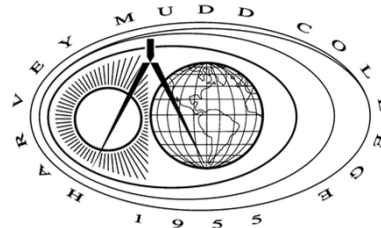


Introduction to CMOS VLSI Design

Lecture 1: Circuits & Layout

David Harris



Harvey Mudd College

Spring 2004

Outline

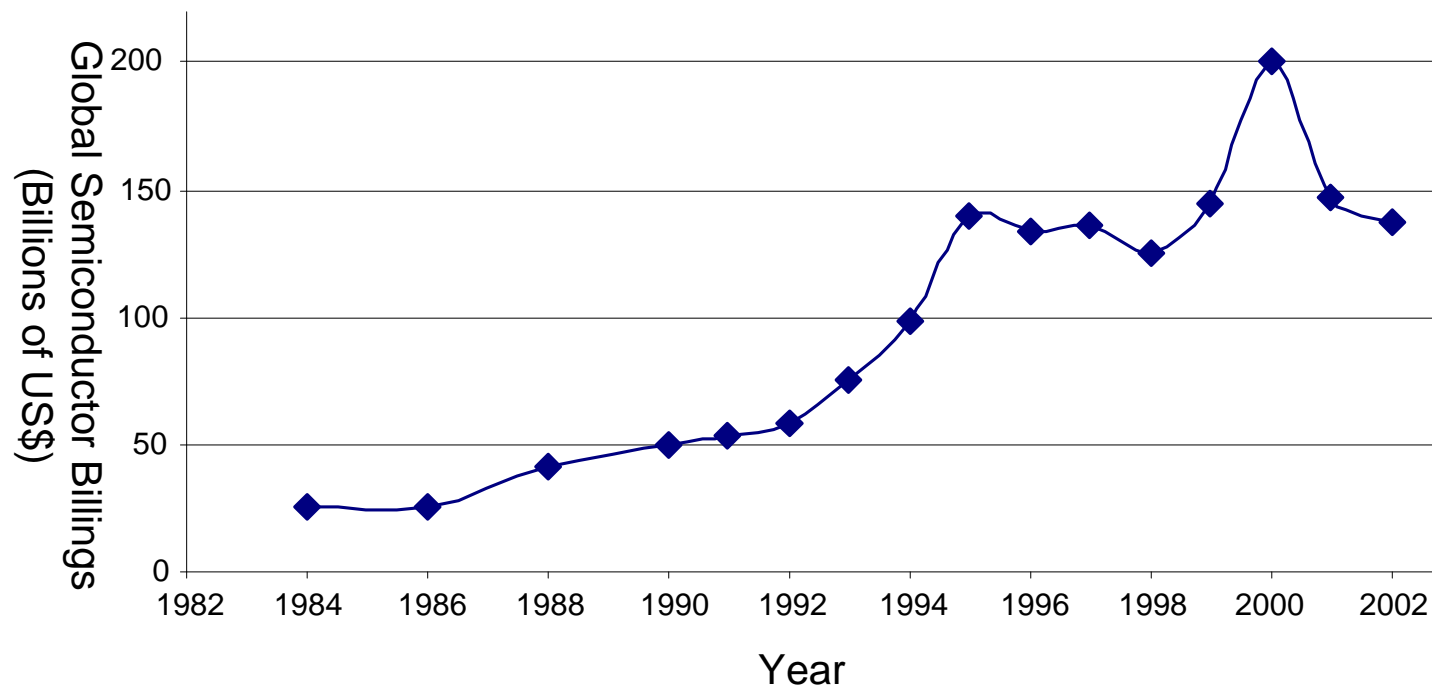
- A Brief History
- CMOS Gate Design
- Pass Transistors
- CMOS Latches & Flip-Flops
- Standard Cell Layouts
- Stick Diagrams

A Brief History

- ❑ 1958: First integrated circuit
 - Flip-flop using two transistors
 - Built by Jack Kilby at Texas Instruments
- ❑ 2003
 - Intel Pentium 4 μ processor (55 million transistors)
 - 512 Mbit DRAM (> 0.5 billion transistors)
- ❑ 53% compound annual growth rate over 45 years
 - No other technology has grown so fast so long
- ❑ Driven by miniaturization of transistors
 - Smaller is cheaper, faster, lower in power!
 - Revolutionary effects on society

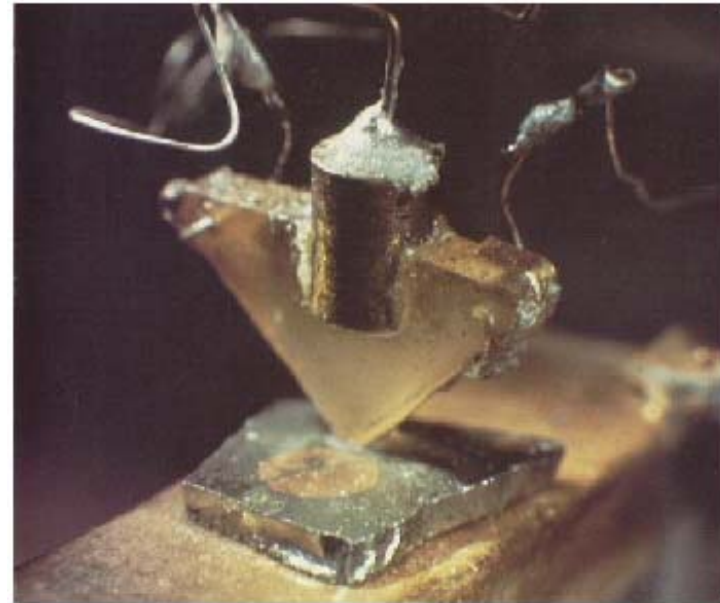
Annual Sales

- 10^{18} transistors manufactured in 2003
 - 100 million for every human on the planet



Invention of the Transistor

- ❑ Vacuum tubes ruled in first half of 20th century Large, expensive, power-hungry, unreliable
- ❑ 1947: first point contact transistor
 - John Bardeen and Walter Brattain at Bell Labs
 - Read *Crystal Fire* by Riordan, Hoddeson

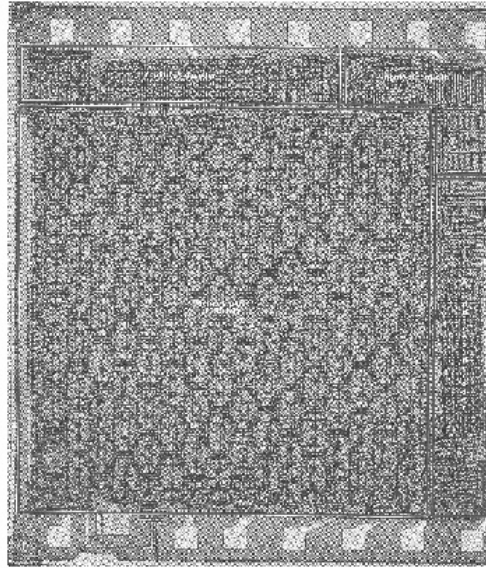


Transistor Types

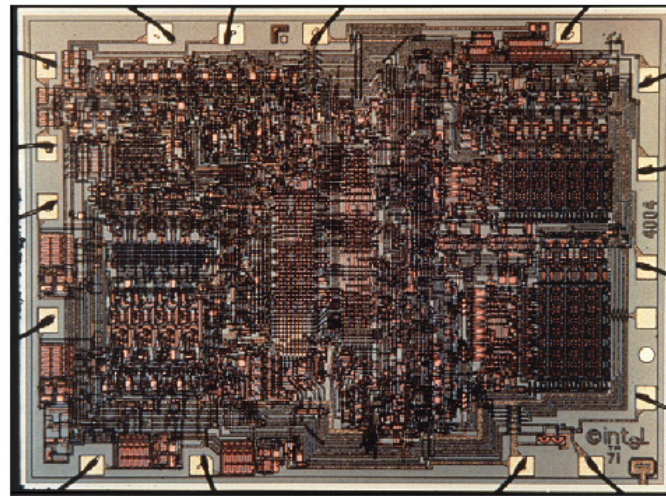
- ❑ Bipolar transistors
 - npn or pnp silicon structure
 - Small current into very thin base layer controls large currents between emitter and collector
 - Base currents limit integration density
- ❑ Metal Oxide Semiconductor Field Effect Transistors
 - nMOS and pMOS MOSFETS
 - Voltage applied to insulated gate controls current between source and drain
 - Low power allows very high integration

MOS Integrated Circuits

- ❑ 1970's processes usually had only nMOS transistors
 - Inexpensive, but consume power while idle



Intel 1101 256-bit SRAM

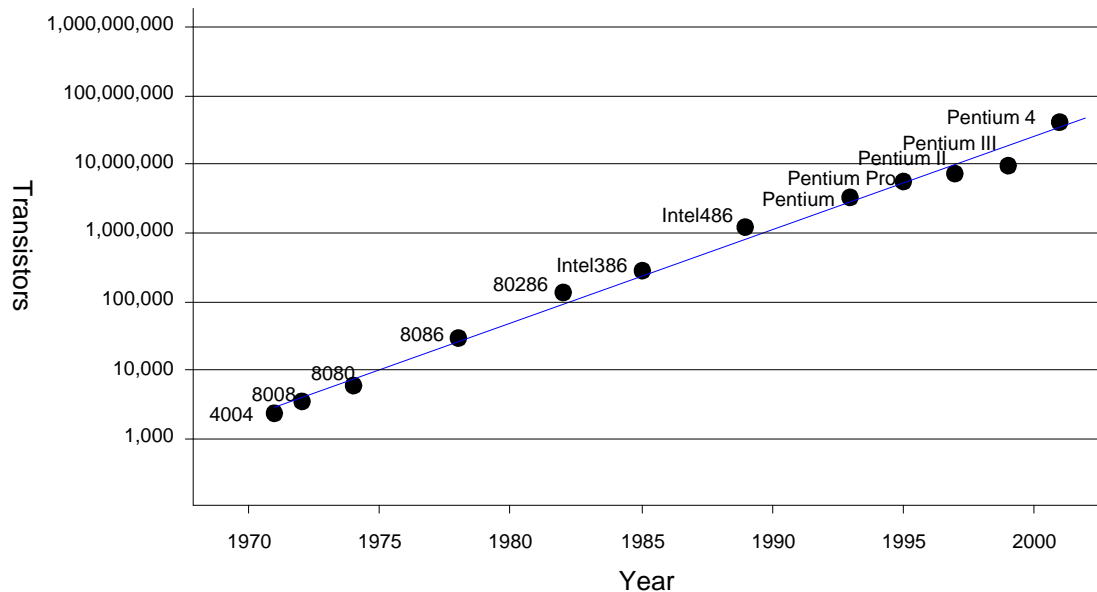


Intel 4004 4-bit μ Proc

- ❑ 1980s-present: CMOS processes for low idle power

Moore's Law

- 1965: Gordon Moore plotted transistor on each chip
 - Fit straight line on semilog scale
 - Transistor counts have doubled every 26 months



