

Fundamentals of Computer Systems

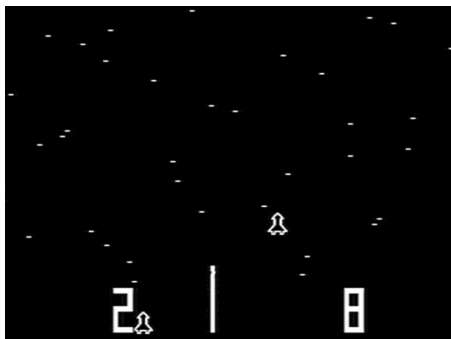
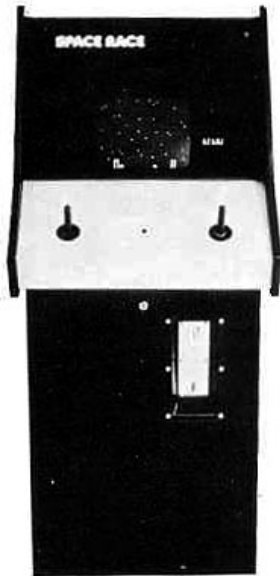
Memory

Stephen A. Edwards

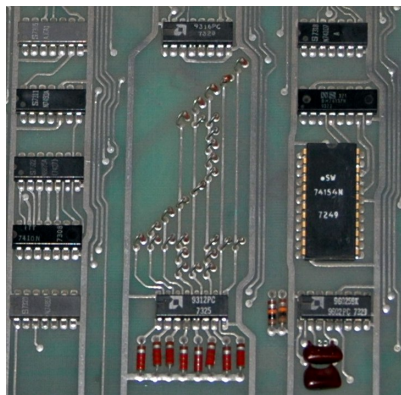
Columbia University

Summer 2021

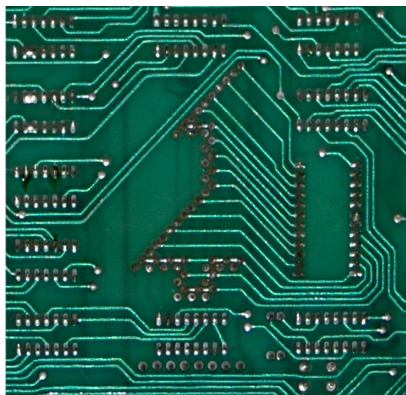
Atari Space Race, 1973



Atari Space Race PCB

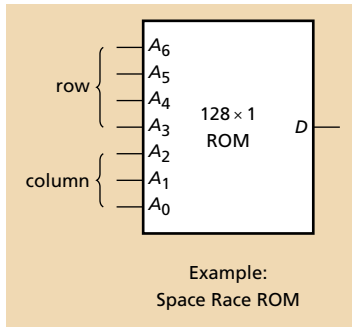
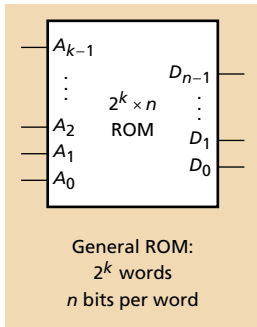


Front

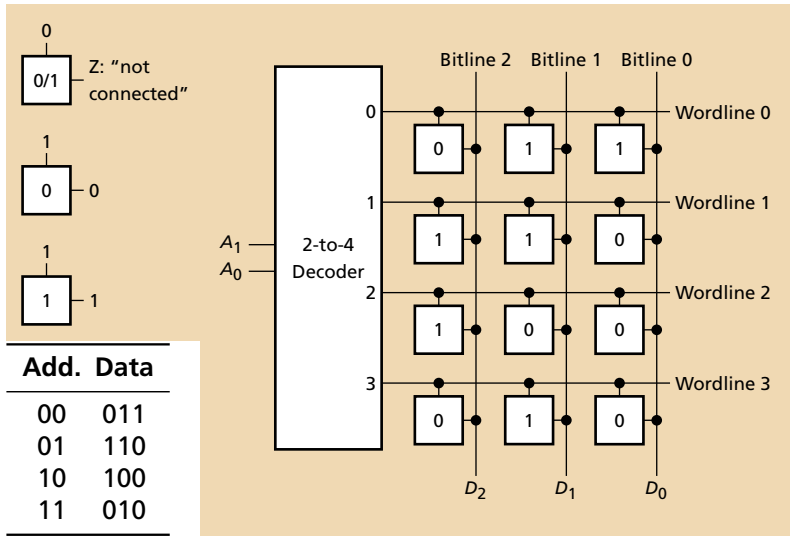


Back (mirrored)

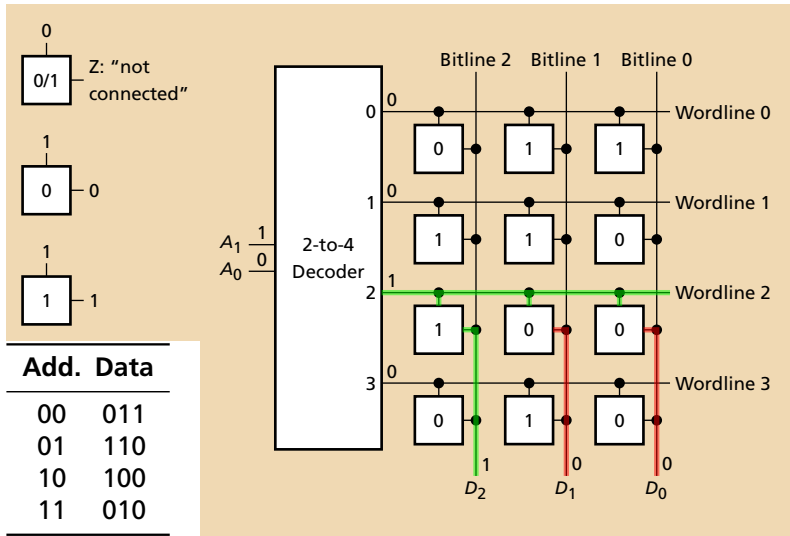
Read-Only Memories: Combinational Functions



