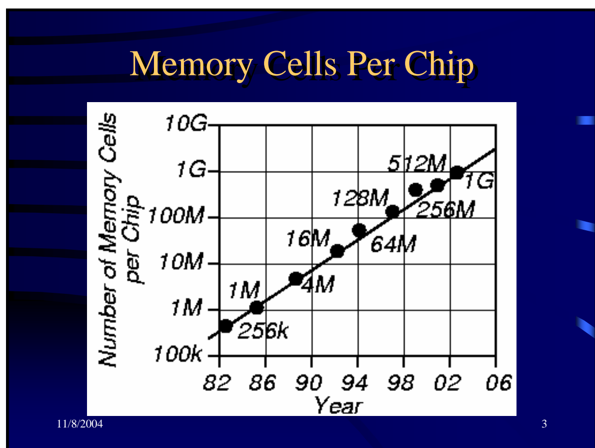
ECE 553: TESTING AND TESTABLE DESIGN OF DIGITAL SYSTES

Memory testing

Overview

- Motivation and introduction
- Functional model of a memory
- A simple minded test and its limitations
- Fault models
- March tests and their capabilities
- Neighborhood tests
- Summary

Memory Cells Per Chip



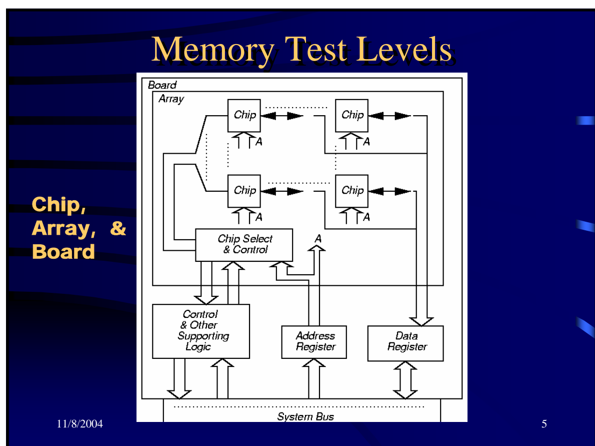
Test Time in Seconds (Memory Size *n* Bits)

Size	Number of Test Algorithm Operations			
n	*n*	$n \times \log_2 n$	$n^{3/2}$	n^2
1 Mb	0.06	1.26	64.5	18.3 hr
4 Mb	0.25	5.54	515.4	293.2 hr
16 Mb	1.01	24.16	1.2 hr	4691.3 hr
64 Mb	4.03	104.7	9.2 hr	75060.0 hr
256 Mb	16.11	451.0	73.3 hr	1200959.9 hr
1 Gb	64.43	1932.8	586.4 hr	19215358.4 hr
2 Gb	128.9	3994.4	1658.6 hr	76861433.7 hr

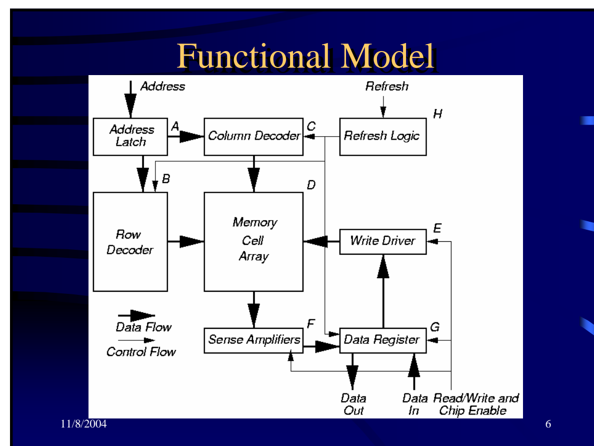
Memory cycle time = 60ns

Memory Test Levels

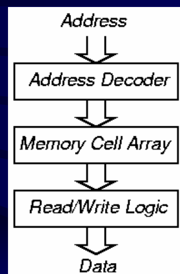
Chip, Array, & Board



Functional Model



Simplified Functional Model



A simple minded test

for cell := 0 to n - 1 (or any other order) do
write 0 to A [cell];
read A [cell]; { Expected value = 0}
write 1 to A [cell];
read A [cell]; { Expected value = 1 }
end for;

What does this test achieve?
What kind of faults does it detect and it fault coverage?