Integration Levels

SSI: 10 gates

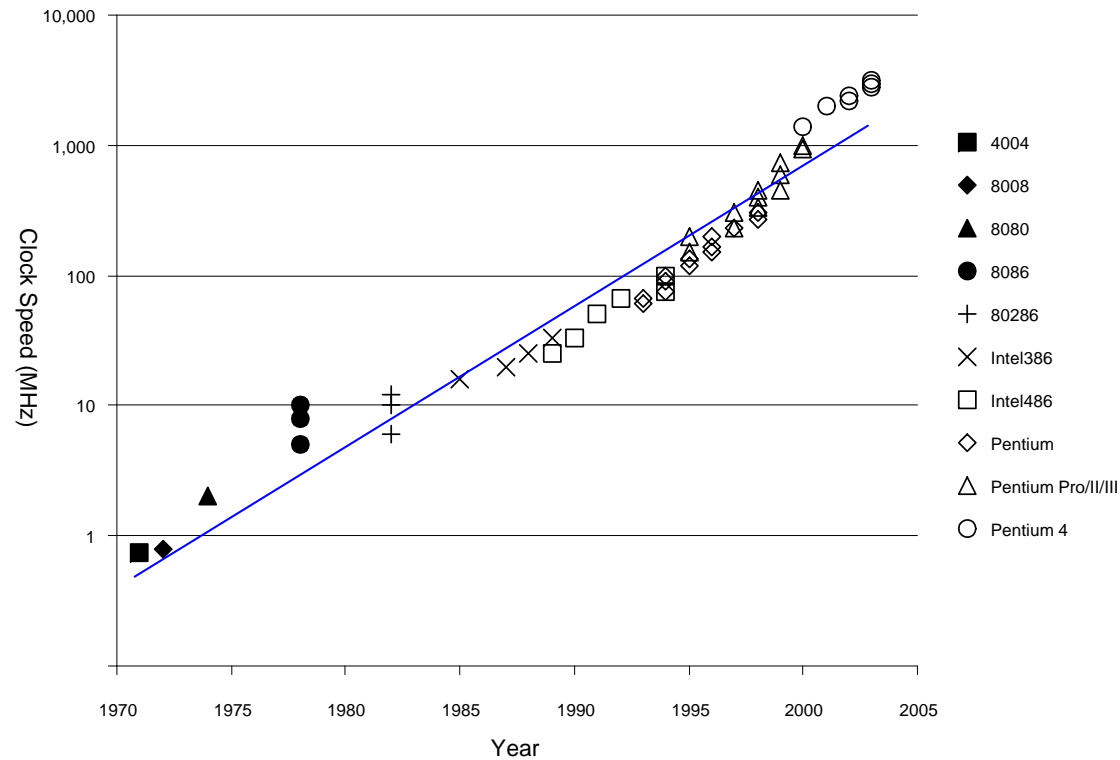
MSI: 1000 gates

LSI: 10,000 gates

VLSI: > 10k gates

Corollaries

- Many other factors grow exponentially
 - Ex: clock frequency, processor performance

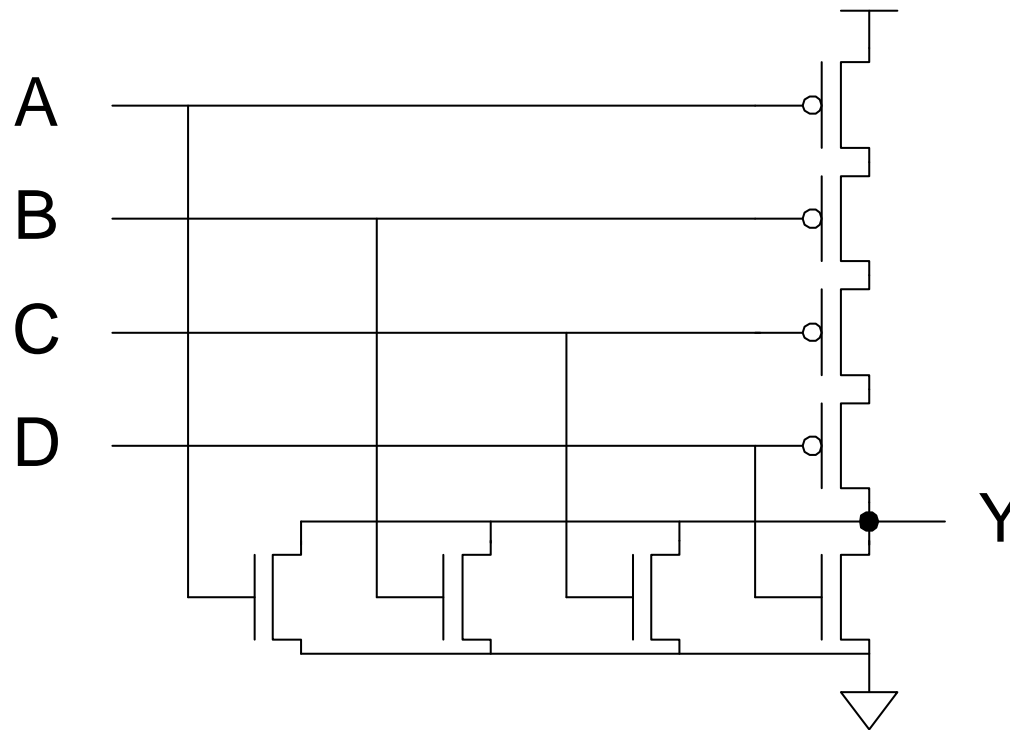


CMOS Gate Design

- Activity:
 - Sketch a 4-input CMOS NAND gate

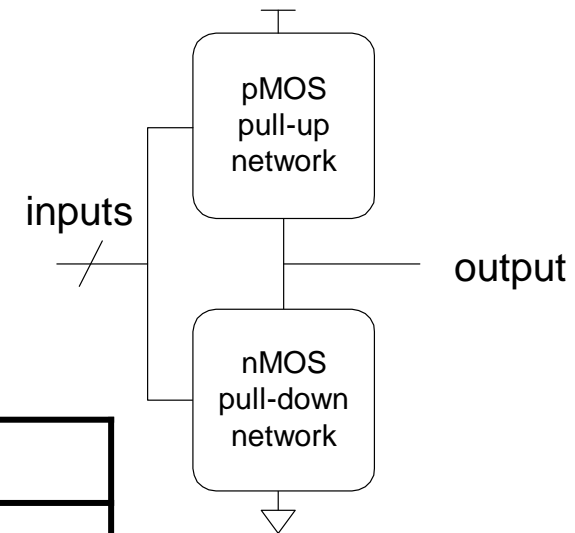
CMOS Gate Design

- Activity:
 - Sketch a 4-input CMOS NOR gate



Complementary CMOS

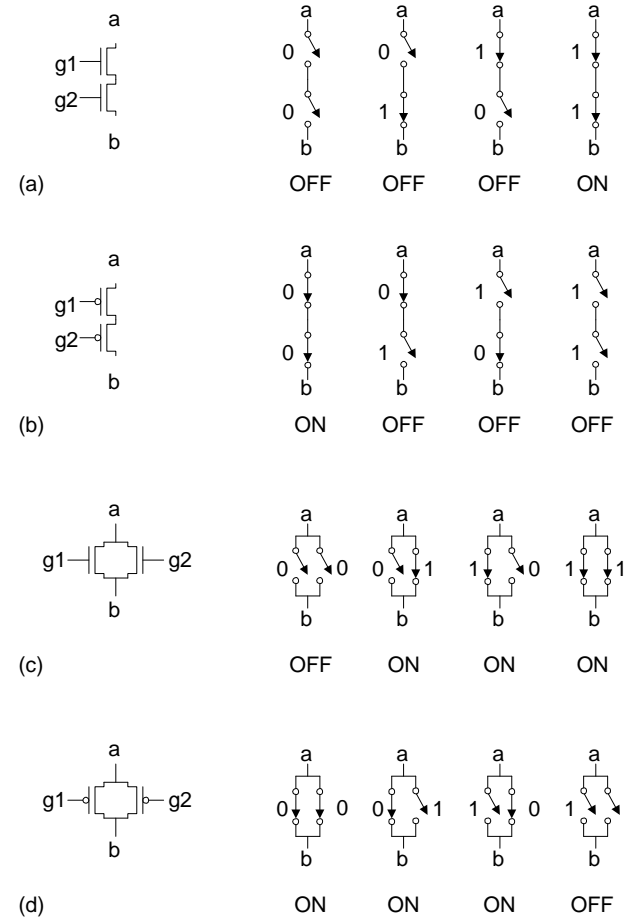
- Complementary CMOS logic gates
 - nMOS *pull-down network*
 - pMOS *pull-up network*
 - a.k.a. static CMOS



	Pull-up OFF	Pull-up ON
Pull-down OFF	Z (float)	1
Pull-down ON	0	X (crowbar)