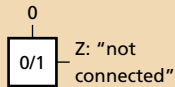
Implementing ROMs



Implementing ROMs

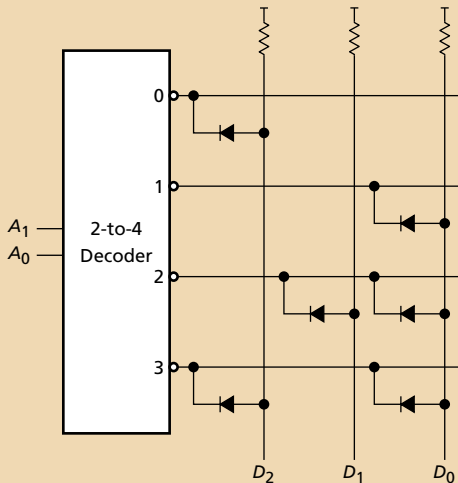


Implementing ROMs

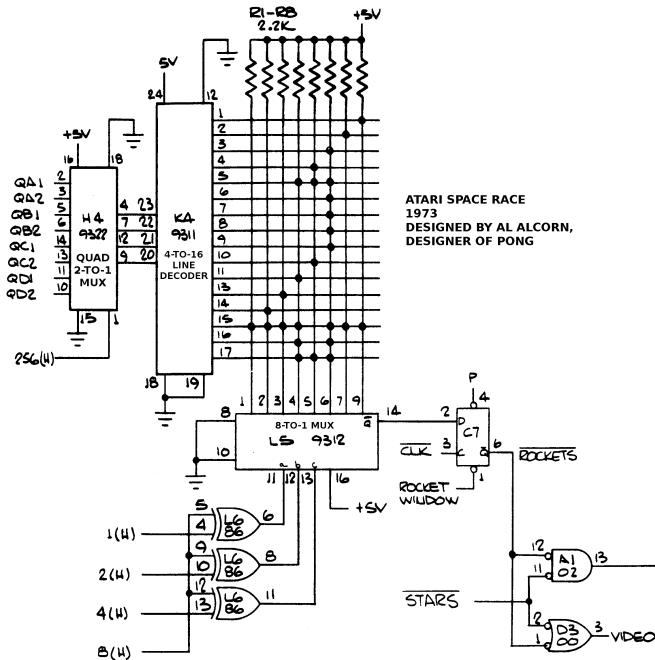


Addr. Data

00	011
01	110
10	100
11	010

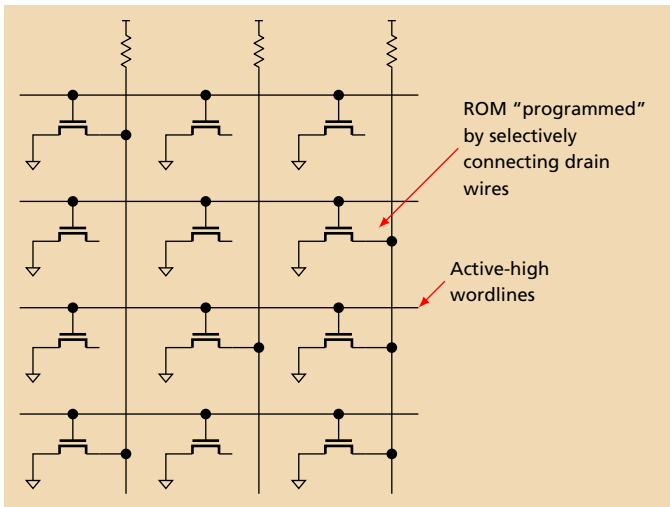


Atari Space Race Schematic

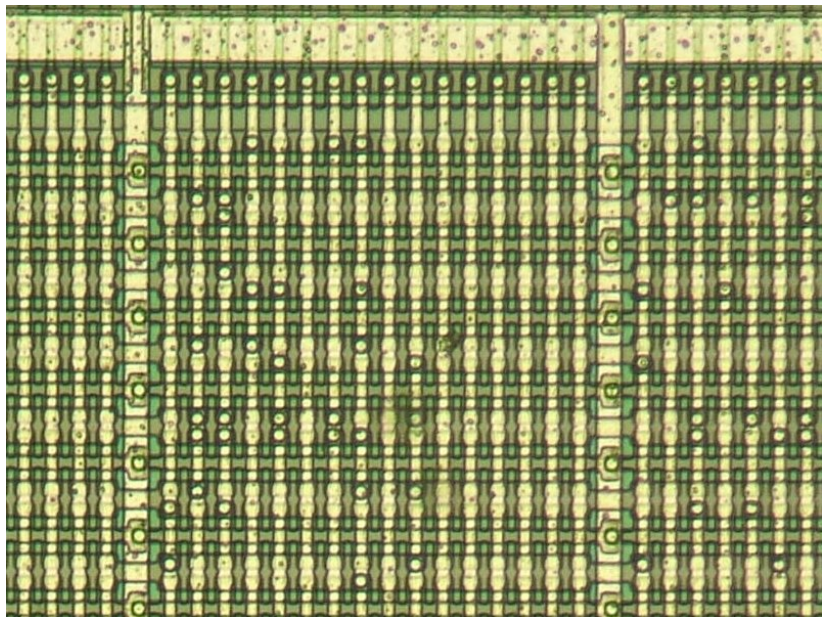


CMOS Mask-Programmed ROMs

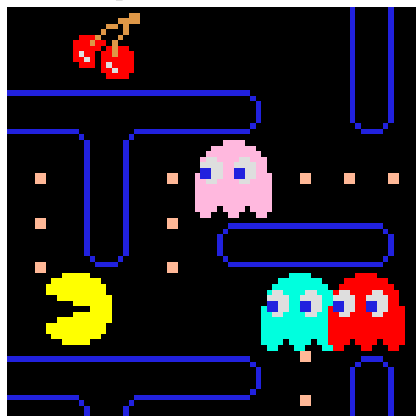
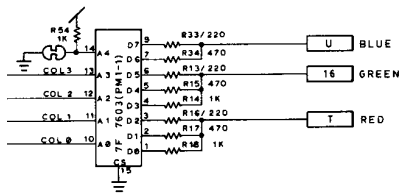
Add. Data	
00	011
01	110
10	100
11	010



