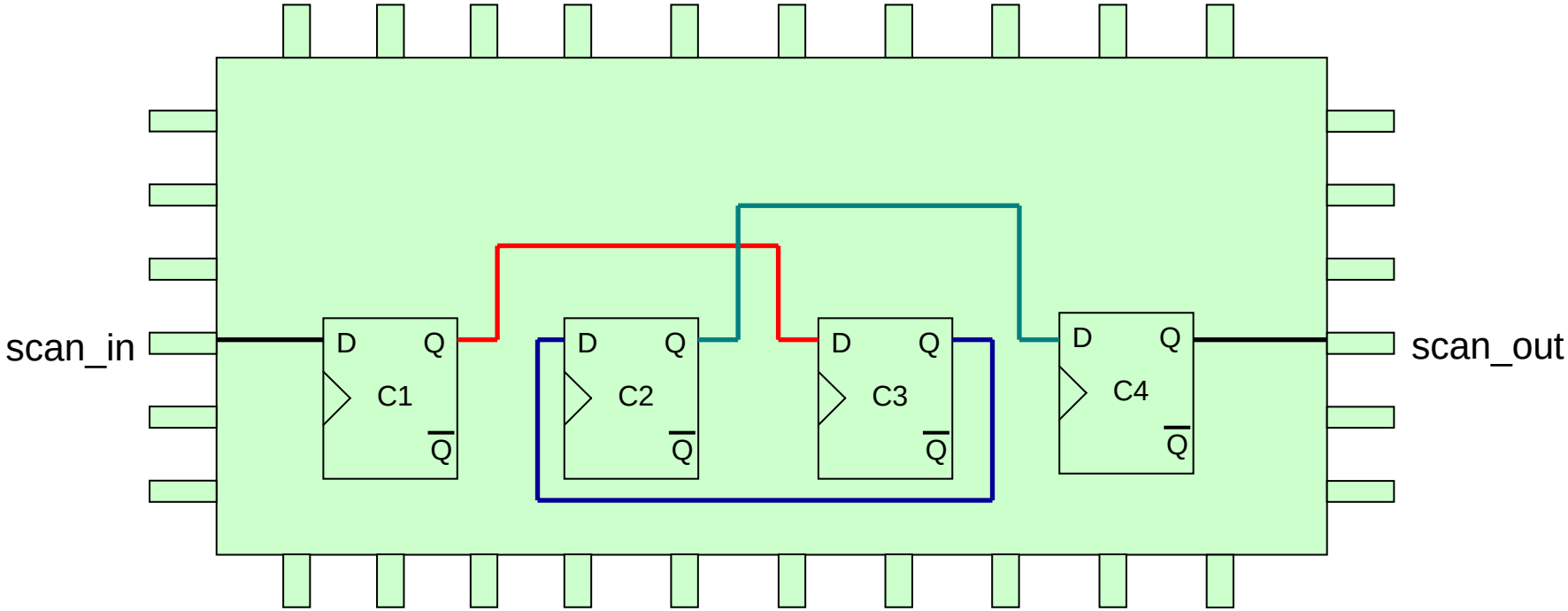

test pattern: 0101

(original form)

test pattern: 0011

(new form)