Functional Faults

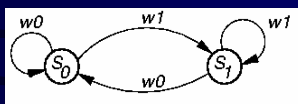
Fault		Functional fault
SAF	*a*	Cell stuck
SAF	*b*	Driver stuck
SAF	*c*	Read/write line stuck
SAF	*d*	Chip-select line stuck
SAF	*e*	Data line stuck
SAF	*f*	Open circuit in data line
CF	*g*	Short circuit between data lines
CF	*h*	Crosstalk between data lines
AF	*i*	Address line stuck
AF	*j*	Open circuit in address line
AF	*k*	Shorts between address lines
AF	*l*	Open circuit in decoder
AF	*m*	Wrong address access
AF	*n*	Multiple simultaneous address access
TF	*o*	Cell can be set to 0 (1) but not to 1 (0)
NPSF	*p*	Pattern sensitive cell interaction

Reduced Functional Faults

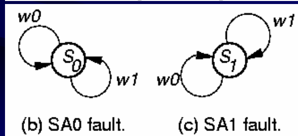
	Fault
SAF	Stuck-at fault
TF	Transition fault
CF	Coupling fault
NPSF	Neighborhood Pattern Sensitive fault

Stuck-at Faults

- *Condition*: For each cell, must read a 0 and a 1.



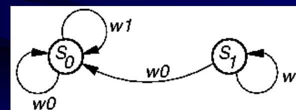
(a) State diagram of a good cell.



(b) SA0 fault. (c) SA1 fault.

Transition Faults

- Cell fails to make 0→1 or 1→0 transition
- *Condition*: Each cell must undergo a ↑ transition and a ↓ transition, and be read after such, before undergoing any further transitions.



< ↑/0> transition fault

Coupling Faults

- *Coupling Fault* (CF): Transition in bit *j* causes unwanted change in bit *i*
- *2-Coupling Fault*: Involves 2 cells, special case of *k-Coupling Fault*
  - Must restrict *k* cells to make practical
- *Inversion* and *Idempotent* CFs -- special cases of *2-Coupling Faults*
- *Bridging* and *State Coupling Faults* involve any # of cells, caused by logic level
- *Dynamic Coupling Fault* (CFdyn) -- Read or write on *j* forces *i* to 0 or 1

March Test Notation

- r0 -- Read a 0 from a memory location
- r1 -- Read a 1 from a memory location
- w0 -- Write a 0 to a memory location
- w1 -- Write a 1 to a memory location
- ↑ -- Write a 1 to a cell containing 0
- ↓ -- Write a 0 to a cell containing 1

March Test Notation (Continued)

- ↕ -- Complement the cell contents
- ⇑ -- Increasing memory addressing
- ⇓ -- Decreasing memory addressing
- ⇕ -- Either increasing or decreasing

MATS+ March Test

M0: { March element ⇕ (w0) }
  for cell := 0 to n - 1 (or any other order) do
    write 0 to A [cell];
M1: { March element ⇑ (r0, w1) }
  for cell := 0 to n - 1 do
    read A [cell]; { Expected value = 0}
    write 1 to A [cell];
M2: {March element ⇓ (r1, w0) }
  for cell := n – 1 down to 0 do
    read A [cell]; { Expected value = 1 }
    write 0 to A [cell];

Address Decoder Faults (ADFs)

- Address decoding error assumptions:
  - Decoder does not become sequential
  - Same behavior during both read & write
- Multiple ADFs must be tested for