Mask ROM Die Photo

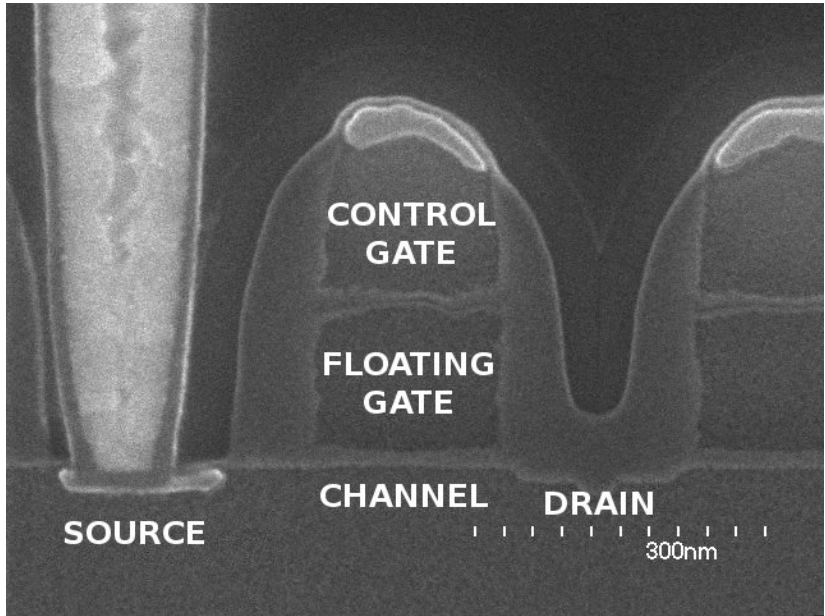


Color PROM in Pac-Man



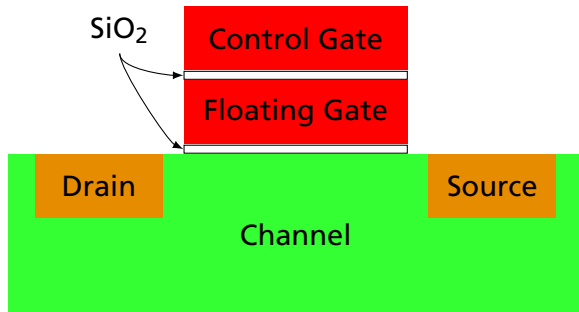
00	00	█
01	07	█
02	66	█
03	EF	█
04	00	█
05	F8	█
06	EA	█
07	6F	█
08	00	█
09	3F	█
0A	00	█
0B	C9	█
0C	38	█
0D	AA	█
0E	AF	█
0F	F6	█
10	00	█
⋮	⋮	
1F	00	█

A Floating Gate MOSFET



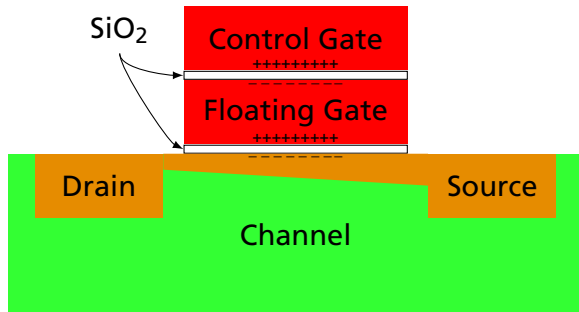
Cross section of a NOR FLASH transistor. Kawai et al., ISSCC 2008 (Renesas)

Floating Gate n-channel MOSFET



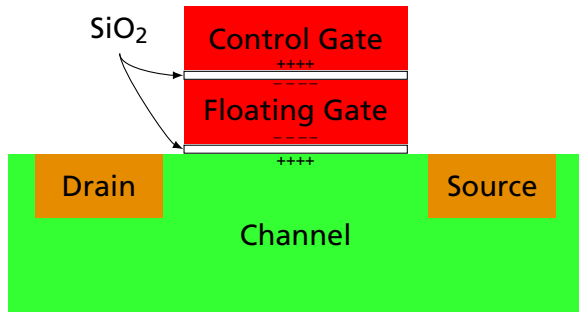
Floating gate uncharged; Control gate at 0V: Off

Floating Gate n-channel MOSFET



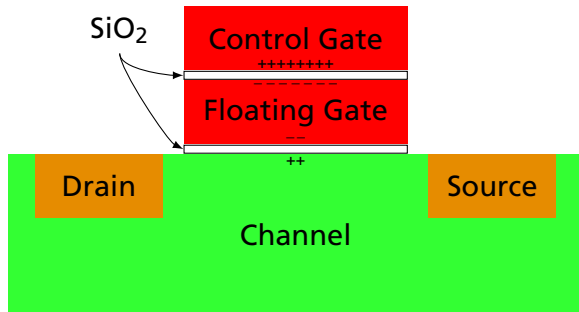
Floating gate uncharged; Control gate positive: On

Floating Gate n-channel MOSFET



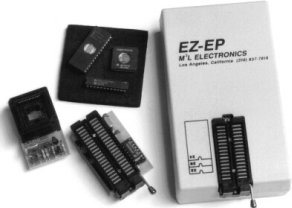
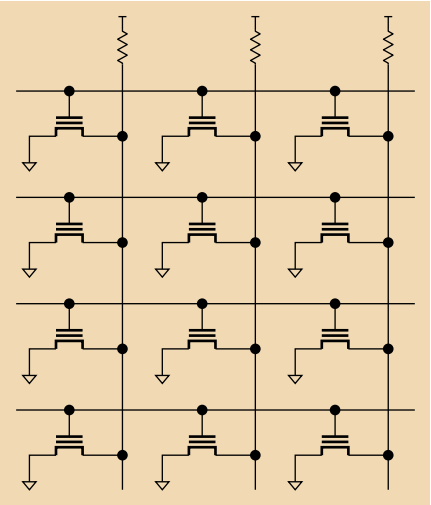
Floating gate negative; Control gate at 0V: Off

