

Memory in SystemVerilog

Prof. Stephen A. Edwards

Columbia University

Spring 2024

Implementing Memory

Memory = Storage Element Array + Addressing

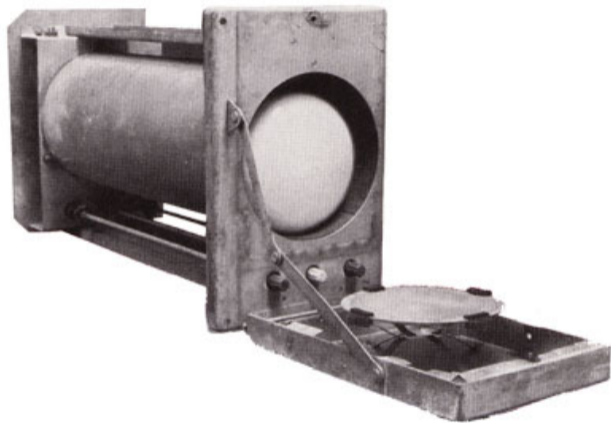
Bits are expensive

They should be dumb, cheap, small, and tightly packed

Bits are numerous

Can't just connect a long wire to each one

Williams Tube



CRT-based random access memory, 1946.
Used on the Manchester Mark I. 2048 bits.

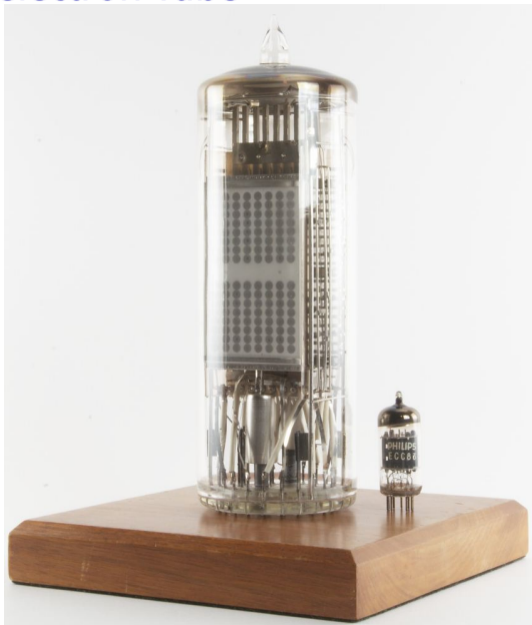
Mercury acoustic delay line



Used in the EDASC, 1947.

32×17 bits

Selectron Tube



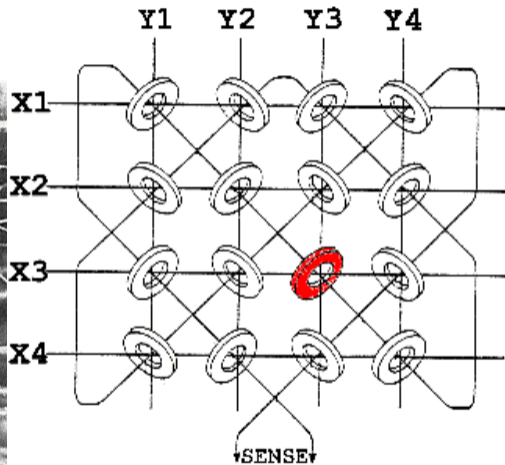
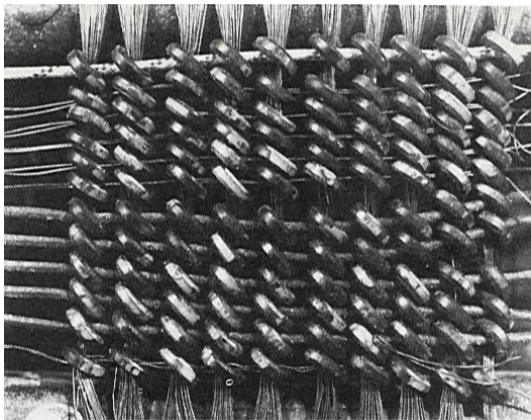
RCA, 1948.

2×128 bits

Four-dimensional addressing

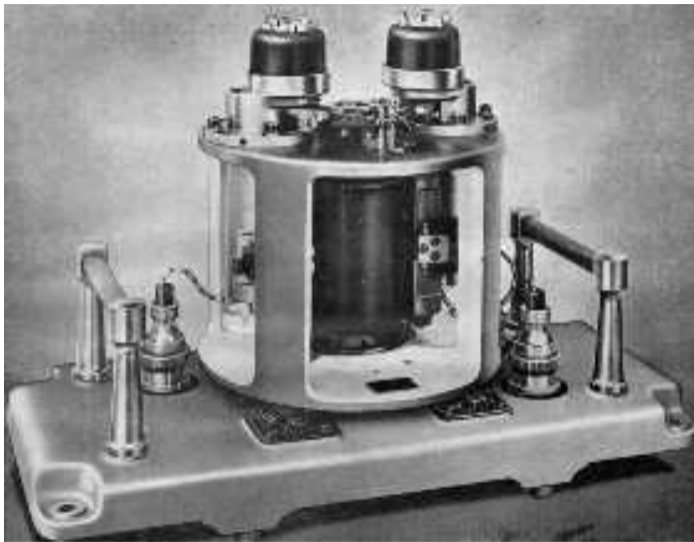
A four-input AND gate at each bit for selection

Magnetic Core




IBM, 1952.

Magnetic Drum Memory



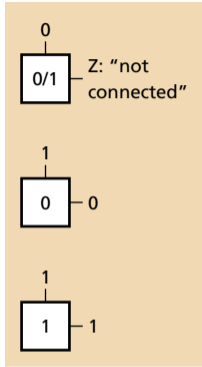
1950s & 60s. Secondary storage.