Scan Chain Reordering

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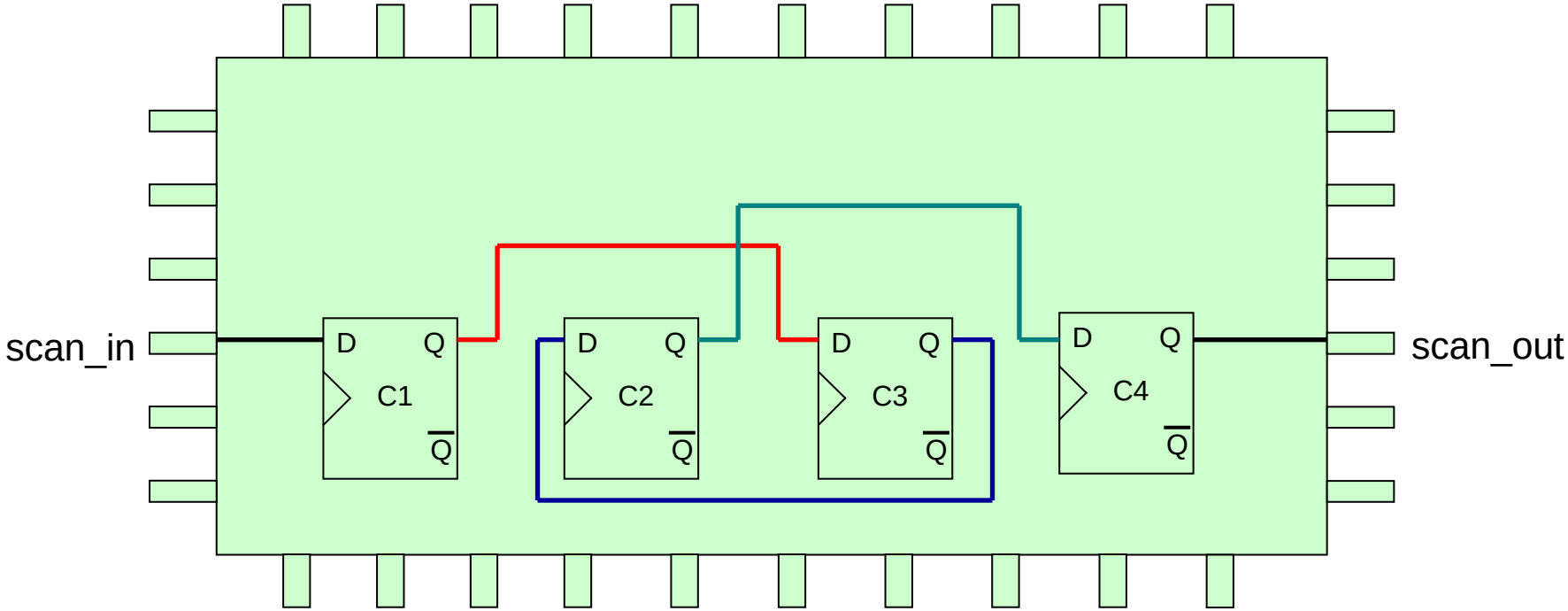

(old)

test pattern1: 0101

test pattern2: 1100

test pattern1: 0011

test pattern2: 1100

(new)

Scan Chain Reordering

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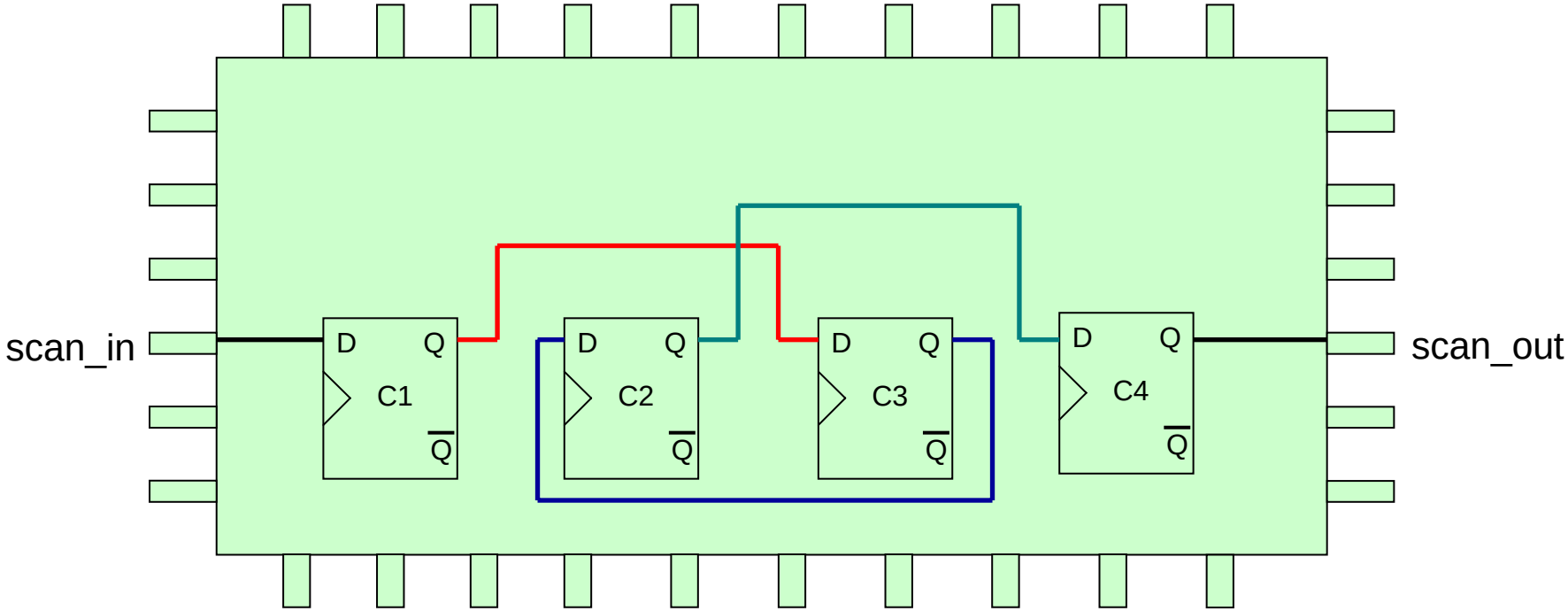


