ECE357: Introduction to VLSI CAD

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Logistics

- Time & Location: MWF 11-11:50 TECH L160
- Instructor: Hai Zhou `haizhou@ece.northwestern.edu`
- Office: L461
- Office Hours: W 3-5P
- Teaching Assistant: Chuan Lin
- Texts:
  VLSI Physical Design Automation: Theory & Practice, Sait & Youssef, World Scientific, 1999.
- Reference:

An Introduction to VLSI Physical Design, Sarrafzadeh & Wong, McGraw Hill, 1996.

- Grading: Participation-10% Project-30% Midterm-30% Homework-30%
- Homework must be turned in before class on each due date, late: -40% per day
- Course homepage: `www.ece.northwestern.edu/~haizhou/ece357`

What can you expect from the course

- Understand modern VLSI design flows (but not the details of tools)
- Understand the physical design problem
- Familiar with the stages and basic algorithms in physical design
- Improve your capability to design algorithms to solve problems
- Improve your capability to think and reason

What do I expect from you

- Active and critical participation
  - speed me up or slow me down if my pace mismatches yours
  - "Your role is not one of sponges, but one of whetstones; only then the spark of intellectual excitement can continue to jump over"
- Read the textbook
- Do your homeworks
  - You can discuss homework with your classmates, but need to write down solutions independently

VLSI (Very Large Scale Integrated) chips

- VLSI chips are everywhere
  - computers
  - commercial electronics: TV sets, DVD, VCR, ...
  - voice and data communication networks
  - automobiles
- VLSI chips are artifacts
  - they are produced according to our will ...

Design: the most challenging human activity

- Design is a process of creating a structure to fulfill a requirement
- Brain power is the scarcest resource
  - Delegate as much as possible to computers–CAD
- Avoid two extreme views:
  - Everything manual: impossible–millions of gates
  - Everything computer: impossible either

Design is always difficult

A main task of a designer is to manage complexity

- Silicon complexity: physical effects no longer be ignored
  - resistive and cross-coupled interconnects; signal integrity; weak and faster gates
  - reliability; manufacturability
- System complexity: more functionality in less time
  - gap between design and fabrication capabilities
  - desire for system-on-chip (SOC)

CAD: A tale of two designs

- Target–hardware design
  - How to create a structure on silicon to implement a function
- Aid–software design (programming)
  - How to create an algorithm to solve a design problem
- Be conscious of their similarities and differences

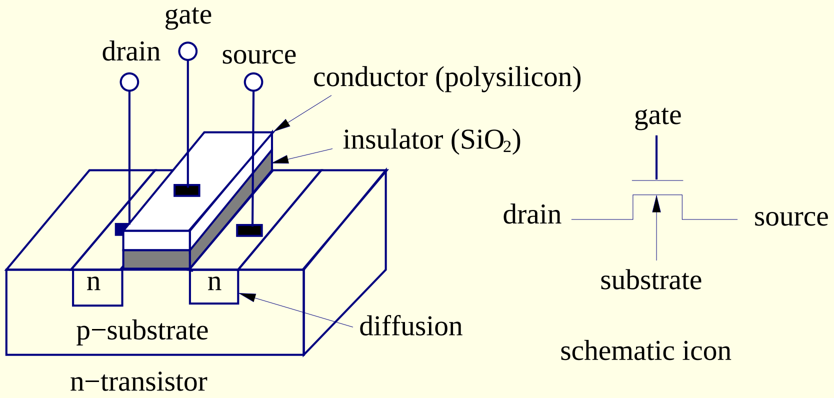
Emphasis of the course

- Design flow
  - Understand how design process is decomposed into many stages
  - What are the problems need to be solved in each stage
- Algorithms
  - Understand how an algorithm solves a design problem
  - Consider the possibility to extend it
- Be conscious and try to improve problem solving skills