Modern Memory Choices



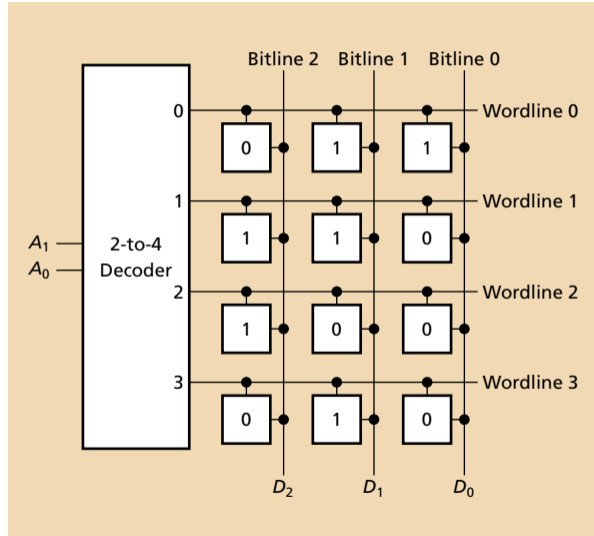
Family	Programmed	Persistence
Mask ROM	at fabrication	∞
PROM	once	∞
EPROM	1000s, UV erase	10 years
FLASH	1000s, block erase	10 years
EEPROM	1000s, byte erase	10 years
NVRAM	∞	5 years
SRAM	∞	while powered
DRAM	∞	64 ms