A_x o—|	|—o C_x	A_y → C_x, C_y	A_x, A_y → C_x
Fault 1	*Fault 2*	*Fault 3*	*Fault 4*
No Cell Accessed for A_x	*No Address to Access cell C_x*	*Multiple Cells Accessed with A_y*	*Multiple Addresses for Cell C_x*

Theorem 9.2

- *A March test satisfying conditions 1 & 2 detects all address decoder faults.*
- ... Means any # of read or write operations
- Before condition 1, must have *wx* element
  - *x* can be 0 or 1, but must be consistent in test

Condition	March element
1	⇑ (rx, …, w $\overline{x}$)
2	⇓ (r $\overline{x}$, …, wx)

Proof Illustration

Combinations that must be tested

A_x — C_x	A_x, C_x, A_y, C_y	A_x, C_x, A_y, C_y	A_x, C_x, A_y, C_y
Fault A (1 + 2)	*Fault B (1 + 3)*	*Fault C (2 + 4)*	*Fault D (3 + 4)*

Conditions for proof

A_v, A_w, A_x, A_y, A_z / C_v, C_w, C_x, C_y, C_z	A_v, A_w, A_x, A_y, A_z / C_v, C_w, C_x, C_y, C_z	A_x, A_y, A_z / C_x, C_y, C_z	A_v, A_w, A_x / C_v, C_w, C_z
Fault C	*Fault D_1*	*Fault D_2*	*Fault D_3*

Necessity Proof

- **Removing *rx* from Condition 1 prevents A or B fault detection when $\bar{x}$ read**
- **Removing *r*$\bar{x}$ from Condition 2 prevents A or B fault detection when *x* read**
- **Removing *r*$\bar{x}$ or *w*$\bar{x}$ from Condition 1 misses fault D2**
- **Removing *r*$\bar{x}$ or *wx* from condition 2 misses fault D3**
- **Removing both writes misses faults C and D1**

Sufficiency Proof

- ***Faults A and B*: Detected by SAF test**
- ***Fault C*: Initialize memory to *h* (*x* or $\bar{x}$). Subsequent March element that reads *h* and writes $\bar{h}$ detects Fault C.**
  - **Marching ⇑ writes $\bar{h}$ to A_v. Detection: read A_w**
  - **Marching ⇓ writes $\bar{h}$ to A_z. Detection: read A_y**
- ***Fault D*: Memory returns random result when multiple cells read simultaneously. Generate fault by writing ⇑⇓ A_x, Detection: read A_w or A_y (or marches)**

Irredundant March Tests

Algorithm	Description
MATS	{ ⇕ (w0); ⇕ (r0, w1); ⇕ (r1) }
MATS+	{ ⇕ (w0); ⇑ (r0, w1); ⇓ (r1, w0) }
MATS++	{ ⇕ (w0); ⇑ (r0, w1); ⇓ (r1, w0, r0) }
MARCH X	{ ⇕ (w0); ⇑ (r0, w1); ⇓ (r1, w0); ⇕ (r0) }
MARCH C—	{ ⇕ (w0); ⇑ (r0, w1); ⇑ (r1, w0); ⇓ (r0, w1); ⇓ (r1, w0); ⇕ (r0) }
MARCH A	{ ⇕ (w0); ⇑ (r0, w1, w0, w1); ⇑ (r1, w0, w1); ⇓ (r1, w0, w1, w0); ⇓ (r0, w1, w0) }
MARCH Y	{ ⇕ (w0); ⇑ (r0, w1, r1); ⇓ (r1, w0, r0); ⇕ (r0) }
MARCH B	{ ⇕ (w0); ⇑ (r0, w1, r1, w0, r0, w1); ⇑ (r1, w0, w1); ⇓ (r1, w0, w1, w0); ⇓ (r0, w1, w0) }