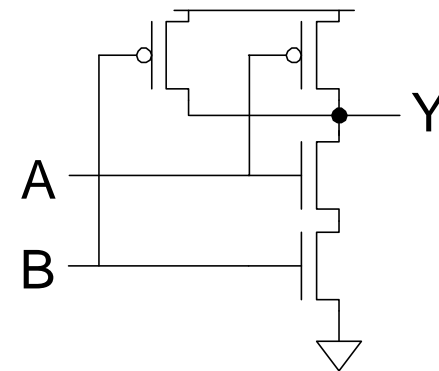
Series and Parallel

- nMOS: 1 = ON
- pMOS: 0 = ON
- *Series*: both must be ON
- *Parallel*: either can be ON



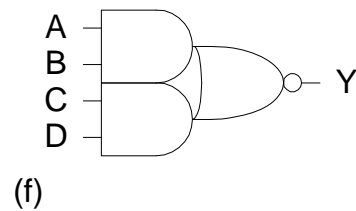
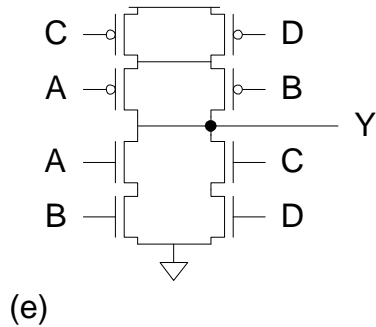
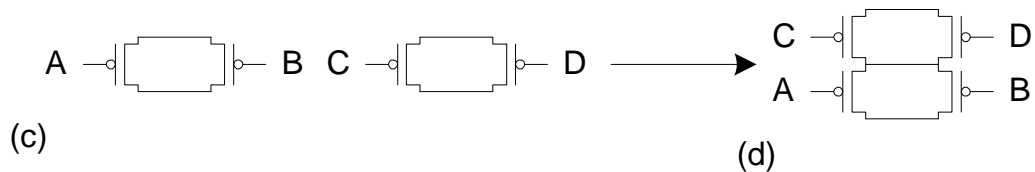
Conduction Complement

- ❑ Complementary CMOS gates always produce 0 or 1
- ❑ Ex: NAND gate
 - Series nMOS: $Y=0$ when both inputs are 1
 - Thus $Y=1$ when either input is 0
 - Requires parallel pMOS
- ❑ Rule of *Conduction Complements*
 - Pull-up network is complement of pull-down
 - Parallel \rightarrow series, series \rightarrow parallel



Compound Gates

- ❑ *Compound gates* can do any inverting function
- ❑ Ex: $Y = \overline{A \square B + C \square D}$ (AND-AND-OR-INVERT, AOI22)

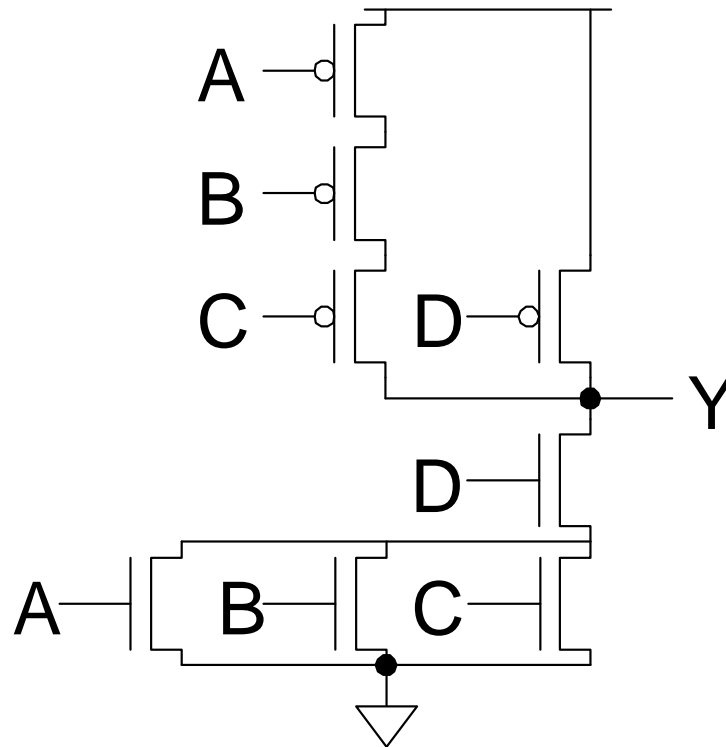


Example: O3A1

$$\square Y = \overline{(A + B + C)} \square D$$

Example: O3AI

$$Y = \overline{(A + B + C)} \cdot D$$

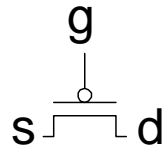
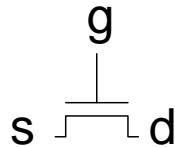


Signal Strength

- ❑ *Strength* of signal
 - How close it approximates ideal voltage source
- ❑ V_{DD} and GND rails are strongest 1 and 0
- ❑ nMOS pass strong 0
 - But degraded or weak 1
- ❑ pMOS pass strong 1
 - But degraded or weak 0
- ❑ Thus nMOS are best for pull-down network

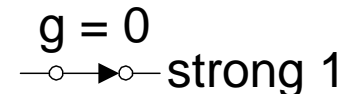
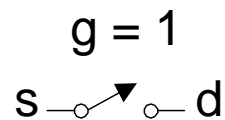
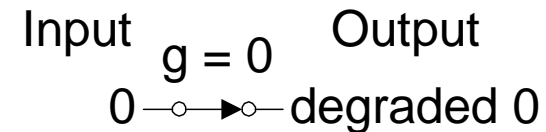
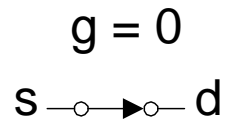
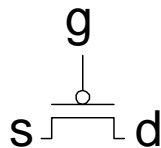
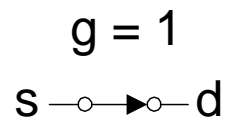
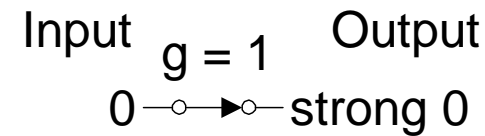
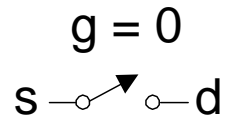
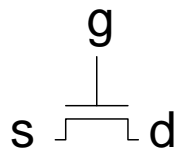
Pass Transistors

- Transistors can be used as switches



Pass Transistors

- Transistors can be used as switches

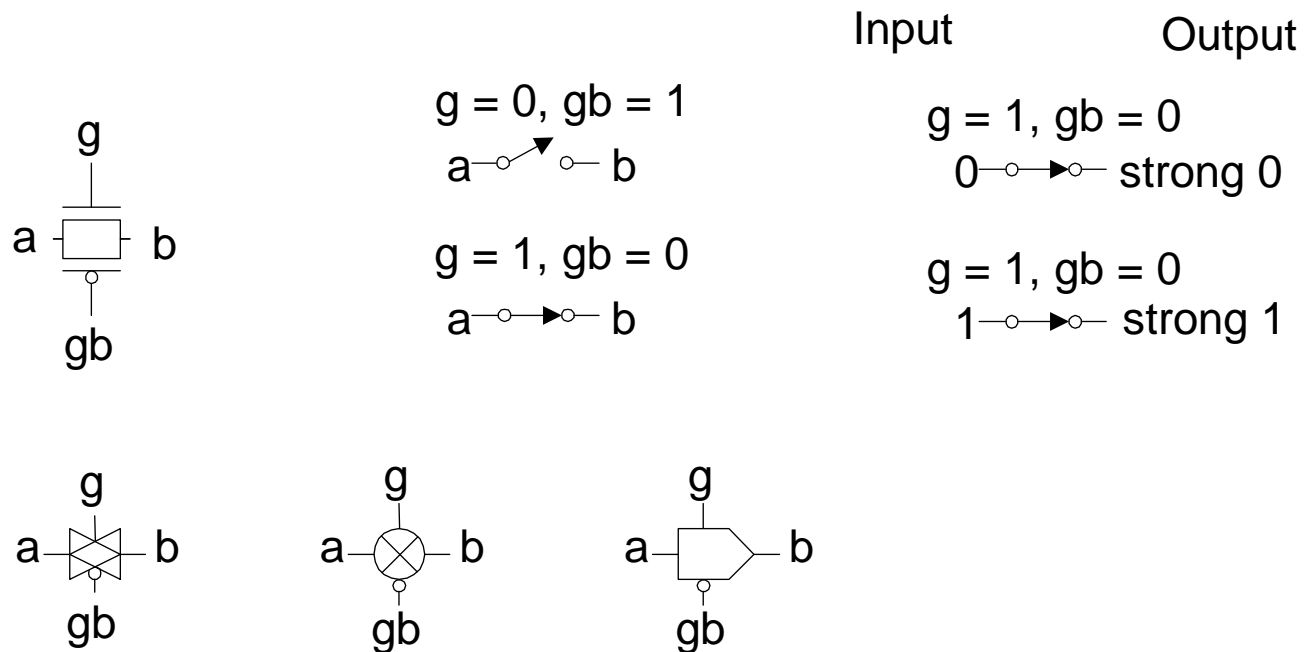


Transmission Gates

- ❑ Pass transistors produce degraded outputs
- ❑ *Transmission gates* pass both 0 and 1 well

Transmission Gates

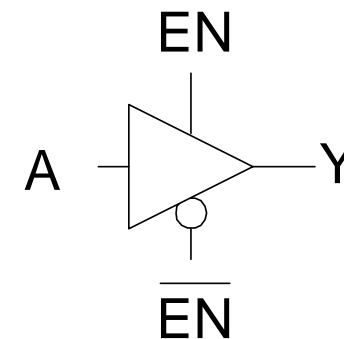
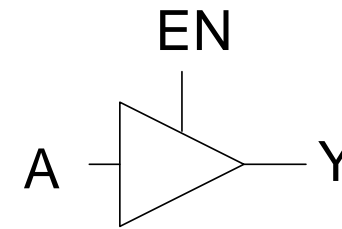
- ❑ Pass transistors produce degraded outputs
- ❑ *Transmission gates* pass both 0 and 1 well