Floating Gate n-channel MOSFET

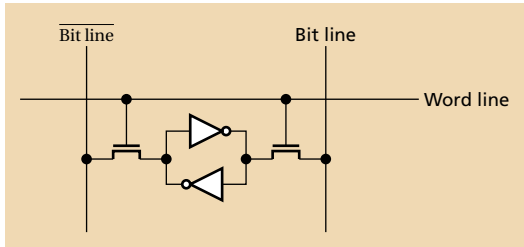


Floating gate negative; Control gate positive: Off

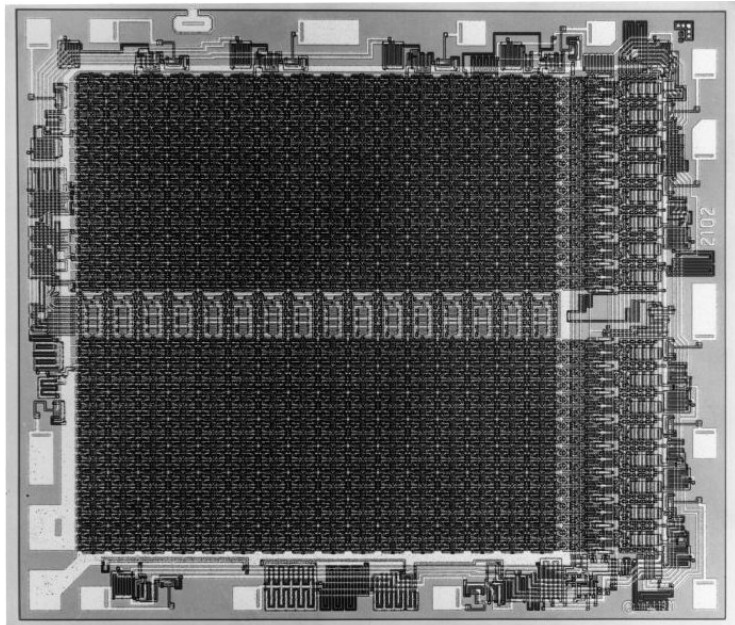
EPROMs and FLASH use Floating-Gate MOSFETs