Irredundant March Test Summary

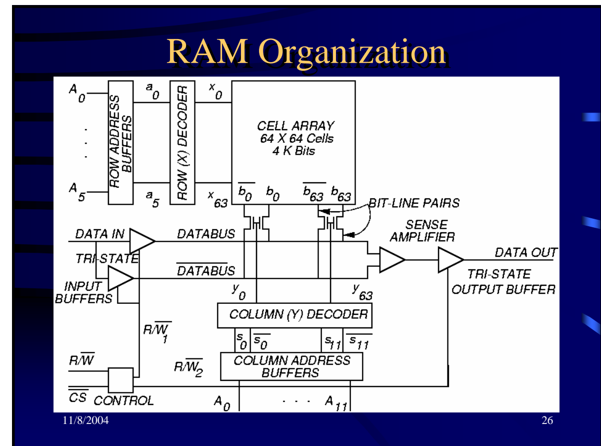
Algorithm	SAF	AF	TF	CF in	CF id	CF dyn	SCF	Linked Faults
MATS	All	Some						
MATS+	All	All						
MATS++	All	All	All					
MARCH X	All	All	All	All				
MARCH C—	All	All	All	All	All	All	All	
MARCH A	All	All	All	All				Some
MARCH Y	All	All	All	All				Some
MARCH B	All	All	All	All				Some

March Test Complexity

Algorithm	Complexity
MATS	$4n$
MATS+	$5n$
MATS++	$6n$
MARCH X	$6n$
MARCH C—	$10n$
MARCH A	$15n$
MARCH Y	$8n$
MARCH B	$17n$

Neighborhood Pattern Sensitive Coupling Faults

RAM Organization

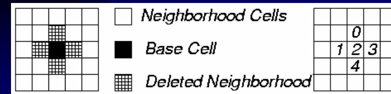


Notation

- **ANPSF --** ***Active Neighborhood Pattern Sensitive Fault***
- **APNPSF –** ***Active and Passive Neighborhood PSF***
- ***Neighborhood*** **-- Immediate cluster of cells whose pattern makes base cell fail**
- **NPSF --** ***Neighborhood Pattern Sensitive Fault***
- **PNPSF --** ***Passive Neighborhood PSF***
- **SNPSF --** ***Static Neighborhood Pattern Sensitive Fault***

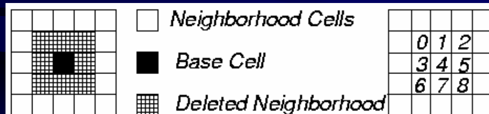
Type 1 Active NPSF

- ***Active*****: Base cell changes when one deleted neighborhood cell transitions**
- ***Condition for detection & location*****: Each base cell must be read in state 0 and state 1, for all possible deleted neighborhood pattern changes.**



Type 2 Active NPSF

- **Used when diagonal couplings are significant, and do not necessarily cause horizontal/vertical coupling**



Passive NPSF

- ***Passive*****: A certain neighborhood pattern prevents the base cell from changing**
- ***Condition for detection and location*****: Each base cell must be written and read in state 0 and in state 1, for all deleted neighborhood pattern changes.**

Static NPSF

- *Static*: Base cell forced into a particular state when deleted neighborhood contains particular pattern.
- Differs from *active* -- need not have a transition to sensitive SNPSF
- *Condition for detection and location*: Apply all 0 and 1 combinations to *k*-cell neighborhood, and verify that each base cell was written.

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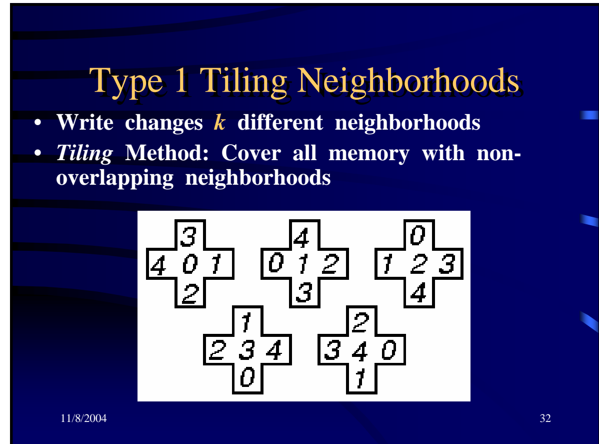
Type 1 Tiling Neighborhoods

- Write changes *k* different neighborhoods
- *Tiling* Method: Cover all memory with non-overlapping neighborhoods



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Two Group Method

- Only for Type-1 neighborhoods
- Use checkerboard pattern, cell is simultaneously a base cell in group 1, and a deleted neighborhood cell in 2

(a) Labels of cells of group-1.