Tristates

- ❑ *Tristate buffer* produces Z when not enabled

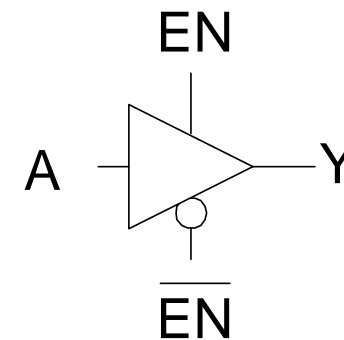
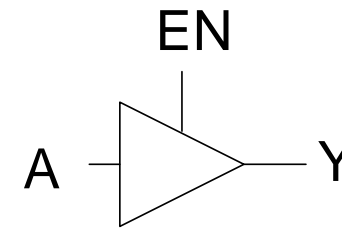
EN	A	Y
0	0	
0	1	
1	0	
1	1	



Tristates

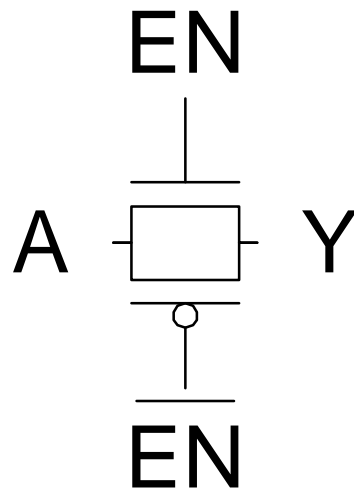
- ❑ *Tristate buffer* produces Z when not enabled

EN	A	Y
0	0	Z
0	1	Z
1	0	0
1	1	1



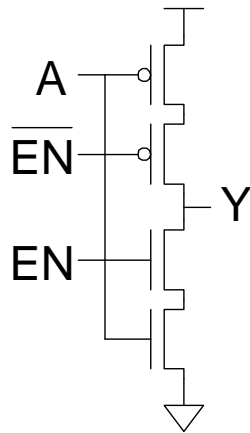
Nonrestoring Tristate

- Transmission gate acts as tristate buffer
 - Only two transistors
 - But *nonrestoring*
 - Noise on *A* is passed on to *Y*



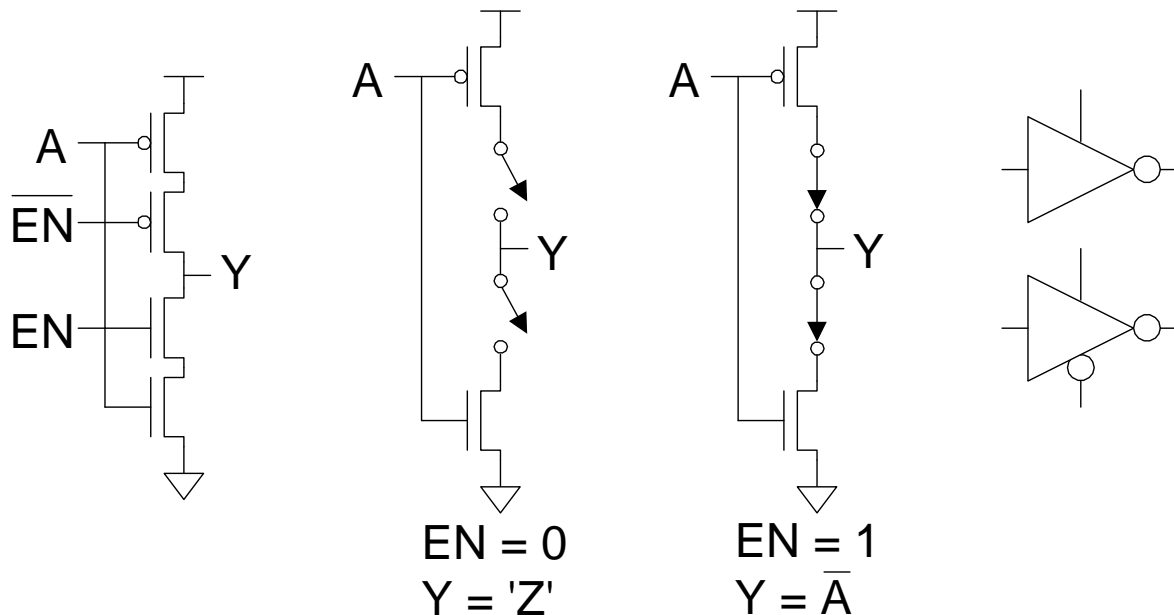
Tristate Inverter

- Tristate inverter produces restored output
 - Violates conduction complement rule
 - Because we want a Z output



Tristate Inverter

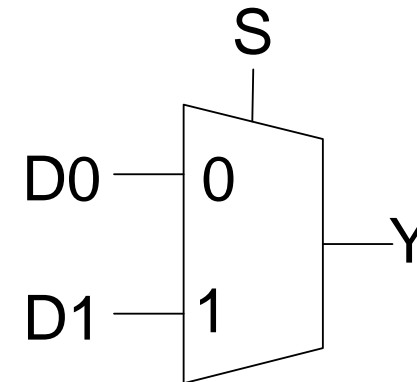
- Tristate inverter produces restored output
 - Violates conduction complement rule
 - Because we want a Z output



Multiplexers

- 2:1 *multiplexer* chooses between two inputs

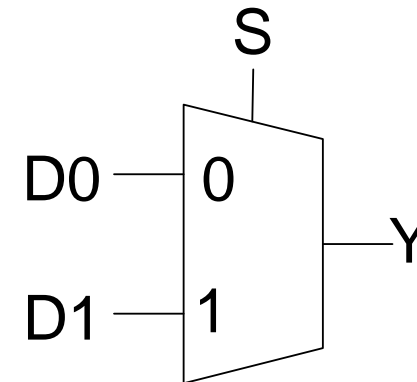
S	D1	D0	Y
0	X	0	
0	X	1	
1	0	X	
1	1	X	



Multiplexers

- 2:1 multiplexer chooses between two inputs

S	D1	D0	Y
0	X	0	0
0	X	1	1
1	0	X	0
1	1	X	1

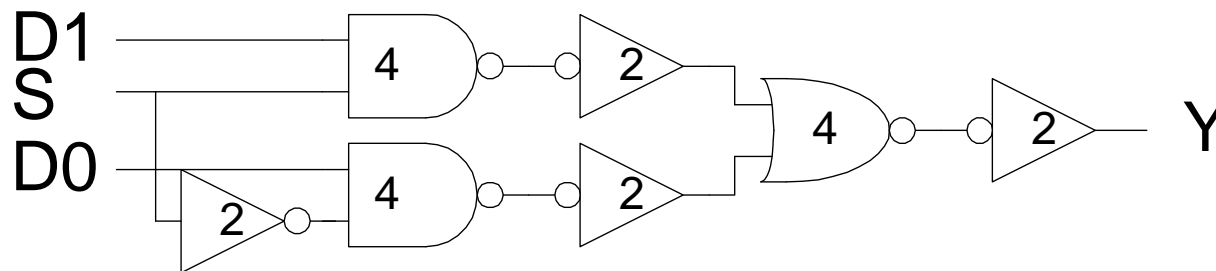
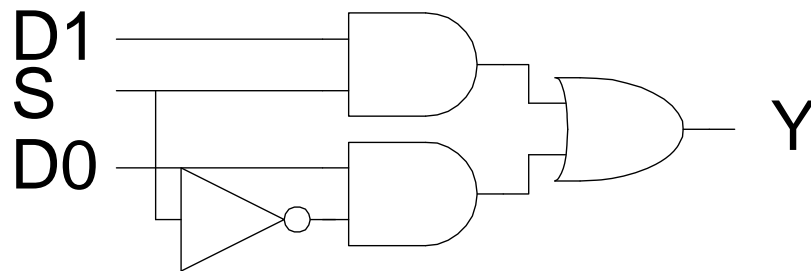


Gate-Level Mux Design

- ❑ $Y = SD_1 + \bar{S}D_0$ (too many transistors)
- ❑ How many transistors are needed?

Gate-Level Mux Design

- ❑ $Y = SD_1 + \bar{S}D_0$ (too many transistors)
- ❑ How many transistors are needed? 20