Implementing ROMs

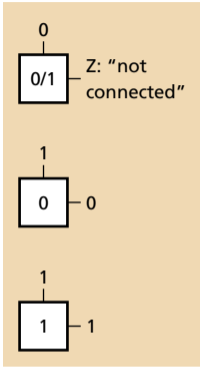


Addr. Data

00	011
01	110
10	100
11	010

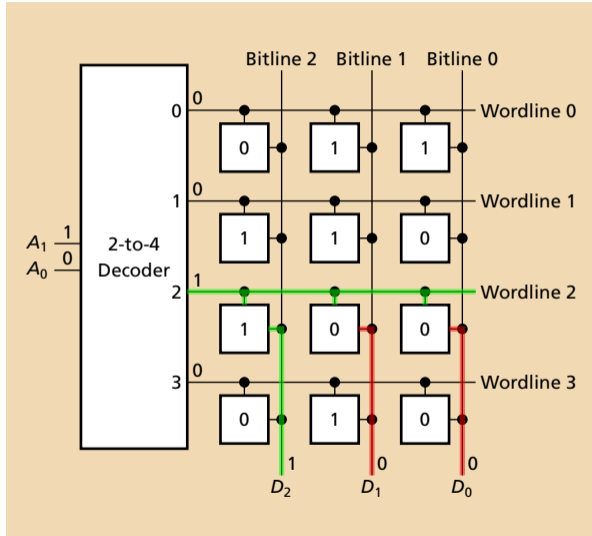


Implementing ROMs

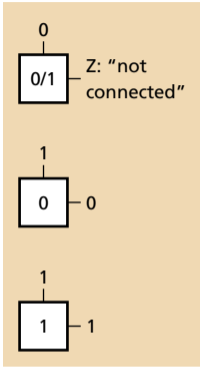


Add. Data

00	011
01	110
10	100
11	010

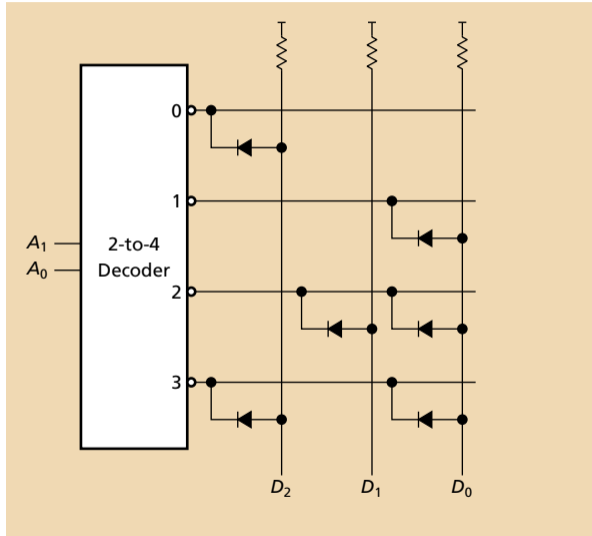


Implementing ROMs

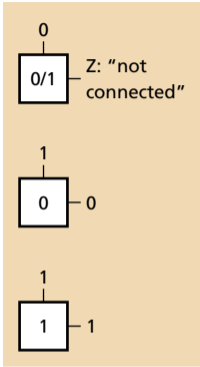


Addr. Data

00	011
01	110
10	100
11	010

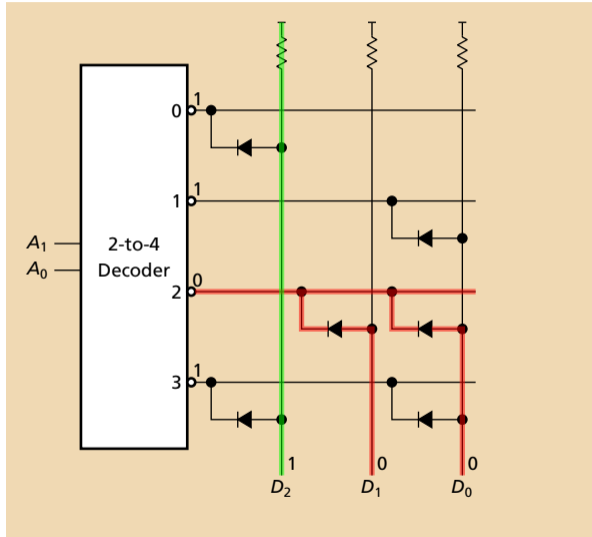


Implementing ROMs

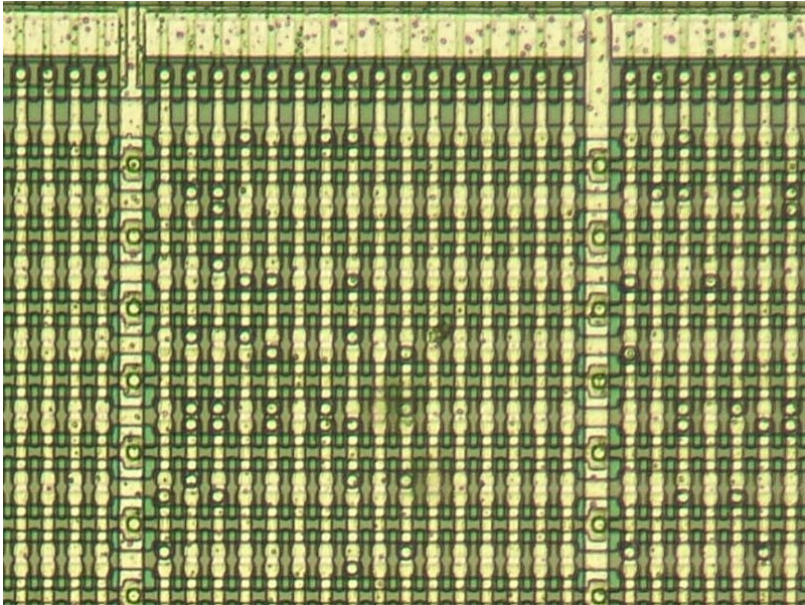


Addr. Data

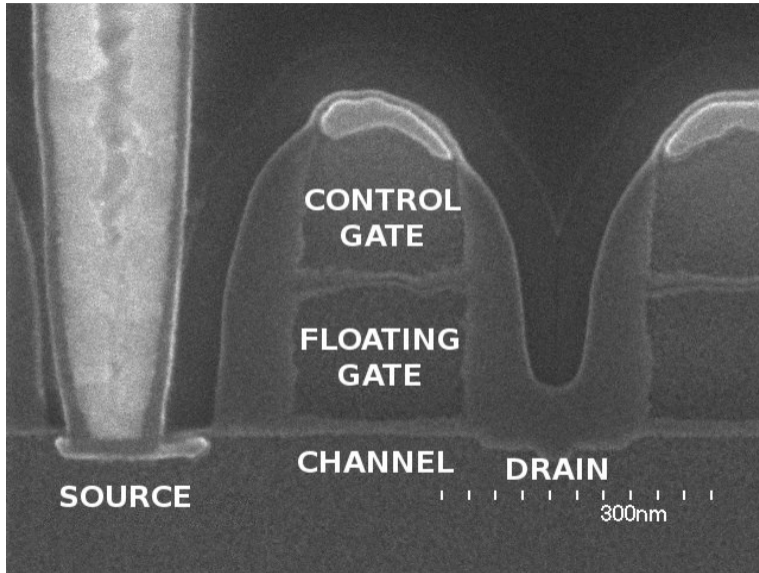
00	011
01	110
10	100
11	010



Mask ROM Die Photo

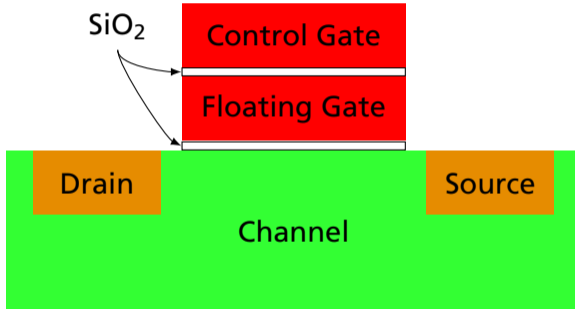


A Floating Gate MOSFET



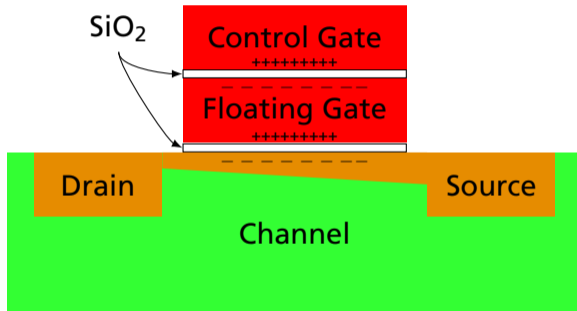
Cross section of a NOR FLASH transistor. Kawai et al., ISSCC 2008 (Renesas)

Floating Gate n-channel MOSFET



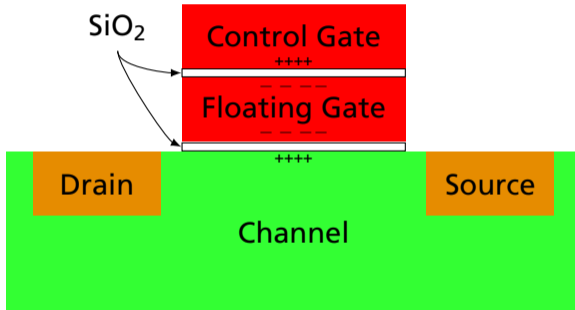
Floating gate uncharged; Control gate at 0V: Off

Floating Gate n-channel MOSFET



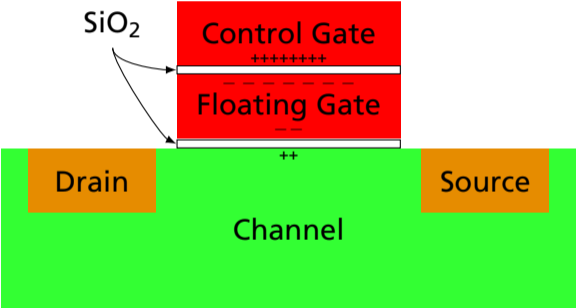
Floating gate uncharged; Control gate positive: On

Floating Gate n-channel MOSFET



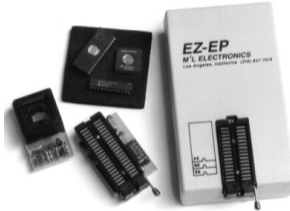
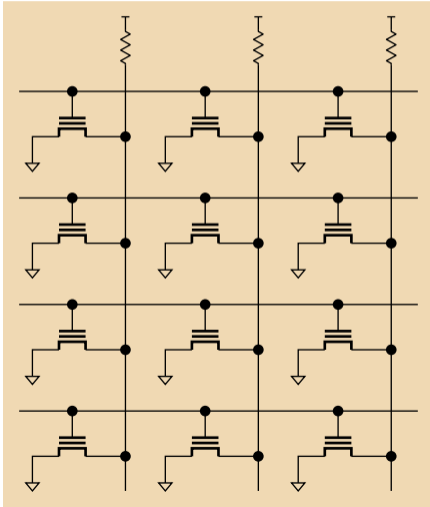
Floating gate negative; Control gate at 0V: Off