(b) Labels of cells of group-2.

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RAM Tests for Layout-Related Faults

Inductive Fault Analysis:

1. Generate defect sizes, location, layers based on fabrication line model
2. Place defects on layout model
3. Extract defective cell schematic & electrical parameters
4. Evaluate cell testing

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Memory Testing Summary

- Multiple fault models are essential
- Combination of tests is essential:
  - March – SRAM and DRAM
  - NPSF -- DRAM
  - DC Parametric -- Both
  - AC Parametric -- Both
- *Inductive Fault Analysis* is now required

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Summary

- Functional and fault model of memory
  - Many fault models
- March tests and their capabilities
  - Variety of tests
- Neighborhood pattern sensitive tests
  - Varity of fault models and tests

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Appendix

Density and Defect Trends

- 1970 -- DRAM Invention (Intel) 1024 bits
- 1993 -- 1st 256 MBit DRAM papers
- 1997 -- 1st 256 MBit DRAM samples
  - 1 ¢/bit --> 120 X 10^{-6} /bit ¢
- Kilburn -- Ferranti Atlas computer (Manchester U.) -- Invented Virtual Memory
  - 1997 -- Cache DRAM -- SRAM cache + DRAM now on 1 chip

Faults

- *System* -- Mixed electronic, electromechanical, chemical, and photonic system (MEMS technology)
- *Failure* -- Incorrect or interrupted system behavior
- *Error* -- Manifestation of fault in system
- *Fault* -- Physical difference between good & bad system behavior

Fault Types

- Fault types:
  - *Permanent* -- System is broken and stays broken the same way indefinitely
  - *Transient* -- Fault temporarily affects the system behavior, and then the system reverts to the *good* machine -- time dependency, caused by environmental condition
  - *Intermittent* -- Sometimes causes a failure, sometimes does not

Failure Mechanisms

- Permanent faults:
  - Missing/Added Electrical Connection
  - Broken Component (IC mask defect or silicon-to-metal connection)
  - Burnt-out Chip Wire
  - Corroded connection between chip & package
  - Chip logic error (Pentium division bug)

Failure Mechanisms (Continued)

- Transient Faults:
  - Cosmic Ray
  - An α particle (ionized Helium atom)
  - Air pollution (causes wire short/open)
  - Humidity (temporary short)
  - Temperature (temporary logic error)
  - Pressure (temporary wire open/short)
  - Vibration (temporary wire open)
  - Power Supply Fluctuation (logic error)
  - Electromagnetic Interference (coupling)
  - Static Electrical Discharge (change state)
  - Ground Loop (misinterpreted logic value)

Failure Mechanisms (Continued)

- **Intermittent Faults:**
  - **Loose Connections**
  - **Aging Components (changed logic delays)**
  - **Hazards and Races in critical timing paths (bad design)**
  - **Resistor, Capacitor, Inductor variances (timing faults)**
  - **Physical Irregularities (narrow wire -- high resistance)**
  - **Electrical Noise (memory state changes)**

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Physical Failure Mechanisms

- **Corrosion**
- **Electromigration**
- **Bonding Deterioration -- *Au* package wires interdiffuse with *Al* chip pads**
- **Ionic Contamination -- Na^+ diffuses through package and into FET gate oxide**
- **Alloying -- *Al* migrates from metal layers into *Si* substrate**
- **Radiation and Cosmic Rays -- 8 MeV, collides with *Si* lattice, generates *n - p* pairs, causes *soft memory error***