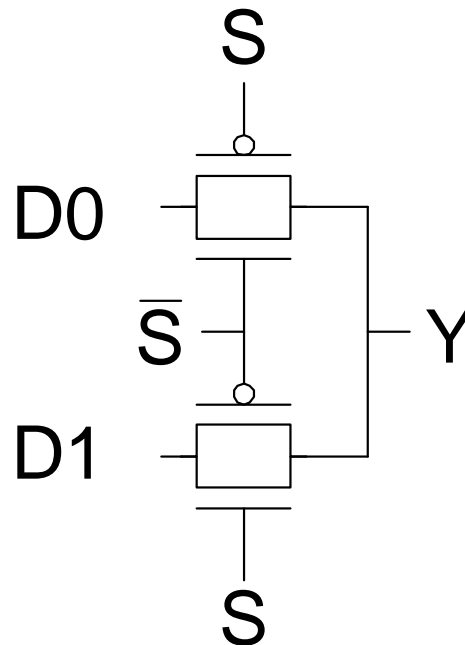


Transmission Gate Mux

- ❑ Nonrestoring mux uses two transmission gates

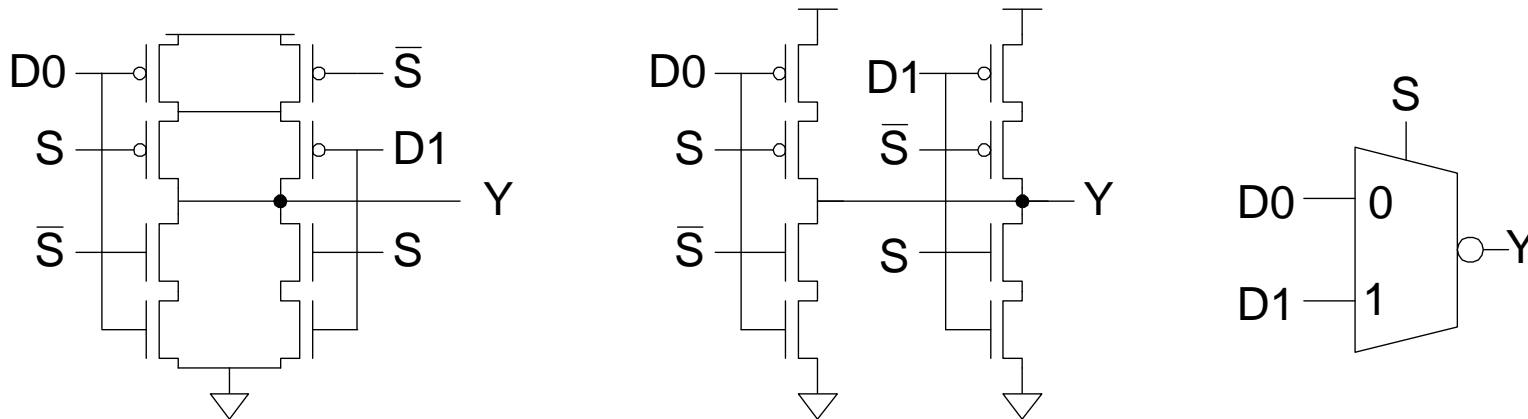
Transmission Gate Mux

- ❑ Nonrestoring mux uses two transmission gates
 - Only 4 transistors



Inverting Mux

- ❑ Inverting multiplexer
 - Use compound AOI22
 - Or pair of tristate inverters
 - Essentially the same thing
- ❑ Noninverting multiplexer adds an inverter

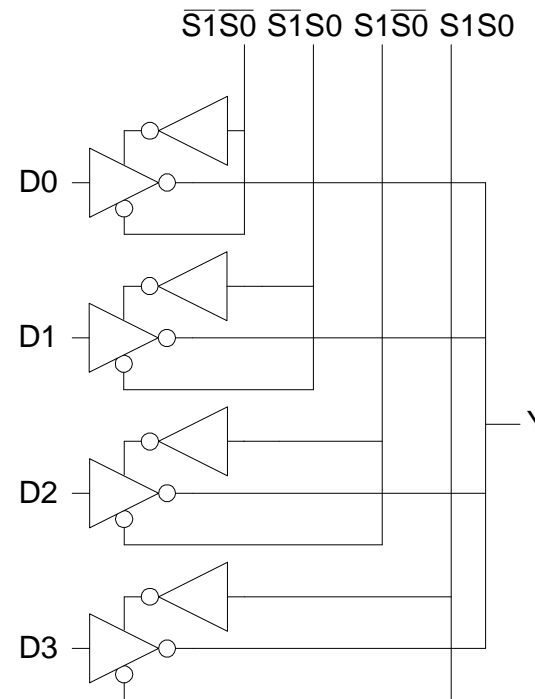
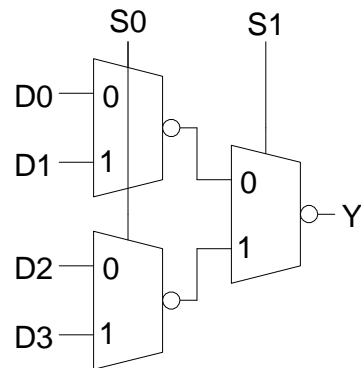


4:1 Multiplexer

- 4:1 mux chooses one of 4 inputs using two selects

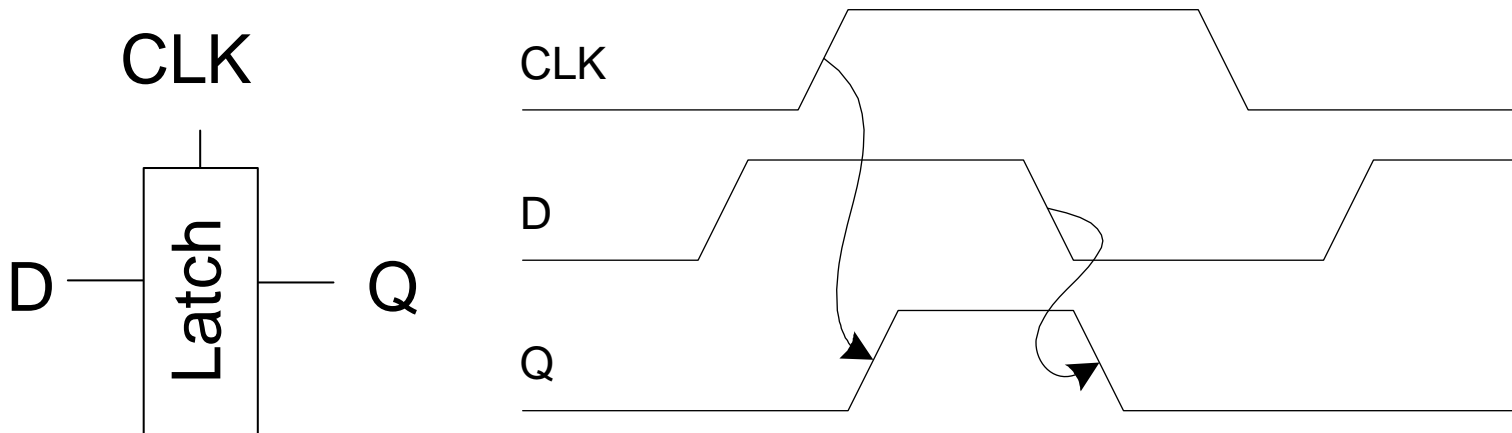
4:1 Multiplexer

- 4:1 mux chooses one of 4 inputs using two selects
 - Two levels of 2:1 muxes
 - Or four tristates



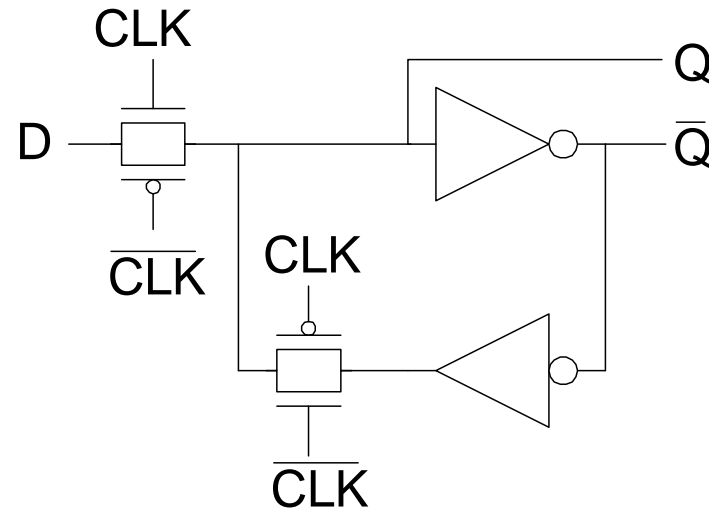
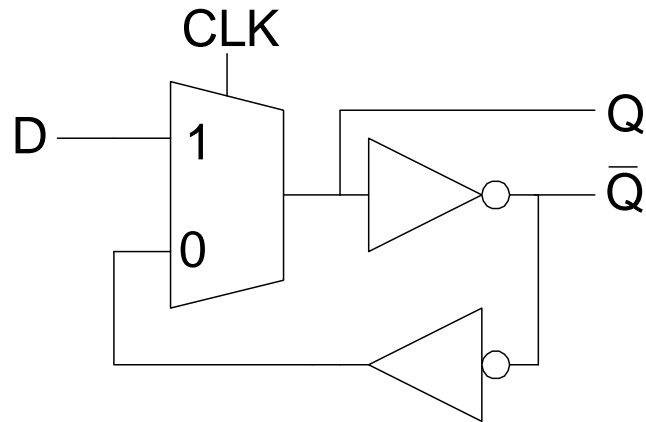
D Latch

- ❑ When $CLK = 1$, latch is *transparent*
 - D flows through to Q like a buffer
- ❑ When $CLK = 0$, the latch is *opaque*
 - Q holds its old value independent of D
- ❑ a.k.a. *transparent latch* or *level-sensitive latch*