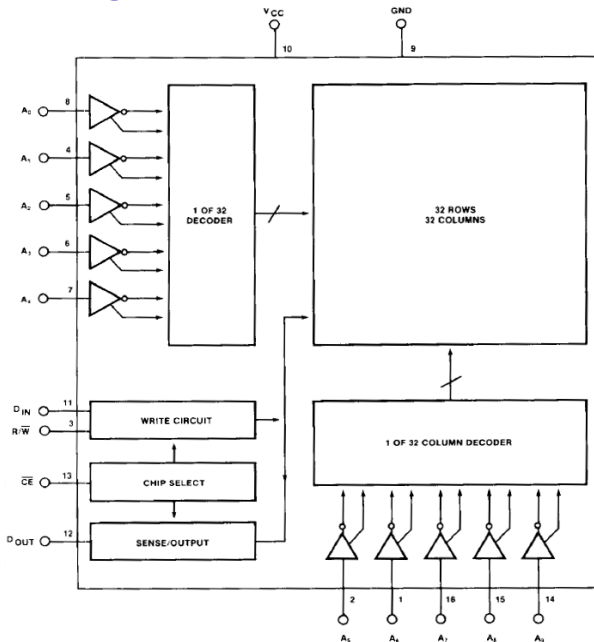
Static Random-Access Memory Cell



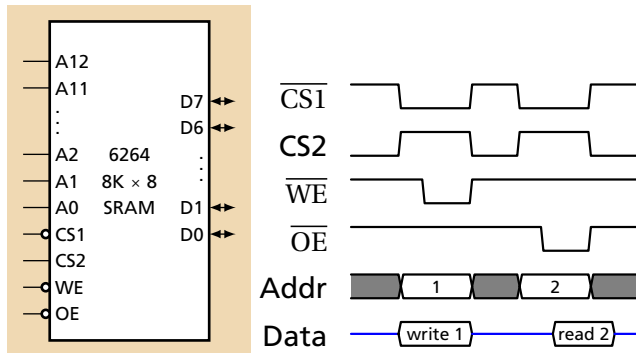
Intel's 2102 SRAM, 1024 × 1 bit, 1972



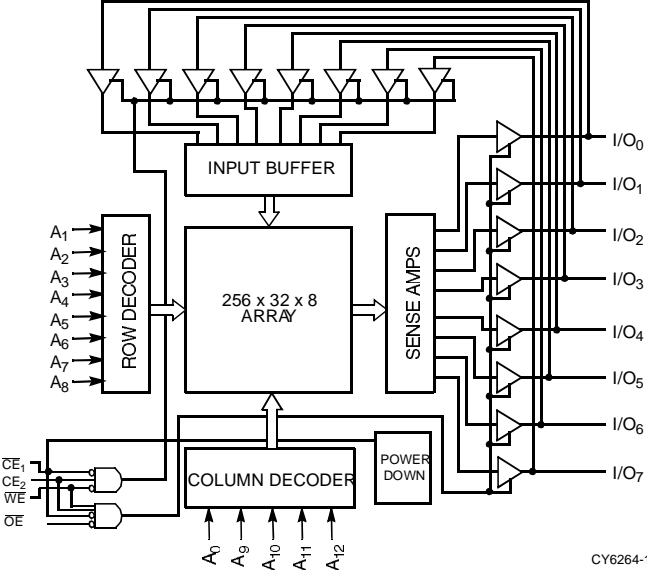
2102 Block Diagram



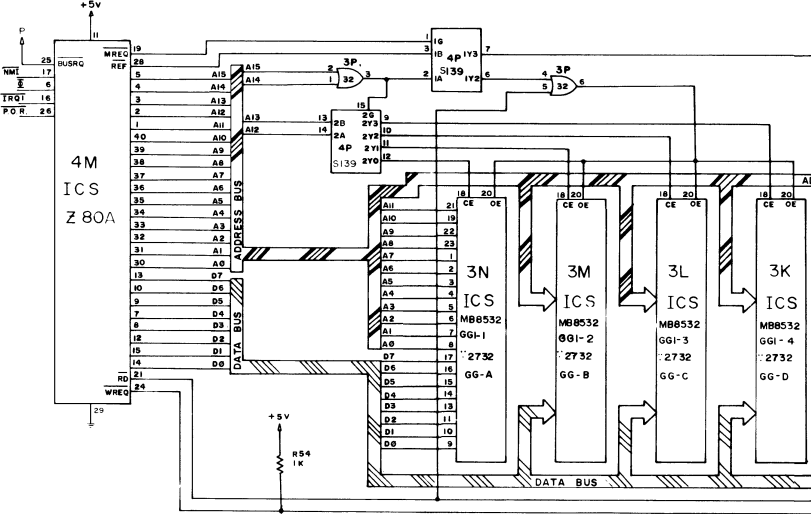
SRAM Timing



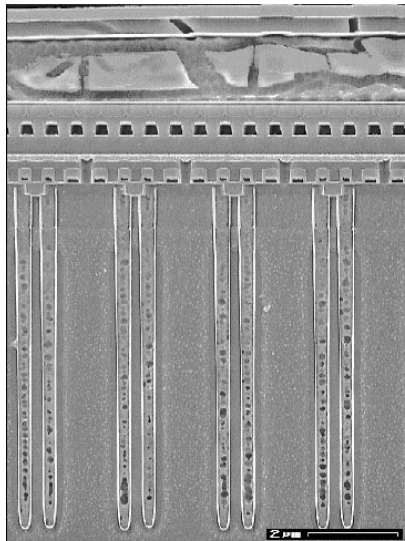
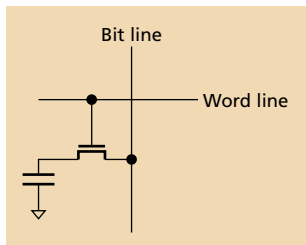
6264 SRAM Block Diagram



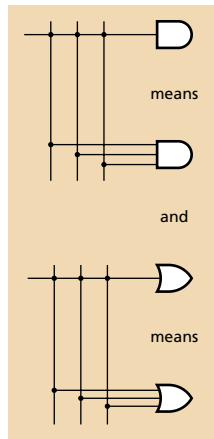
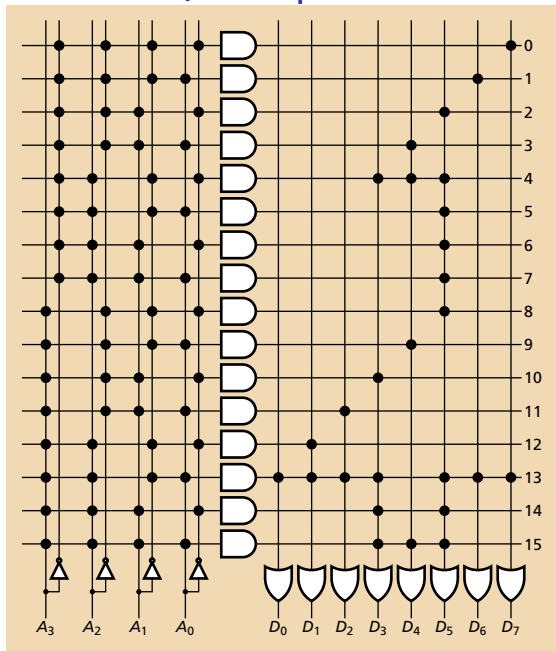
Galaga CPU detail (Namco/Midway 1981)



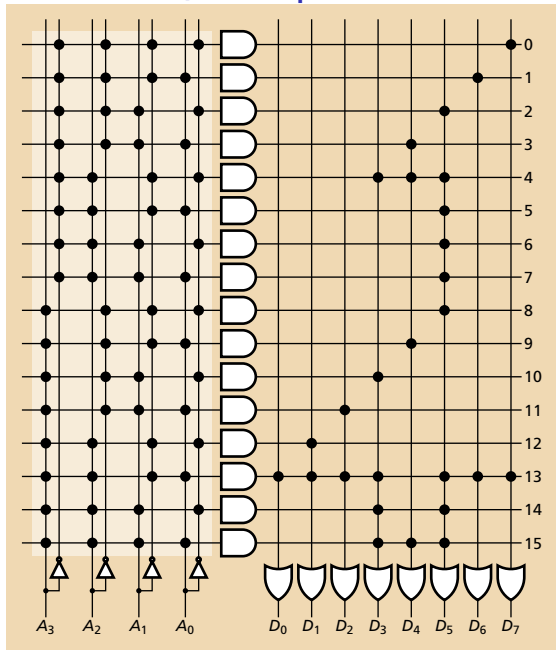
Dynamic RAM Cell



Our Old Pal, the Space Race ROM



Our Old Pal, the Space Race ROM

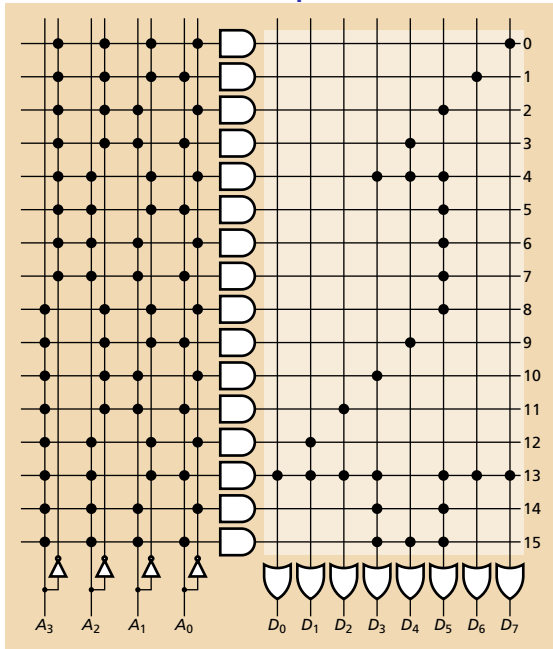


The decoder or
"AND plane"