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Fault Modeling

- ***Behavioral* (black-box) Model -- State machine modeling all memory content combinations -- Intractable**
- ***Functional* (gray-box) Model -- Used**
- ***Logic Gate* Model -- Not used Inadequately models transistors & capacitors**
- ***Electrical* Model -- Very expensive**
- ***Geometrical* Model -- Layout Model**
  - **Used with *Inductive Fault Analysis***

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Reduced Functional Model (van de Goor)

- ***n* Memory bits, *B* bits/word, *n*/*B* addresses**
- **Access happens when Address Latch contents change**
- **Low-order address bits operate column decoder, high-order operate row decoder**
- **read -- Precharge bit lines, then activate row**
- **write -- Keep driving bit lines during evaluation**
- **Refresh -- Read all bits in 1 row and simultaneously refresh them**

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Inversion Coupling Faults (CFin)

- **↑ or ↓ in cell *j* inverts contents of cell *i***
- ***Condition*: For all cells that are coupled, each should be read after a series of possible CFins may have occurred, and the # of coupled cell transitions must be odd (to prevent the CFins from masking each other).**
- **<↑; ↕> and <↓; ↕>**

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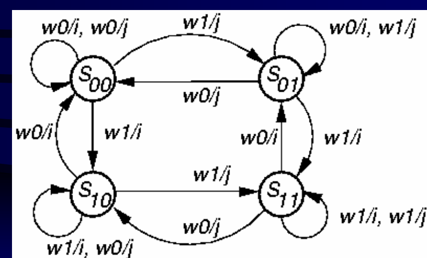
Good Machine State Transition Diagram



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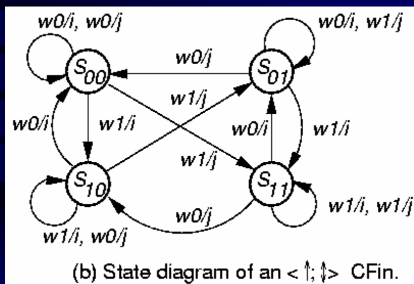
CFin State Transition Diagram

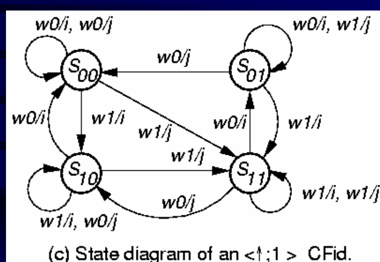


(b) State diagram of an < ↑; ↕> CFin.

Idempotent Coupling Faults (CFid)

- ↑ or ↓ transition in *j* sets cell *i* to 0 or 1
- *Condition*: For all coupled faults, each should be read after a series of possible CFids may have happened, such that the sensitized CFids do not mask each other.
- *Asymmetric*: coupled cell only does ↑ or ↓
- *Symmetric*: coupled cell does both due to fault
- < ↑; 0>, < ↑; 1>, < ↓; 0>, < ↓; 1>

CFid Example



(c) State diagram of an <↑;1 > CFid.

Dynamic Coupling Faults (CFdyn)

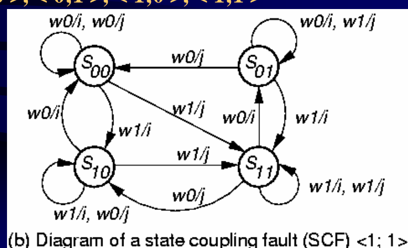
- Read or write in cell of 1 word forces cell in different word to 0 or 1
- <r0 | w0 ; 0>, <r0 | w0 ; 1>, < r1 | w1 ; 0>, and <r1 | w1; 1>
  - | Denotes "OR" of two operations
- More general than CFid, because a CFdyn can be sensitized by any read or write operation