Floating Gate n-channel MOSFET

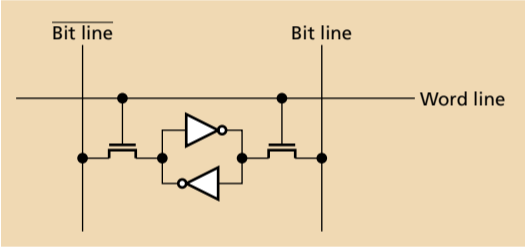


Floating gate negative; Control gate positive: Off

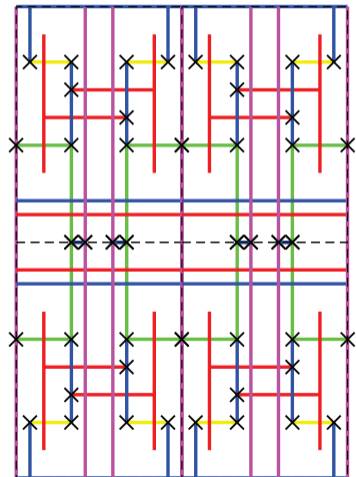
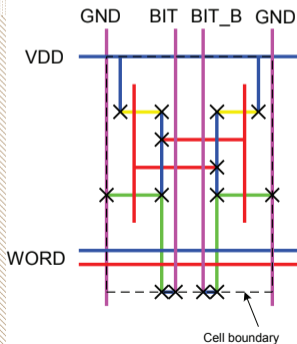
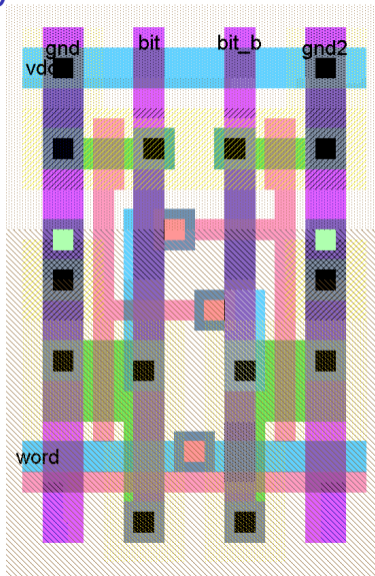
EPROMs and FLASH use Floating-Gate MOSFETs



Static Random-Access Memory Cell

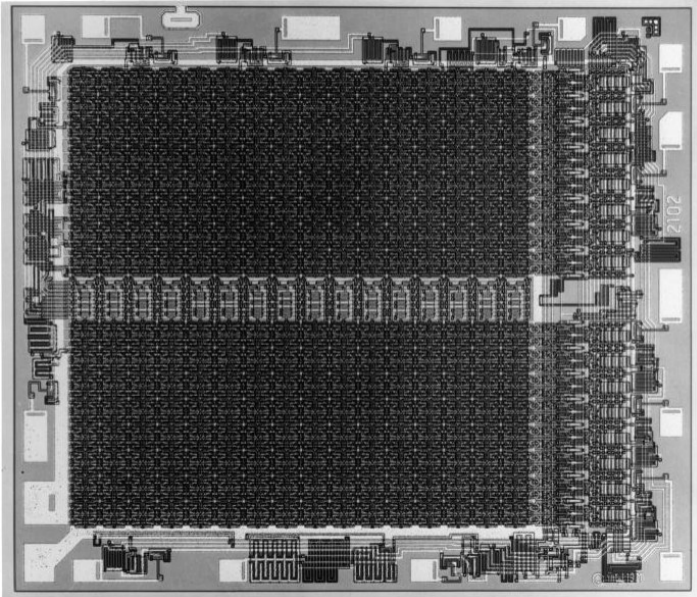


Layout of a 6T SRAM Cell

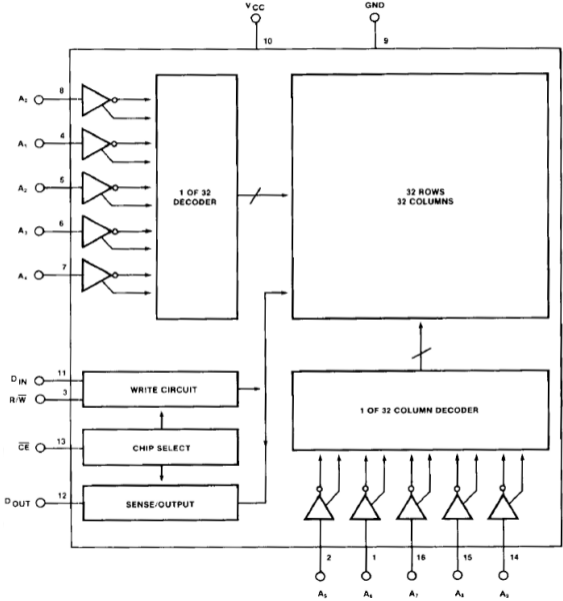


Weste and Harris. *Introduction to CMOS VLSI Design*. Addison-Wesley, 2010.

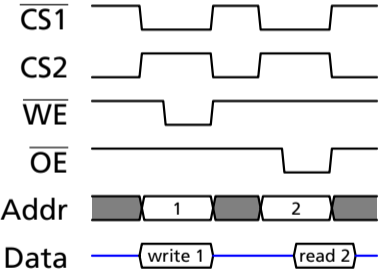
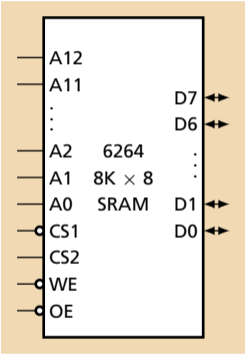
Intel's 2102 SRAM, 1024 × 1 bit, 1972