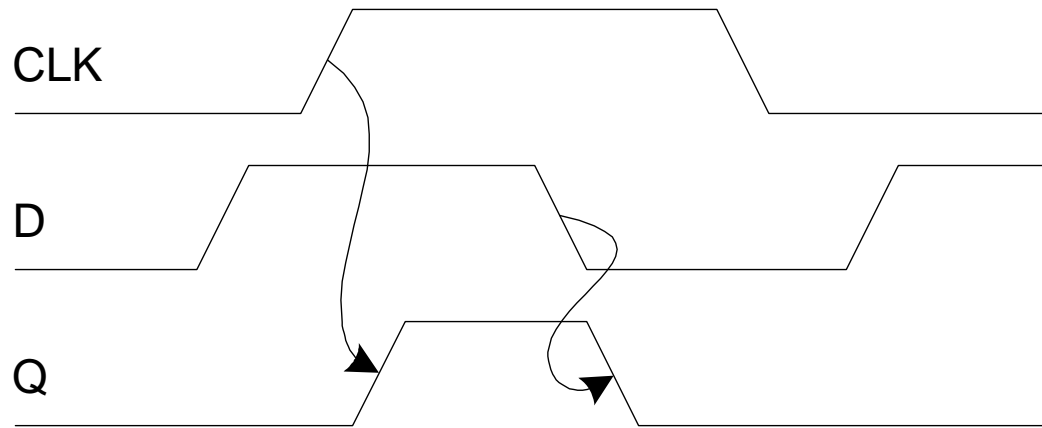
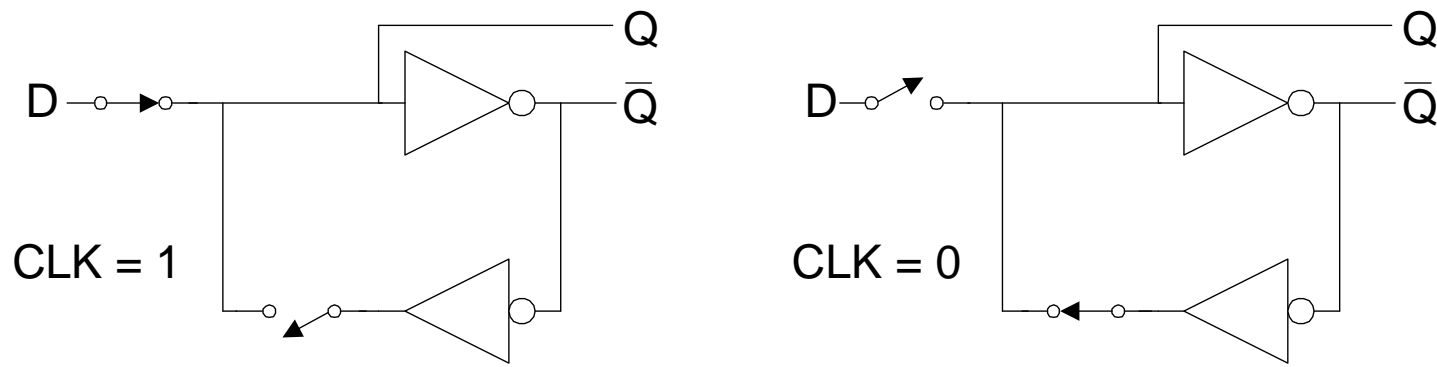


D Latch Design

- ❑ Multiplexer chooses D or old Q

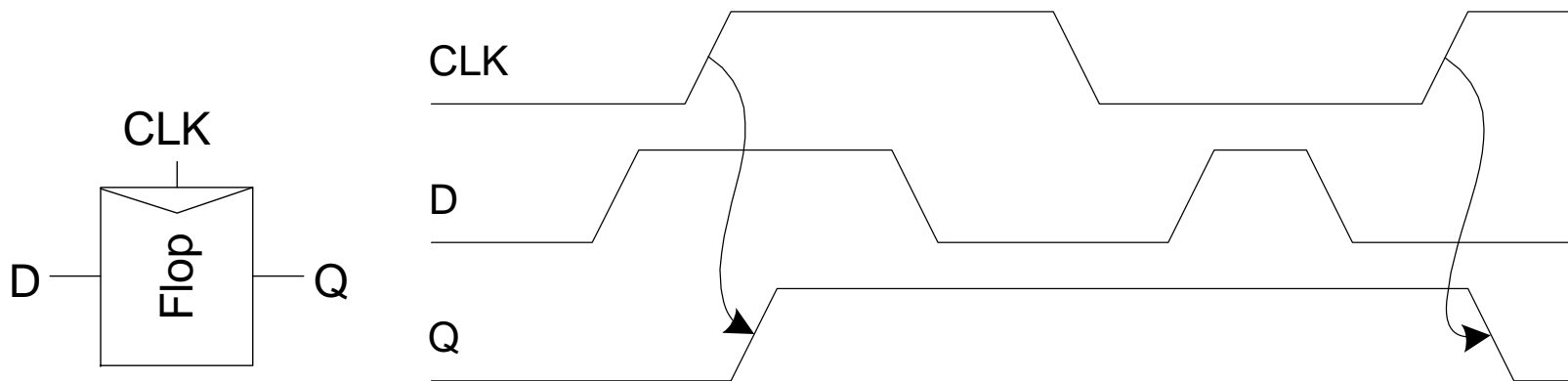


D Latch Operation



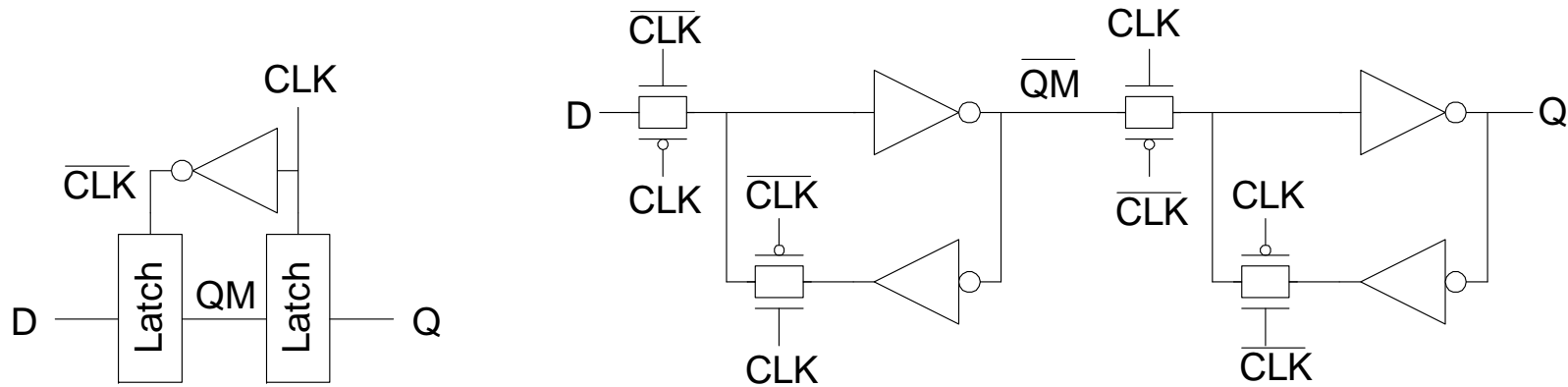
D Flip-flop

- ❑ When CLK rises, D is copied to Q
- ❑ At all other times, Q holds its value
- ❑ a.k.a. *positive edge-triggered flip-flop, master-slave flip-flop*

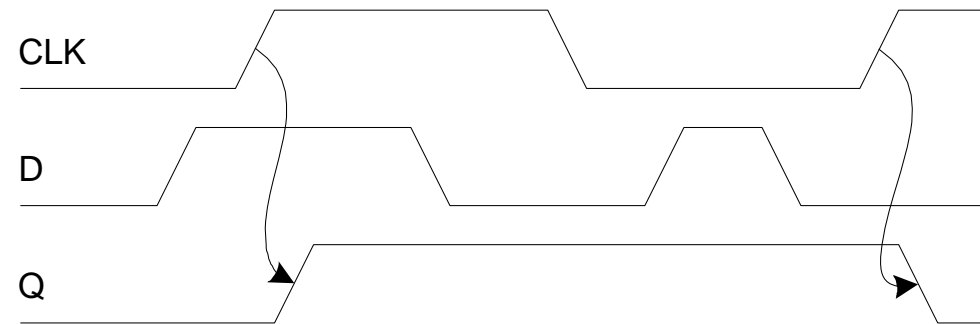
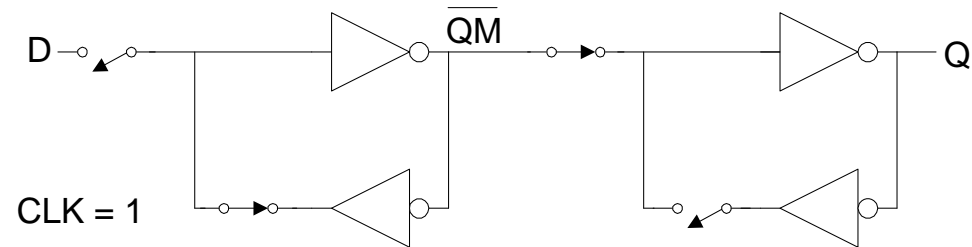
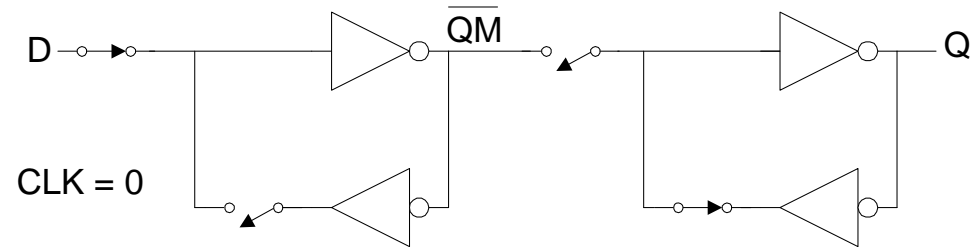