(old)

test pattern1: 0101

test pattern2: 1100

test pattern1: 0011

test pattern2: 1010

(new)

Definition: Frame and Distance

- Frame：a vector of inputs applied to the same scan cell
  - Frame width = # of test patterns
  - # of Frame = # of scan cells
- Distance between 2 frames：
  - extended hamming distance

	F[1]	F[2]	F[3]	F[4]	F[5]
T[1]	1	0	1	X	X
T[2]	X	0	1	0	1
T[3]	0	1	X	0	0

Total Distance Minization

- Minimize the total distance of the test data
- Method
  - Compute distances between every two frames
  - Construct a complete, simple, undirected graph
    - Vertex: frame
    - Distance: Distance between Vertexes
  - Solve Hamilton Path
    - The shortest path that passes through every vertex just one time
    - NP-hard
    - Greedy algorithm

Algorithm 1 – Scan Chain Reordering (A Simplified Version)

- Input: original frames (F[1], F[2], F[3], ...)
- Output: reordered frames (F[1]', F[2]', F[3]', ...)

- Step 1:
  - F[1]' <= F[1], and remove F1 from the original set
- Step n:
  - chose a frame F[m] closest to F[n-1]' from the rest of the original set
  - F[n]' <= F[m], and remove F[m] from the original set

- Problems:
  - don't-cares in frames will be eventually decided as 0s or 1s
  - frame distance calculated at step n might be inaccurate

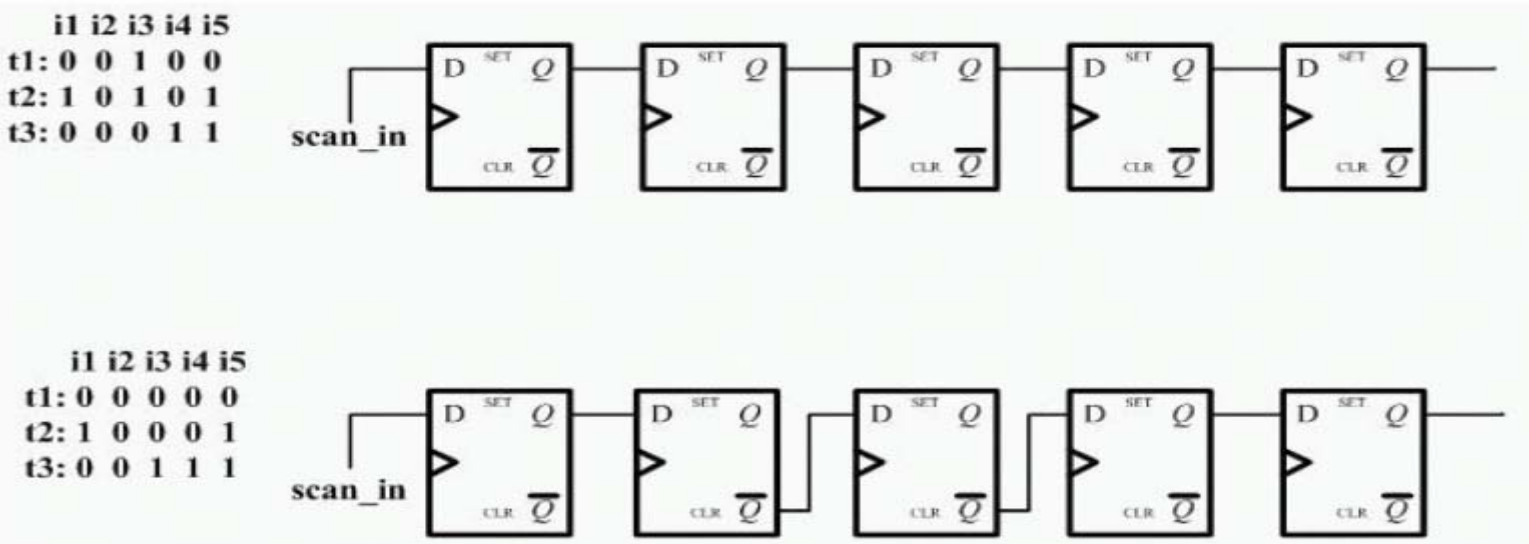
Algorithm 1 – Scan Chain Reordering (An Improved Version)