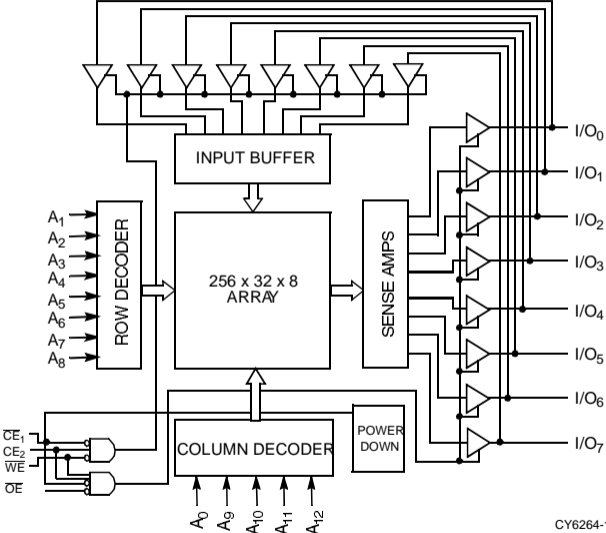
2102 Block Diagram



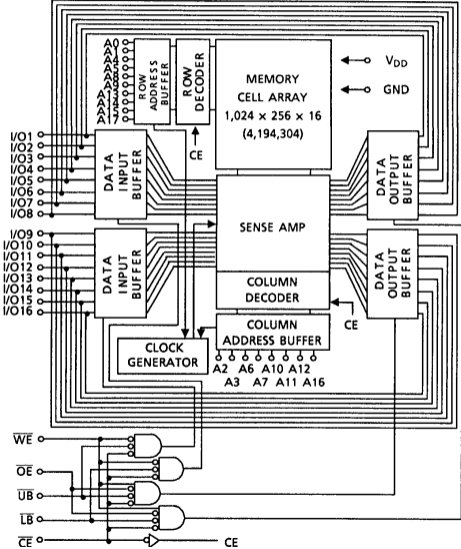
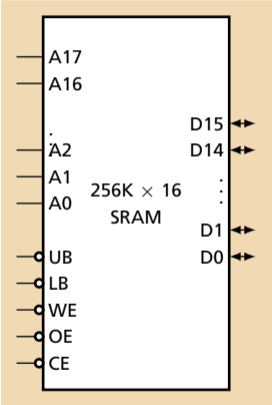
SRAM Timing



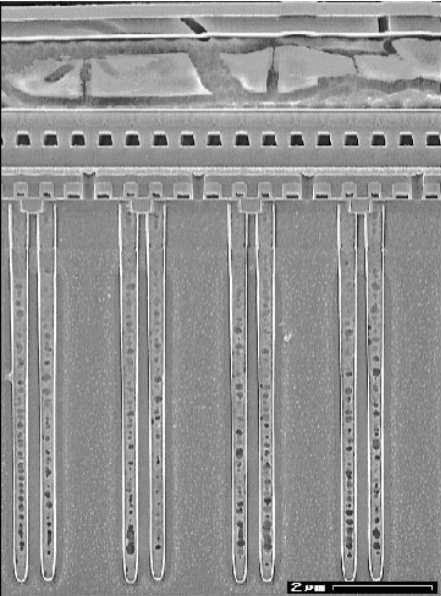
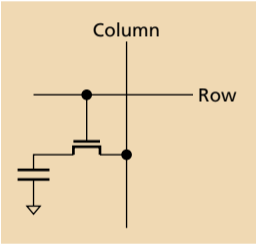
6264 SRAM Block Diagram



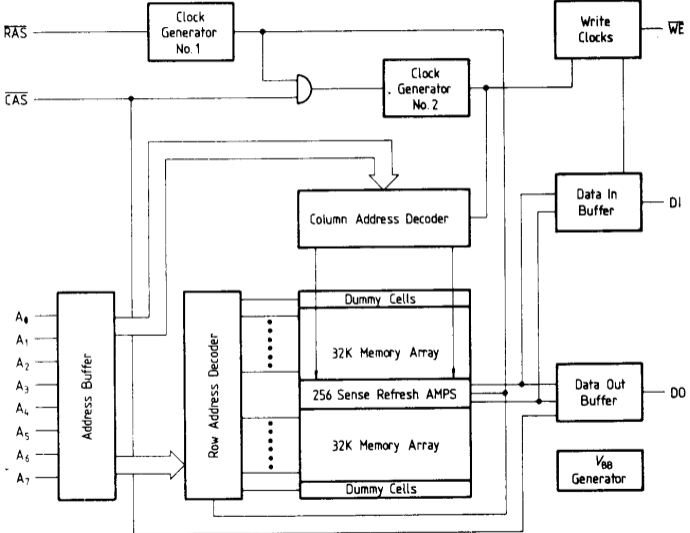
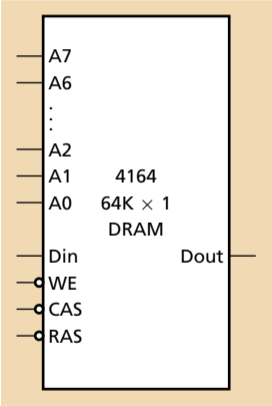
Toshiba TC55V16256J 256K × 16