D Flip-flop Design

- Built from master and slave D latches

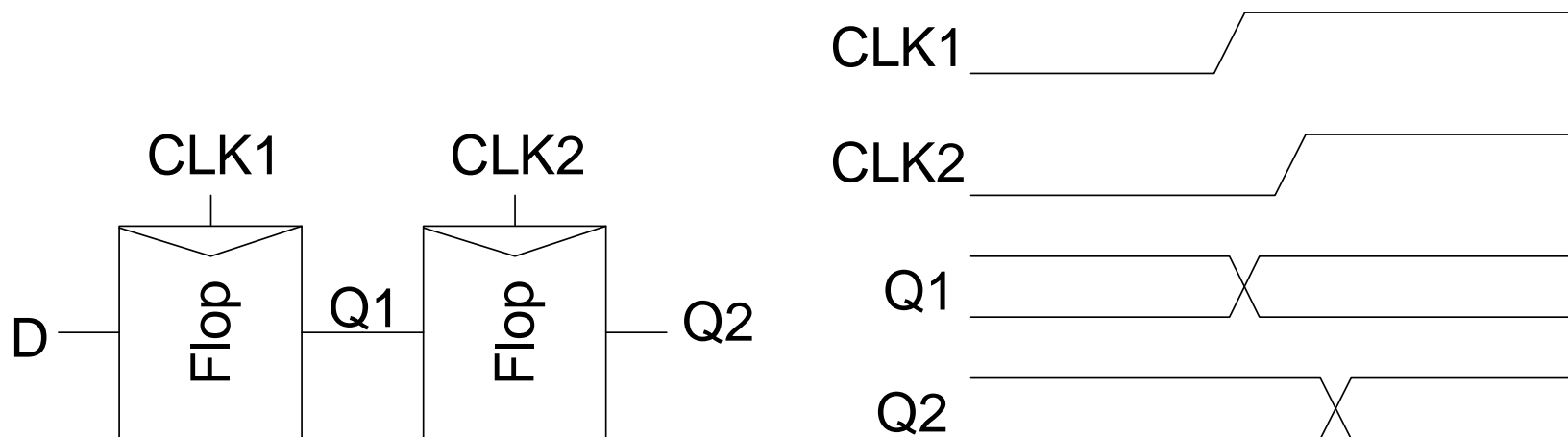


D Flip-flop Operation



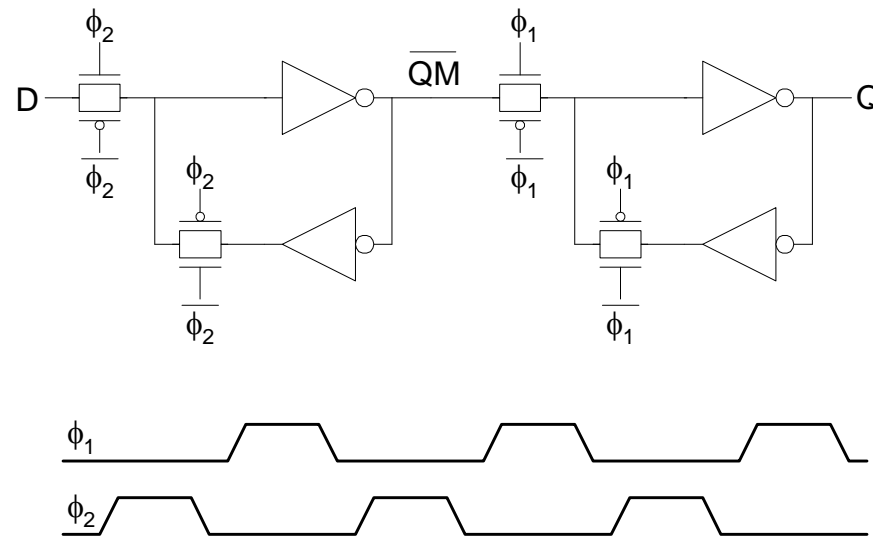
Race Condition

- ❑ Back-to-back flops can malfunction from clock skew
 - Second flip-flop fires late
 - Sees first flip-flop change and captures its result
 - Called *hold-time failure* or *race condition*



Nonoverlapping Clocks

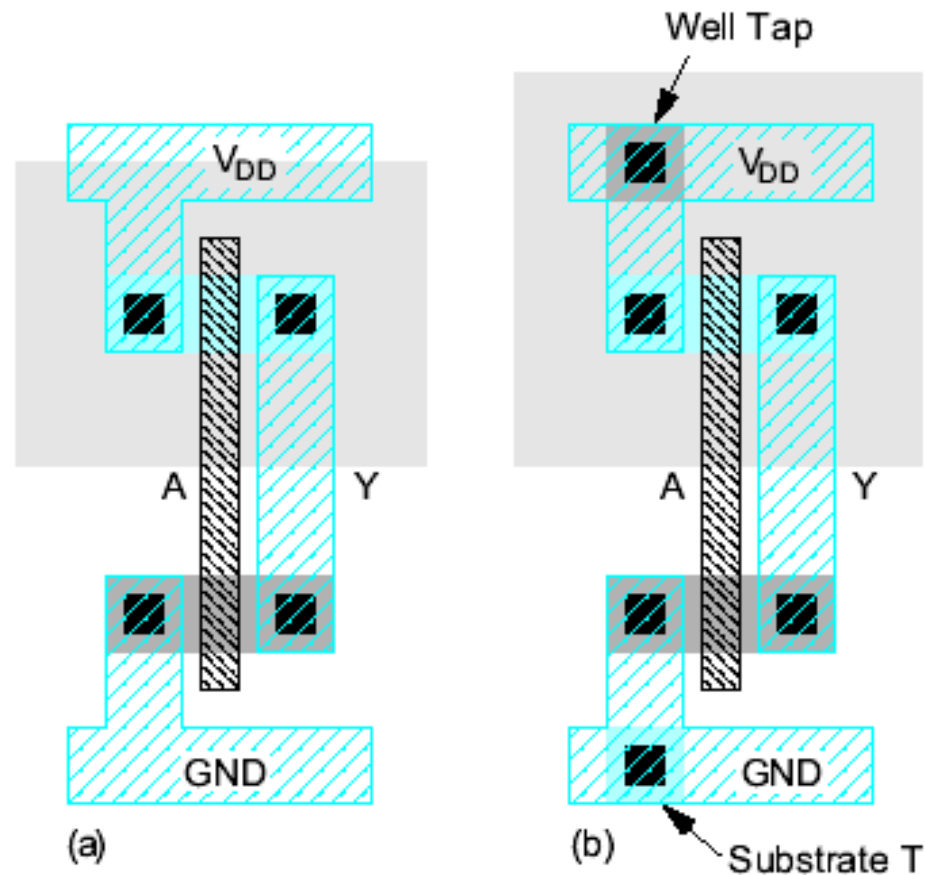
- ❑ Nonoverlapping clocks can prevent races
 - As long as nonoverlap exceeds clock skew
- ❑ We will use them in this class for safe design
 - Industry manages skew more carefully instead



Gate Layout

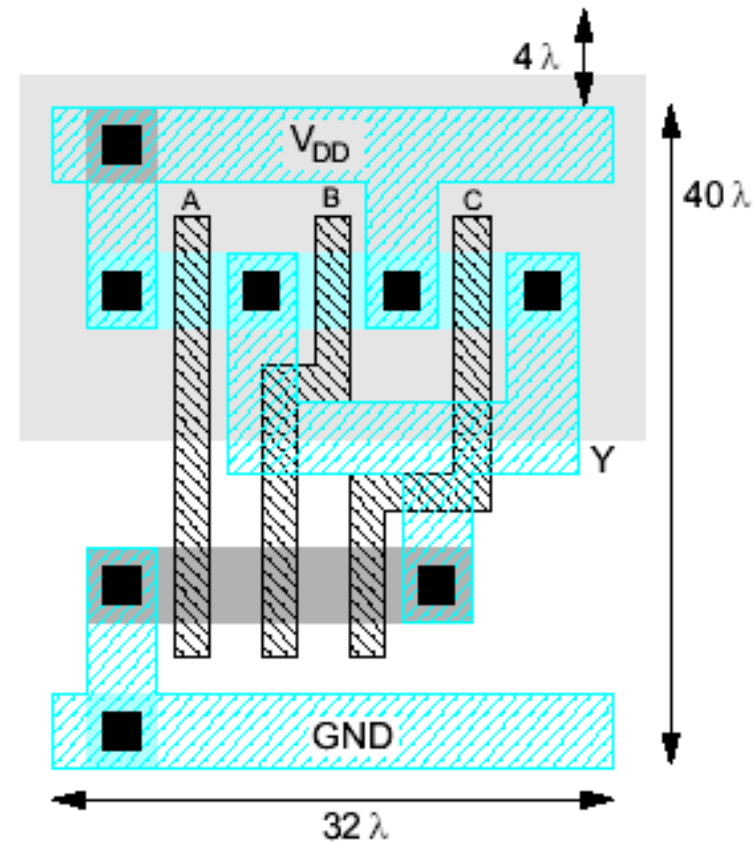
- ❑ Layout can be very time consuming
 - Design gates to fit together nicely
 - Build a library of standard cells
- ❑ Standard cell design methodology
 - V_{DD} and GND should abut (standard height)
 - Adjacent gates should satisfy design rules
 - nMOS at bottom and pMOS at top
 - All gates include well and substrate contacts

Example: Inverter



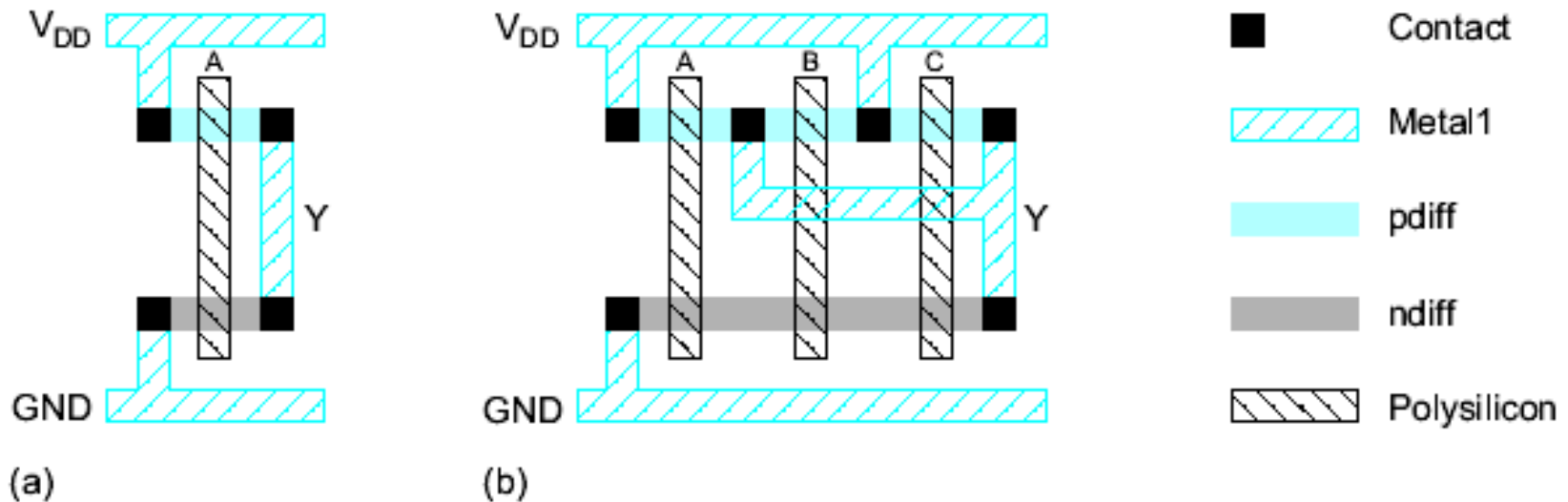
Example: NAND3

- ❑ Horizontal N-diffusion and p-diffusion strips
- ❑ Vertical polysilicon gates
- ❑ Metal1 V_{DD} rail at top
- ❑ Metal1 GND rail at bottom
- ❑ 32λ by 40λ