Bridging Faults

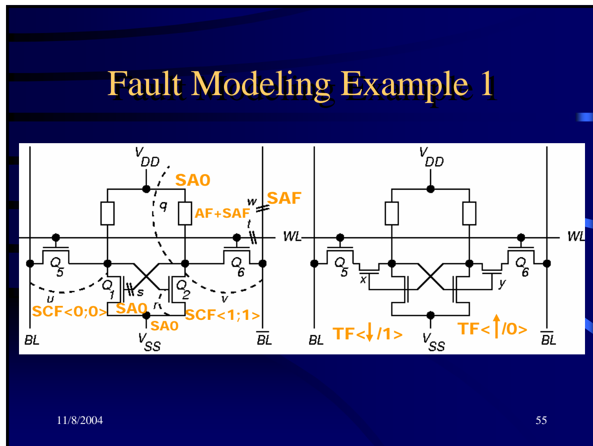
- Short circuit between 2+ cells or lines
- 0 or 1 state of *coupling cell*, rather than coupling cell transition, causes *coupled cell* change
- Bidirectional fault -- *i* affects *j*, *j* affects *i*
- *AND Bridging Faults* (ABF):
  - < 0,0 / 0,0 >, <0,1 / 0,0 >, <1,0 / 0,0>, <1,1 / 1,1>
- *OR Bridging Faults* (OBF):
  - < 0,0 / 0,0 >, <0,1 / 1,1 >, <1,0 / 1,1>, <1,1 / 1,1>

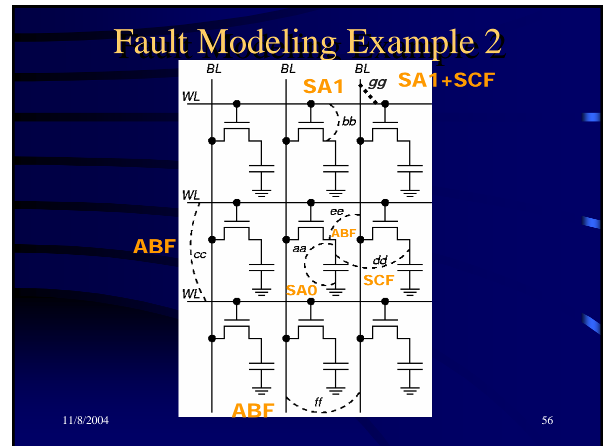
State Coupling Faults

- *Coupling cell / line j* is in a given state *y* that forces *coupled cell / line i* into state *x*
- < 0;0 >, < 0;1 >, < 1;0 >, < 1;1 >



(b) Diagram of a state coupling fault (SCF) <1; 1>.





Multiple Fault Models

- Coupling Faults: In real manufacturing, any # can occur simultaneously
- Linkage: A fault influences behavior of another
- Example March test that fails:
  - { ⇕(w0) ; ⇑(r0, w1); ⇓(w0, w1); ⇕(r1)}
  - Wor...

(a) Unlinked faults. (b) Linked faults.

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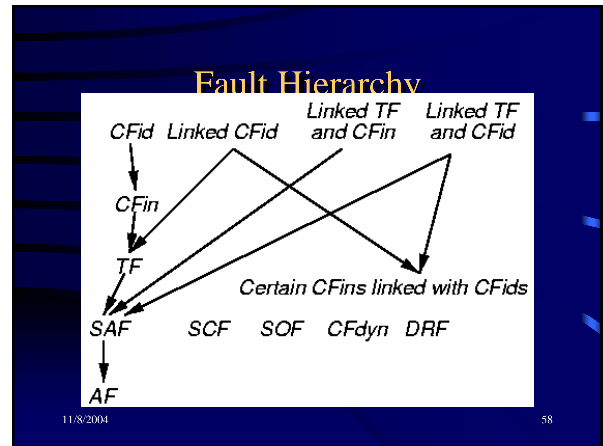