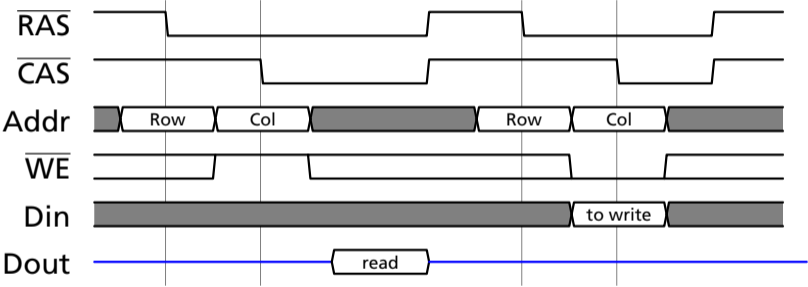
Dynamic RAM Cell



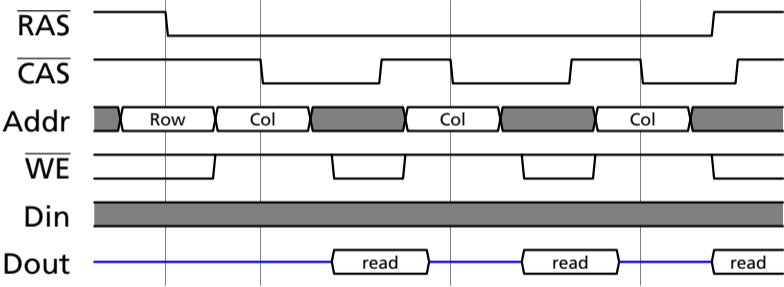
Ancient (c. 1982) DRAM: 4164 64K × 1



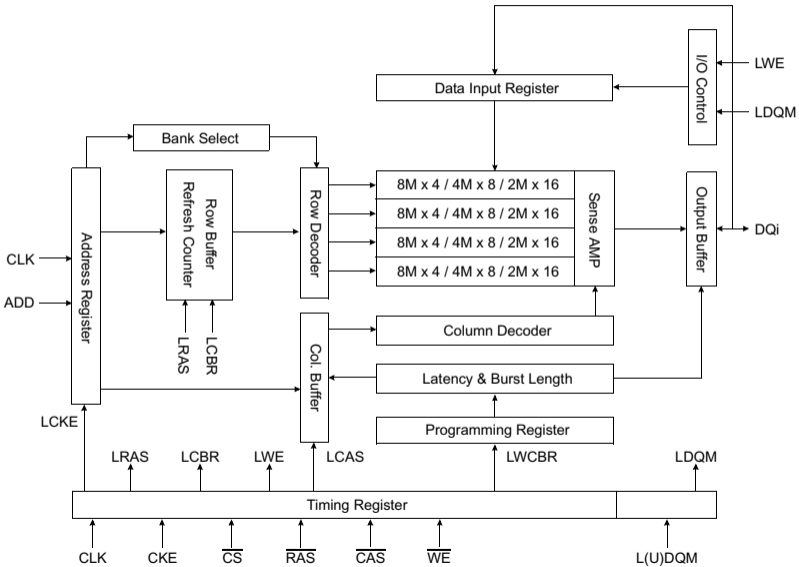
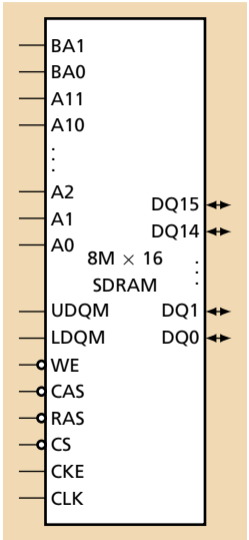
Basic DRAM read and write cycles



Page Mode DRAM read cycle



Samsung 8M × 16 SDRAM

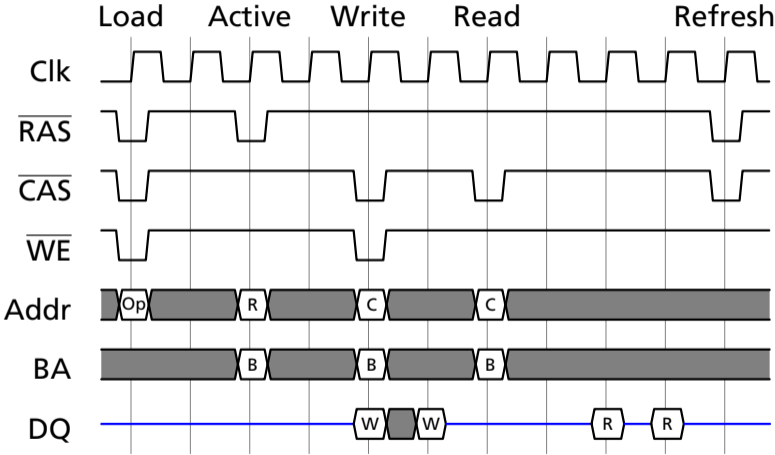


SDRAM: Control Signals

$\overline{\text{RAS}}$	$\overline{\text{CAS}}$	$\overline{\text{WE}}$	Action
1	1	1	NOP
0	0	0	Load mode register
0	1	1	Active (select row)
1	0	1	Read (select column, start burst)
1	0	0	Write (select column, start burst)
1	1	0	Terminate Burst
0	1	0	Precharge (deselect row)
0	0	1	Auto Refresh

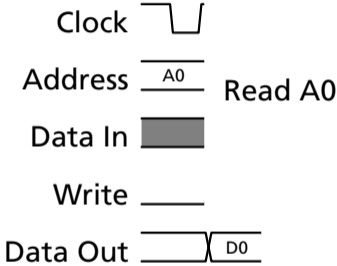
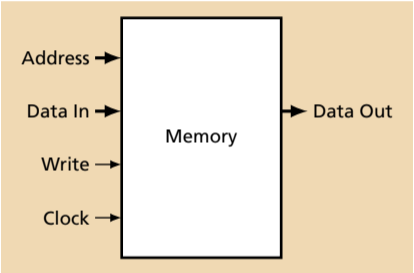
Mode register: selects 1/2/4/8-word bursts, CAS latency, burst on write

SDRAM: Timing with 2-word bursts

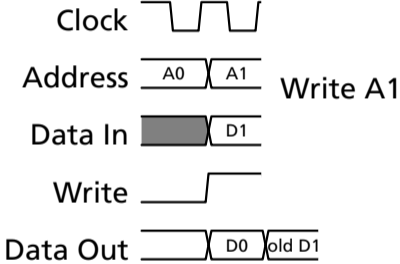
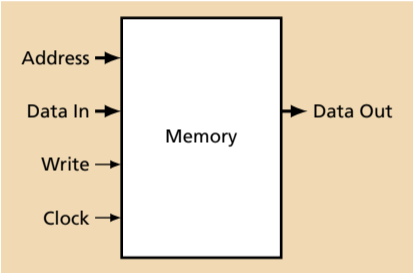


Using Memory in SystemVerilog

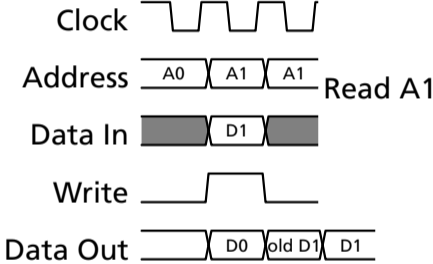
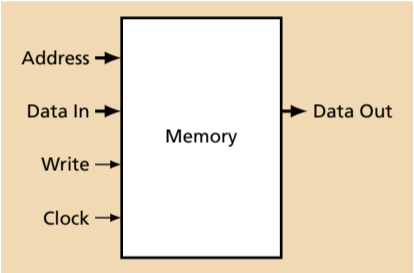
Synchronous SRAM



Synchronous SRAM



Synchronous SRAM



Memory: A Fundamental Bottleneck



Plenty of bits, but

You can only see a small window each clock cycle

Using memory = scheduling memory accesses

Software hides this from you:
sequential programs naturally schedule accesses

In hardware, you must schedule memory accesses

Modeling Synchronous Memory in SystemVerilog

```
module memory(  
  input logic      clk      ,  
  input logic      write    ,  
  input logic [3:0] address ,  
  input logic [7:0] data_in ,  
  output logic [7:0] data_out);  
  
  logic [7:0] mem [15:0];  
  
  always_ff @(posedge clk)  
  begin  
    if (write)  
      mem[address] <= data_in;  
    data_out <= mem[address];  
  end  
  
endmodule
```