- Idea:
  - maintain a reference frame FR for selecting the closest frame from the original set
  - FR = f(FR, F[n-1]')
- Step n:
  - chose a frame F[m] closest to FR from the rest of the original set

		F[n-1]'		
		0	1	X
FR	0	0	X	0
	1	X	1	1
	X	0	1	1

Algorithm 2 -- Scan Polarity Adjustment

- Flip a frame
  - no area overhead, no influence on timing
- Double the original frame set with flipped frames



Algorithm 3 – Test Pattern Reordering

- Reorder patterns to reduce runs
- A directed graph
  - vertexes： ZERO, ONE
  - edges:
    - source: last bit of pattern i
    - sink: first bit of pattern i+1
- Minimize ZERO->ONE or ONE->ZERO edges

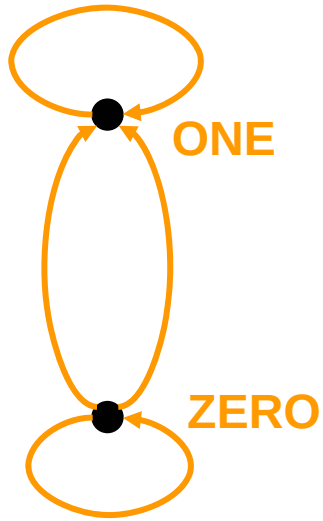
Patterns

011100

010101

001111

100101



Final Algorithm -- RunBasedReordering (RBR)

- Scan chain reordering
- Scan polarity adjustment
- Test pattern reordering

Comparison on Compression Ratio

- Compression Ratio(CR) = (1-TE/TD)*100%

Circuits	|TD|	# of SC	# of TP	EFDR		SPA		RBR		
				bits	CR(¥%)	bits	CR(¥%)	bits	CR(¥%)	time(s)
s5378f	23754	214	111	11006	53.67	8502	64.21	7469	**68.56**	0.03
s9234f	39273	247	159	20162	48.66	10608	**72.99**	11727	70.14	0.07
s13207f	165200	700	236	28932	82.49	18518	88.79	11847	**92.83**	0.28
s15850f	76986	611	126	24127	68.66	15900	79.35	11477	**85.09**	0.16
s35932f	28208	1763	16	5415	80.80	13880	50.79	1250	**95.57**	0.14
s38417	164736	1664	99	62568	62.02	57118	65.33	24746	**84.98**	0.83
s38584f	19104	1464	136	71121	64.28	53774	72.99	39099	**80.36**	1.14
Average	-	-	-	-	65.80	-	70.64	-	**82.50**	-

Comparison on Power consumption

circuits	EFDR		RBR		Power Saving	
	Peak	Avg	Peak	Avg	Peak(%)	Avg(%)
s5378f	11522	3525	3661	717	**68.23**	**79.66**
s9234f	14103	4022	4717	899	**66.55**	**77.65**
s13207f	94886	7892	9379	590	**90.12**	**92.52**
s15850f	70894	13659	12092	1839	**82.94**	**86.54**
s35932f	108957	40214	5780	2696	**94.70**	**93.30**
s38417f	437935	118077	47399	12292	**89.18**	**89.59**
s38584f	481171	86305	115917	18942	**75.91**	**78.05**
Average	--	--	--	--	**81.09**	**85.33**

Related Work on Scan Chain Reordering

- Conventional
  - save routing resource
    - make adjacent scan cells physically closer
  - check of hold violations of timing
    - adjacent scan cells not too close
- Our purpose
  - data compression
  - power saving

Summary

- The test problem
- A new test data compression technique (RBR)
  - Scan chain reordering
  - Scan polarity adjustment
  - Test pattern reordering
- Experimentation
  - superior than the state-of-the-art
    - compression ratio
    - power consumption

Thank you