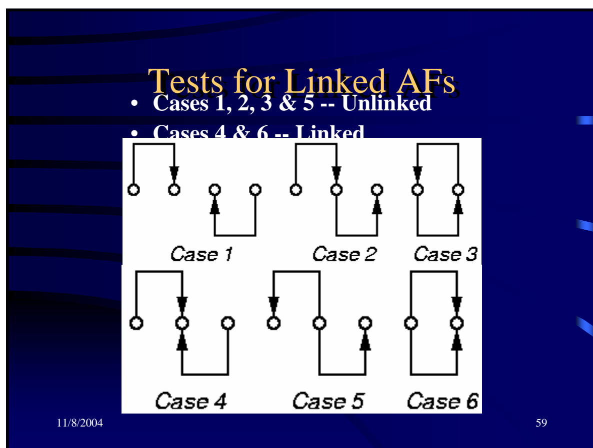

DRAM/SRAM Fault Modeling

DRAM or SRAM Faults	Model
Shorts & opens in memory cell array	SAF,SCF
Shorts & opens in address decoder	AF
Access time failures in address decoder	Functional
Coupling capacitances between cells	CF
Bit line shorted to word line	IDDQ
Transistor gate shorted to channel	IDDQ
Transistor stuck-open fault	SOF
Pattern sensitive fault	PSF
Diode-connected transistor 2 cell short	
Open transistor drain	
Gate oxide short	
Bridging fault	

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SRAM Only Fault Modeling

Faults found only in SRAM	Model
Open-circuited pull-up device	DRF
Excessive bit line coupling capacitance	CF

DRAM Only Fault Modeling

Faults only in DRAM	Model
Data retention fault (sleeping sickness)	DRF
Refresh line stuck-at fault	SAF
Bit-line voltage imbalance fault	PSF
Coupling between word and bit line	CF
Single-ended bit-line voltage shift	PSF
Precharge and decoder clock overlap	AF

Functional RAM Testing with March Tests

- **March Tests can detect AFs -- NPSF Tests Cannot**
- **Conditions for AF detection:**
  - Need ⇑ (r x̄, w x)
  - Need ⇓ (r x, w x)

MATS+ Example Cell (2,1) SA0 Fault

0 0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0 0
(a) Good machine after M0.	(b) Good machine after M1.	(c) Good machine after M2.
0 0 0 0 0 0 0 0 0	1 1 1 0 1 1 1 1 1	0 0 0 0 0 0 0 0 0
(d) Bad machine after M0.	(e) Bad machine after M1.	(f) Bad machine after M2.

MATS+:
{ M0: ⇕ (w0); M1: ⇑ (r0, w1); M2: ⇓ (r1, w0) }

MATS+ Example Cell (2, 1) SA1 Fault

0 0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0 0
(a) Good machine after M0.	(b) Good machine after M1.	(c) Good machine after M2.
0 0 0 1 0 0 0 0 0	1 1 1 1 1 1 1 1 1	0 0 0 1 0 0 0 0 0
(d) Bad machine after M0.	(e) Bad machine after M1.	(f) Bad machine after M2.

MATS+:
{ M0: ⇕ (w0); M1: ⇑ (r0, w1); M2: ⇓ (r1, w0) }

MATS+ Example Multiple AF Type C

- **Cell (2,1) is not addressable**
- **Address (2,1) maps into (3,1) & vice versa**
- **Can't write (2,1), read (2,1) gives random #**

0 0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0 0
(a) Good machine after M0.	(b) Good machine after M1.	(c) Good machine after M2.

0 0 0 X 0 0 0 0 0	1 1 1 X 0 0 1 0 0	1 1 1 X 1 1 1 1 1	0 0 0 X 0 0 0 0 0
(d) Bad machine after M0.	(e) Bad machine after M1 for cell (2, 1).	(f) Bad machine after M1.	(g) Bad machine after M2.

MATS+:
{ M0: ⇕ (w0); M1: ⇑ (r0, w1); M2: ⇓ (r1), w0 }