Write enable

4-bit address

8-bit input bus

8-bit output bus

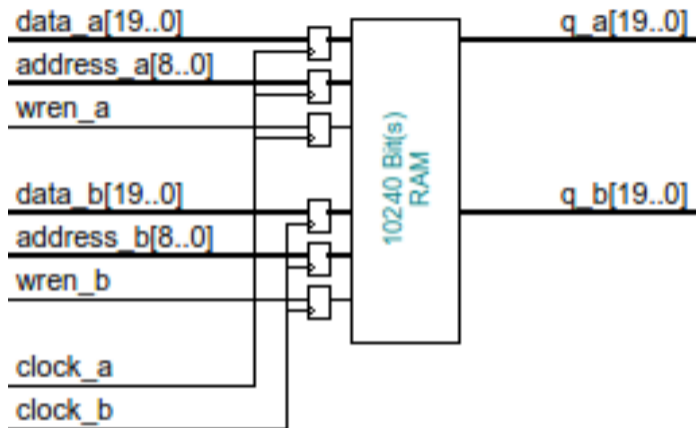
The memory array: 16 8-bit bytes

Clocked

Write to array when asked

Always read (old) value from array

M10K Blocks in the Cyclone V



10 kilobits per block

Dual ported: two addresses, write enable signals

Data busses can be 1–20 bits wide

Our Cyclone 5CSEMA5 has 397 = 496 KB

Memory in Quartus: the Megafunction Wizard

Which megafunction would you like to customize? Select a megafunction from the list below

Which device family will you be using? Cyclone V

Which type of output file do you want to create?

- AHDL
- VHDL
- Verilog HDL

What name do you want for the output file?

/home/sedwards/svn/classes/2014/4840/dummy/memory ...

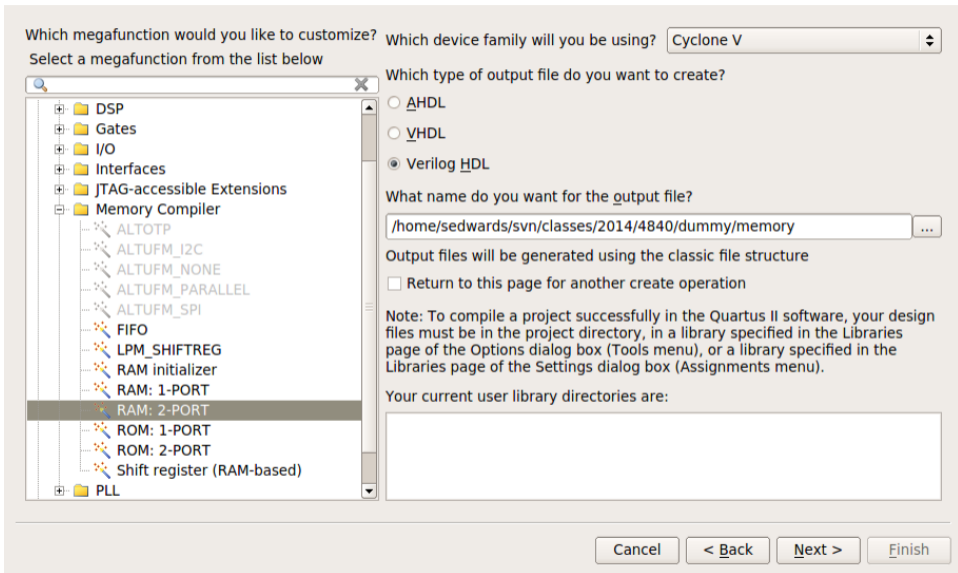
Output files will be generated using the classic file structure

Return to this page for another create operation


Note: To compile a project successfully in the Quartus II software, your design files must be in the project directory, in a library specified in the Libraries page of the Options dialog box (Tools menu), or a library specified in the Libraries page of the Settings dialog box (Assignments menu).

Your current user library directories are:

Cancel < Back Next > Finish



Memory: Single- or Dual-Ported



RAM: 2-PORT

[About](#) [Documentation](#)

1 Parameter Settings | 2 EDA | 3 Summary

General > Widths/Blk Type > Clks/Rd, Byte En > Regs/Clkens/Aclrs > Output1 > Output2 > Mem Init >

Currently selected device family: Cyclone V

Match project/default

How will you be using the dual port RAM?

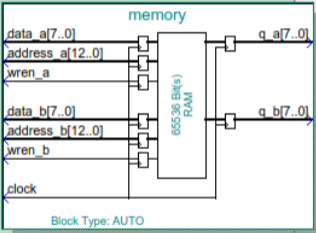
With one read port and one write port

With two read/write ports

How do you want to specify the memory size?


As a number of words

As a number of bits



Block Type: AUTO

Memory: Select Port Widths



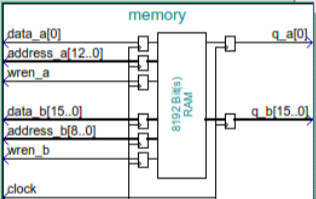
RAM: 2-PORT

[About](#) [Documentation](#)

1 Parameter Settings | 2 EDA | 3 Summary

General > **Widths/Blk Type** > Clks/Rd, Byte En > Regs/Clks/Aclrs > Output1 > Output2 > Mem Init >

memory



Block Type: M10K

How many bits of memory?

Use different data widths on different ports

Read/Write Ports

How wide should the 'q_a' output bus be?

How wide should the 'data_a' input bus be?

How wide should the 'q_b' output bus be?

Note: You could enter arbitrary values for width and depth

What should the memory block type be?

Auto MLAB M10K M144K LCs

Set the maximum block depth to words

Memory: One or Two Clocks



RAM: 2-PORT

[About](#)[Documentation](#)

1 Parameter Settings

2 EDA

3 Summary

General

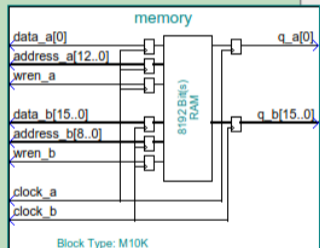
Widths/Blk Type

Clks/Rd, Byte En

Regs/Clkens/Aclrs

Output2

Mem Init



What clocking method do you want to use?