In a RAM or ROM,
computes every
minterm

Pattern is not
programmable

Our Old Pal, the Space Race ROM

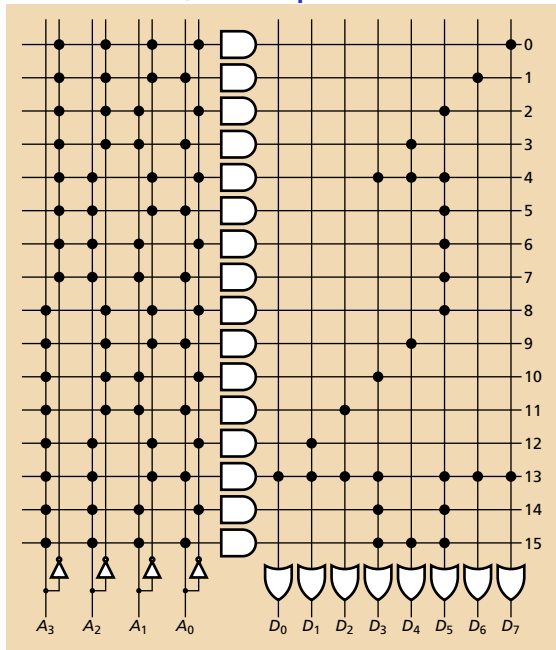


The decoder or “OR plane”

One term for every output

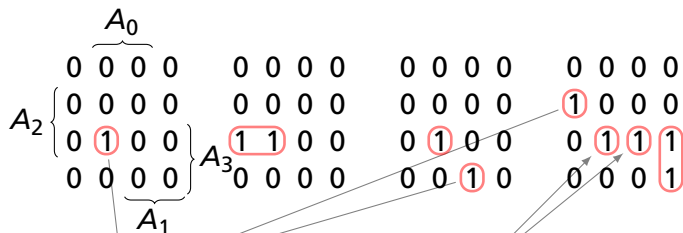
Pattern is programmable = the contents of the ROM

Our Old Pal, the Space Race ROM



Can we do better?