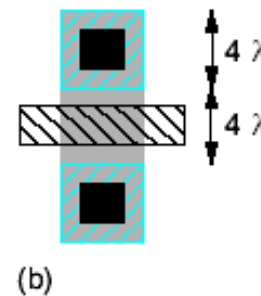
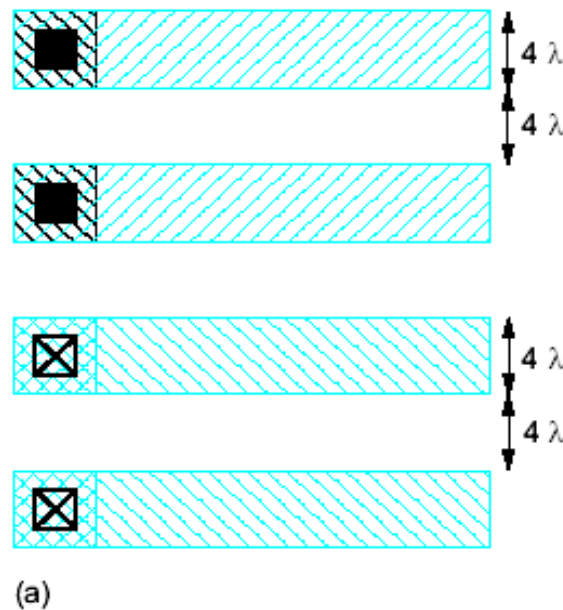
Stick Diagrams

- *Stick diagrams* help plan layout quickly
 - Need not be to scale
 - Draw with color pencils or dry-erase markers



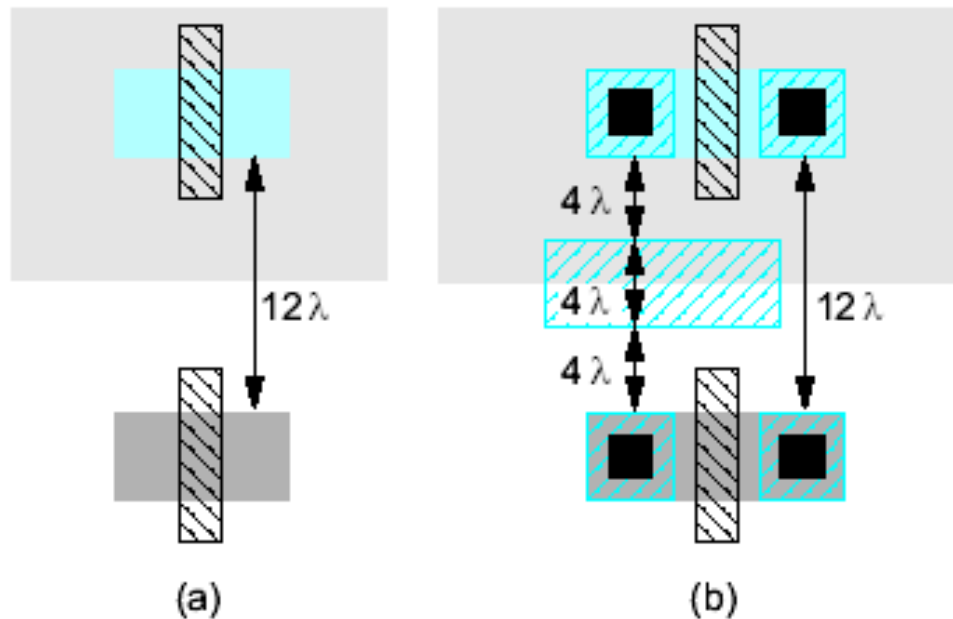
Wiring Tracks

- A *wiring track* is the space required for a wire
 - 4λ width, 4λ spacing from neighbor = 8λ pitch
- Transistors also consume one wiring track



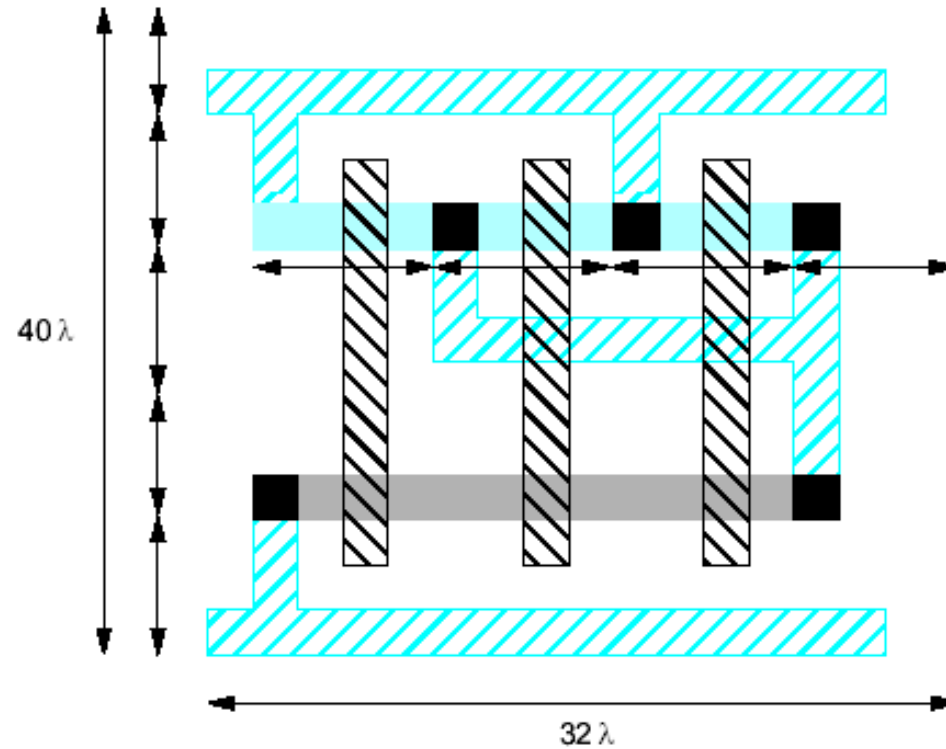
Well spacing

- ❑ Wells must surround transistors by 6λ
 - Implies 12λ between opposite transistor flavors
 - Leaves room for one wire track



Area Estimation

- Estimate area by counting wiring tracks
 - Multiply by 8 to express in λ



Example: O3AI

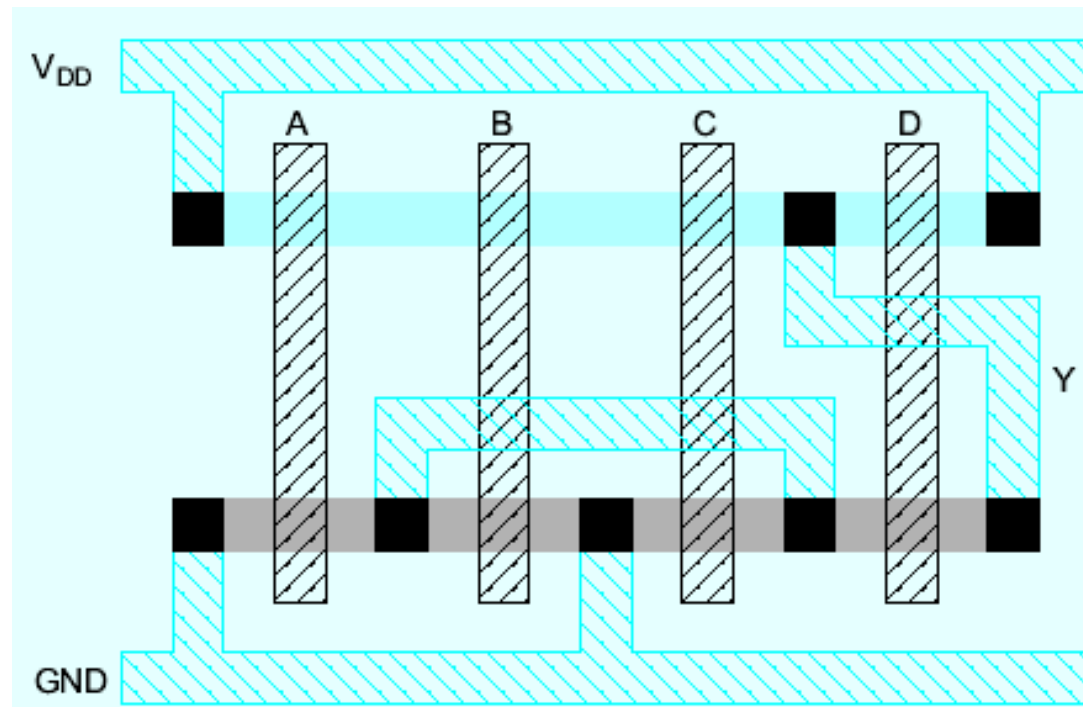
- Sketch a stick diagram for O3AI and estimate area

$$- Y = \overline{(A + B + C)} \square D$$

Example: O3AI

- Sketch a stick diagram for O3AI and estimate area

$$- Y = \overline{(A + B + C)} \square D$$



Example: O3AI

- Sketch a stick diagram for O3AI and estimate area

$$- Y = \overline{(A + B + C)} \square D$$