- Single clock
- Dual clock: use separate 'read' and 'write' clocks
- Dual clock: use separate 'input' and 'output' clocks
- No clock (fully asynchronous)
- Dual clock: use separate clocks for A and B ports

Create 'rden_a' and 'rden_b' read enable signals

Byte Enable Ports


Create byte enable for port A

Create byte enable for port B

What is the width of a byte for byte enables? bits

Enable error checking and correcting (ECC) to check and correct single bit errors and detect double errors

Memory: Output Ports Need Not Be Registered



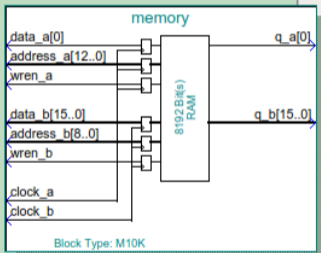
RAM: 2-PORT

About Documentation

1 Parameter Settings 2 EDA 3 Summary

General > Widths/Blk Type > Clks/Rd, Byte En > **Regs/Clks/Aclrs** > Output2 > Mem Init >

memory



Block Type: M10K

Which ports should be registered?

- Write input ports
'data_a', 'waddress_a', and 'wren_a'
- Read input ports
'rdaddress' and 'rden'
- Read output port(s)
'q_a' and 'q_b'

Create one clock enable signal for each clock signal

Use different clock enables for registers

Create an 'aclr' asynchronous clear for the registered ports

More Options... More Options... More Options...

Memory: Wizard-Generated Verilog Module

This generates the following SystemVerilog module:

```
module memory (
    input logic [12:0] address_a, // Port A:
    input logic clock_a, // 8192 1-bit words
    input logic [0:0] data_a,
    input logic wren_a, // Write enable
    output logic [0:0] q_a,

    input logic [8:0] address_b, // Port B:
    input logic clock_b, // 512 16-bit words
    input logic [15:0] data_b,
    input logic wren_b, // Write enable
    output logic [15:0] q_b);
```

Instantiate like any module; Quartus treats specially

Two Ways to Ask for Memory

1. Use the Megafunction Wizard
 - + Warns you in advance about resource usage
 - Awkward to change
2. Let Quartus infer memory from your code
 - + Better integrated with your code
 - Easy to inadvertently ask for garbage

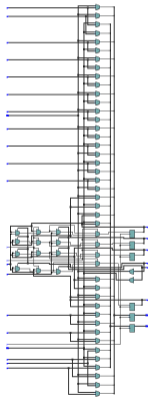
The Perils of Memory Inference

Failure: Exploded!

Synthesized to an 854-page schematic with
10280 registers (no M10K blocks)

Page 1 looked like this:

```
module twoport(  
  input logic clk,  
  input logic [8:0] aa, ab,  
  input logic [19:0] da, db,  
  input logic wa, wb,  
  output logic [19:0] qa, qb);  
  
  logic [19:0] mem [511:0];  
  
  always_ff @(posedge clk) begin  
    if (wa) mem[aa] <= da;  
    qa <= mem[aa];  
    if (wb) mem[ab] <= db;  
    qb <= mem[ab];  
  end  
  
endmodule
```



The Perils of Memory Inference

```
module twoport2(  
    input logic clk,  
    input logic [8:0] aa, ab,  
    input logic [19:0] da, db,  
    input logic wa, wb,  
    output logic [19:0] qa, qb);  
  
    logic [19:0] mem [511:0];  
  
    always_ff @(posedge clk) begin  
        if (wa) mem[aa] <= da;  
        qa <= mem[aa];  
    end  
  
    always_ff @(posedge clk) begin  
        if (wb) mem[ab] <= db;  
        qb <= mem[ab];  
    end  
  
endmodule
```

Failure

Still didn't work:

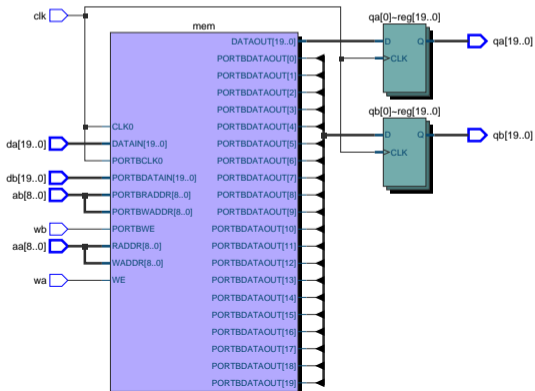
RAM logic "mem" is uninferred due to unsupported read-during-write behavior

The Perils of Memory Inference

```
module twoport3(  
  input logic clk,  
  input logic [8:0] aa, ab,  
  input logic [19:0] da, db,  
  input logic wa, wb,  
  output logic [19:0] qa, qb);  
  
  logic [19:0] mem [511:0];  
  
  always_ff @(posedge clk) begin  
    if (wa) begin  
      mem[aa] <= da;  
      qa <= da;  
    end else qa <= mem[aa];  
  end  
  
  always_ff @(posedge clk) begin  
    if (wb) begin  
      mem[ab] <= db;  
      qb <= db;  
    end else qb <= mem[ab];  
  end  
  
endmodule
```

Finally!

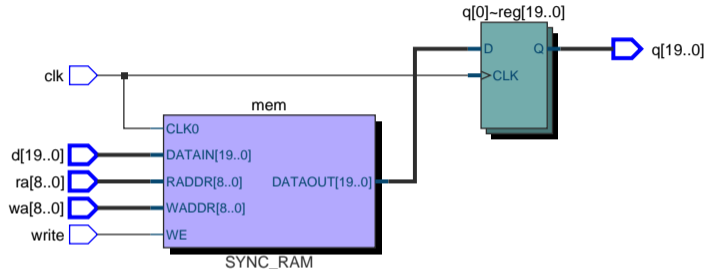
Took this structure from a template:
Edit→Insert Template→Verilog HDL→Full
Designs→RAMs and ROMs→True Dual-Port
RAM (single clock)



The Perils of Memory Inference

Also works: separate read and write addresses

```
module twoport4(  
    input logic clk,  
    input logic [8:0] ra, wa,  
    input logic write,  
    input logic [19:0] d,  
    output logic [19:0] q);  
  
    logic [19:0] mem [511:0];  
  
    always_ff @(posedge clk) begin  
        if (write) mem[wa] <= d;  
        q <= mem[ra];  
    end  
  
endmodule
```



Conclusion:

Inference is fine for single port or one read and one write port.

Use the Megafunction Wizard for anything else.