Simplifying the Space Race ROM

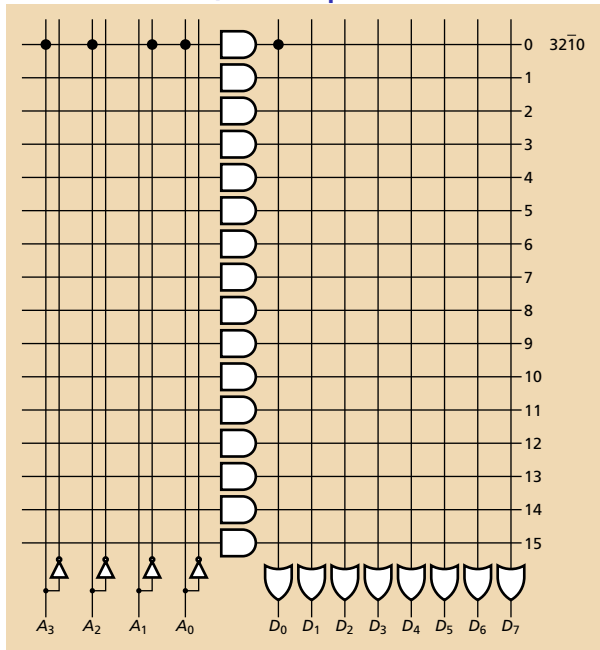


Essential minterms

mean don't expand these

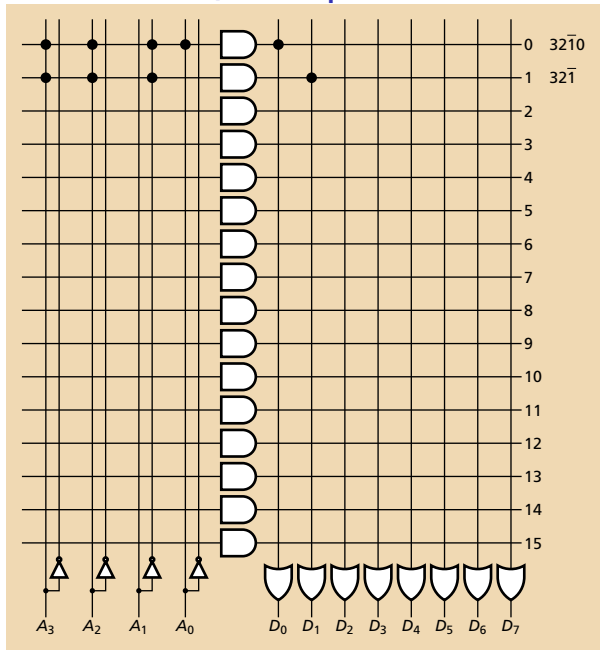


Our New PAL, the Space Race ROM



$$D_0 = 32\bar{1}0$$

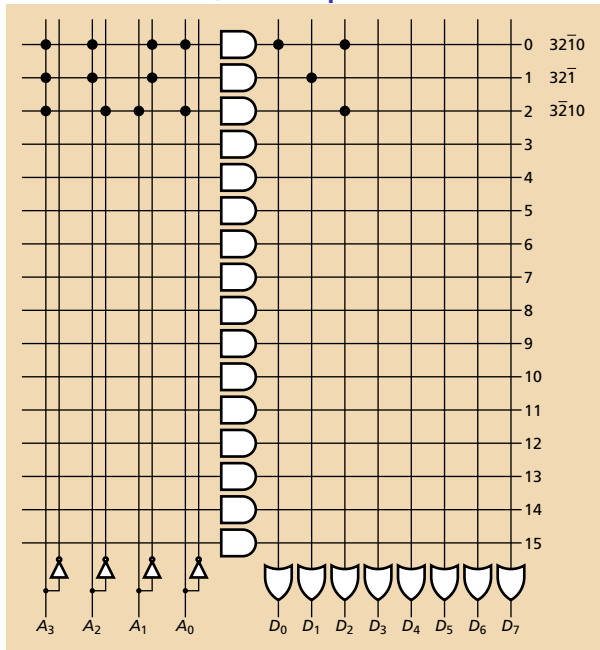
Our New PAL, the Space Race ROM



$$D_0 = 32\bar{1}0$$

$$D_1 = 32\bar{1}$$

Our New PAL, the Space Race ROM

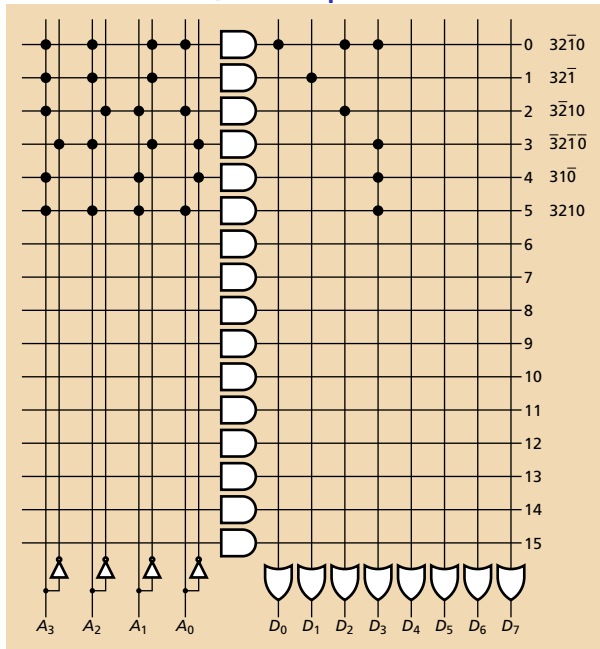


$$D_0 = 3\bar{2}10$$

$$D_1 = 3\bar{2}1$$

$$D_2 = 3\bar{2}10 + 3\bar{2}10$$

Our New PAL, the Space Race ROM



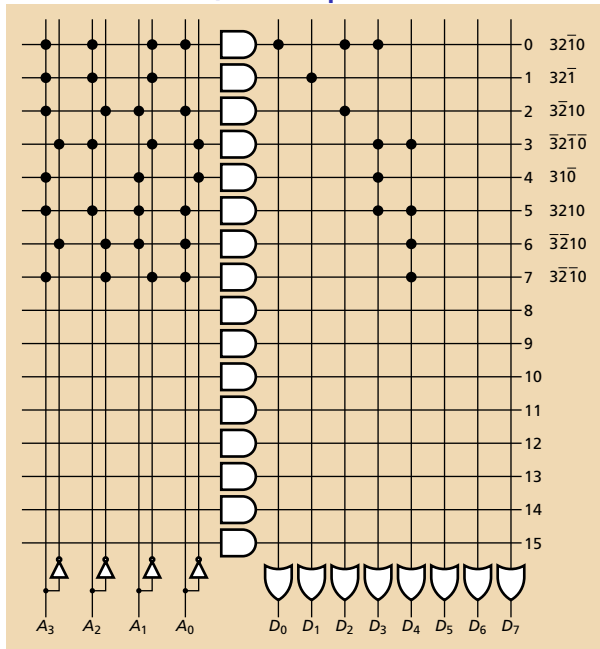
$$D_0 = 3\bar{2}\bar{1}0$$

$$D_1 = 3\bar{2}\bar{1}$$

$$D_2 = 3\bar{2}\bar{1}0 + 3\bar{2}\bar{1}0$$

$$D_3 = \bar{3}\bar{2}\bar{1}\bar{0} + 3\bar{1}\bar{0} + 3\bar{2}\bar{1}0 + 3\bar{2}10$$

Our New PAL, the Space Race ROM



$$D_0 = 32\bar{1}0$$

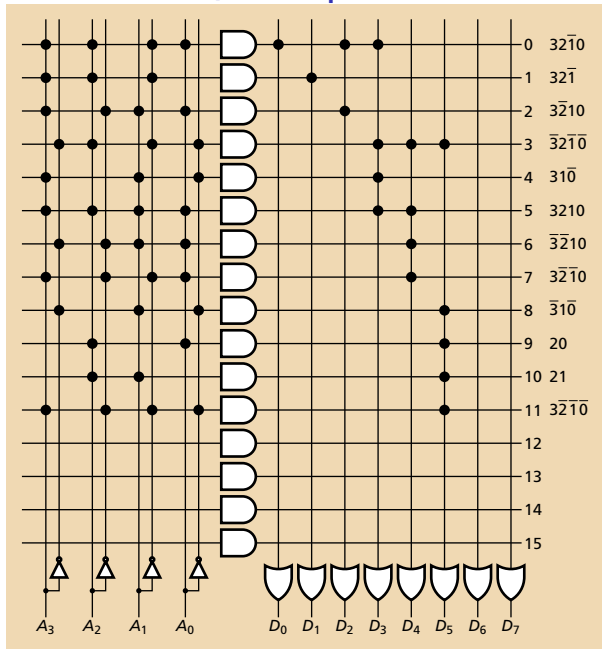
$$D_1 = 32\bar{1}$$

$$D_2 = 3\bar{2}10 + \bar{3}2\bar{1}0$$

$$D_3 = \bar{3}2\bar{1}0 + 31\bar{0} + 3\bar{2}10 + 3210$$

$$D_4 = \bar{3}210 + \bar{3}2\bar{1}0 + 3\bar{2}\bar{1}0 + 3210$$

Our New PAL, the Space Race ROM



$$D_0 = 3\bar{2}\bar{1}0$$

$$D_1 = 3\bar{2}\bar{1}$$

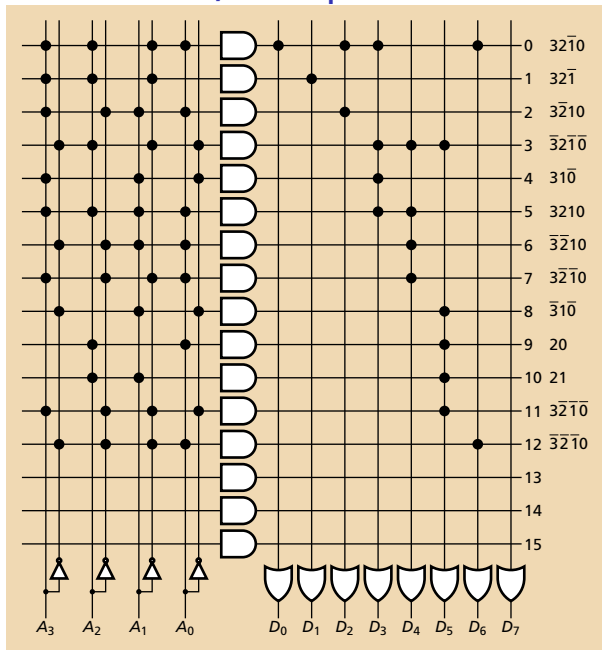
$$D_2 = \bar{3}\bar{2}\bar{1}0 + 3\bar{2}\bar{1}0$$

$$D_3 = \bar{3}\bar{2}\bar{1}\bar{0} + 3\bar{1}\bar{0} + \bar{3}\bar{2}\bar{1}0 + 3\bar{2}\bar{1}0$$

$$D_4 = \bar{3}\bar{2}\bar{1}0 + \bar{3}\bar{2}\bar{1}\bar{0} + \bar{3}\bar{2}\bar{1}\bar{0} + 3\bar{2}\bar{1}0 + 3\bar{2}\bar{1}0$$

$$D_5 = \bar{3}\bar{1}\bar{0} + 20 + 21 + \bar{3}\bar{2}\bar{1}\bar{0} + \bar{3}\bar{2}\bar{1}\bar{0}$$

Our New PAL, the Space Race ROM



$$D_0 = 32\bar{1}0$$

$$D_1 = 32\bar{1}$$

$$D_2 = 3\bar{2}10 + 32\bar{1}0$$

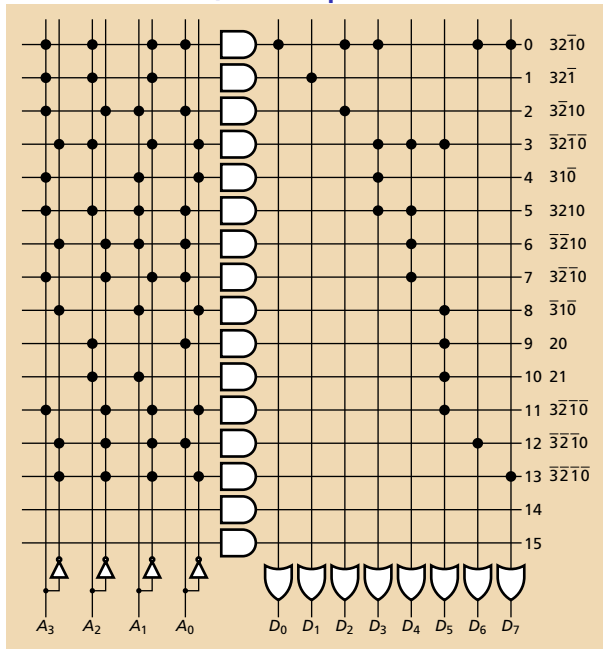
$$D_3 = \bar{3}2\bar{1}0 + 31\bar{0} + 32\bar{1}0 + 3210$$

$$D_4 = \bar{3}2\bar{1}0 + \bar{3}2\bar{1}0 + 3\bar{2}\bar{1}0 + 3210$$

$$D_5 = \bar{3}1\bar{0} + 20 + 21 + 3\bar{2}\bar{1}0 + 32\bar{1}0$$

$$D_6 = \bar{3}2\bar{1}0 + 32\bar{1}0$$

Our New PAL, the Space Race ROM



$$D_0 = 32\bar{1}0$$

$$D_1 = 32\bar{1}$$

$$D_2 = 3\bar{2}10 + 32\bar{1}0$$

$$D_3 = \bar{3}2\bar{1}0 + 31\bar{0} + 32\bar{1}0 + 3210$$

$$D_4 = \bar{3}2\bar{1}0 + \bar{3}2\bar{1}0 + 3\bar{2}\bar{1}0 + 3210$$

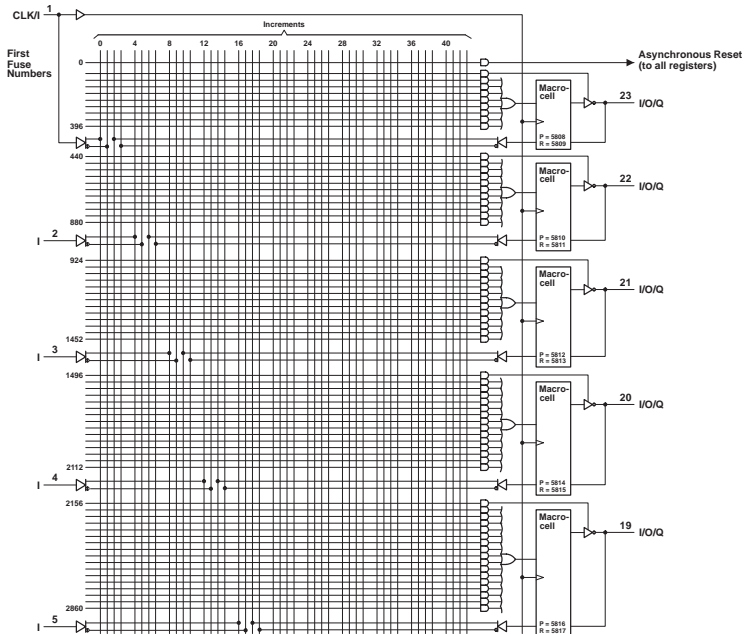
$$D_5 = \bar{3}1\bar{0} + 20 + 21 + \bar{3}2\bar{1}0 + 32\bar{1}0$$

$$D_6 = \bar{3}2\bar{1}0 + 32\bar{1}0$$

$$D_7 = \bar{3}2\bar{1}0 + 32\bar{1}0$$

Saved two ANDs

A 22V10 PAL: Programmable AND/Fixed OR



Field-Programmable Gate Arrays (FPGAs)