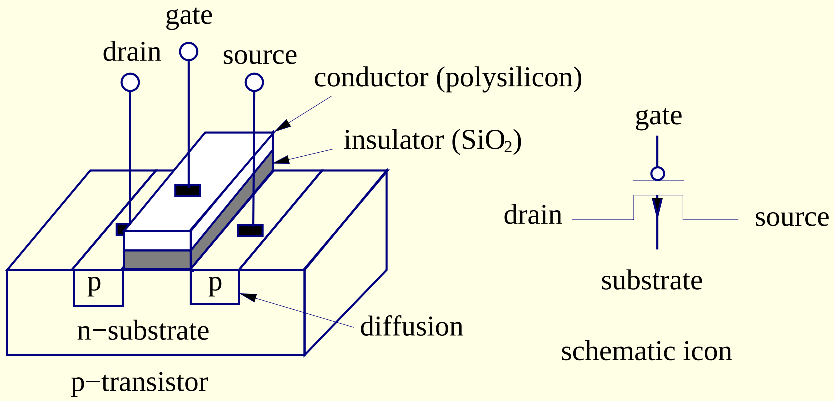
Basics of MOS Devices

- The most popular VLSI technology: MOS (Metal-Oxide-Semiconductor).
- CMOS (Complementary MOS) dominates nMOS and pMOS, due to CMOS's lower power dissipation, high regularity, etc.
- Physical structure of MOS transistors and their schematic icons: nMOS, pMOS.
- Layout of basic devices:
  - CMOS inverter
  - CMOS NAND gate
  - CMOS NOR gate

MOS Transistors

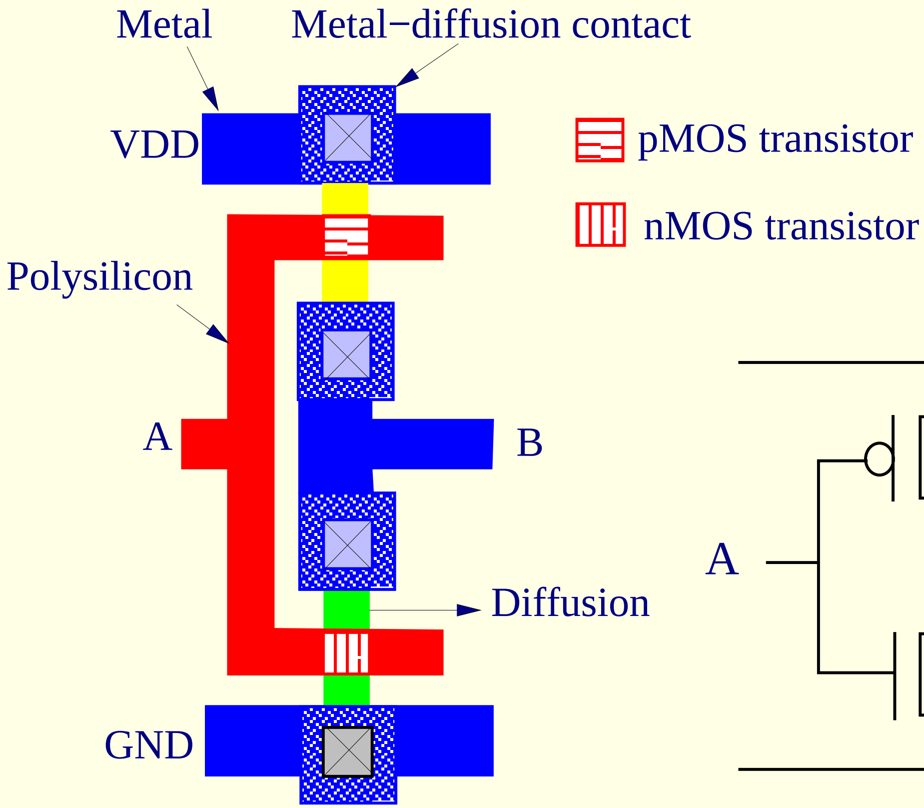


The nMOS switch passes "0" well.



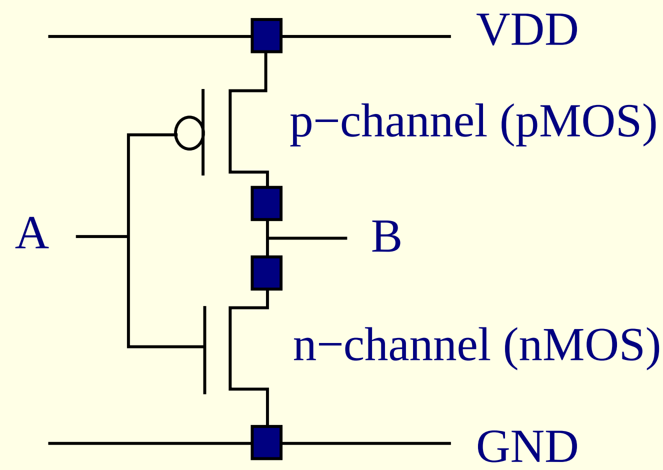
The pMOS switch passes "1" well.

A CMOS Inverter

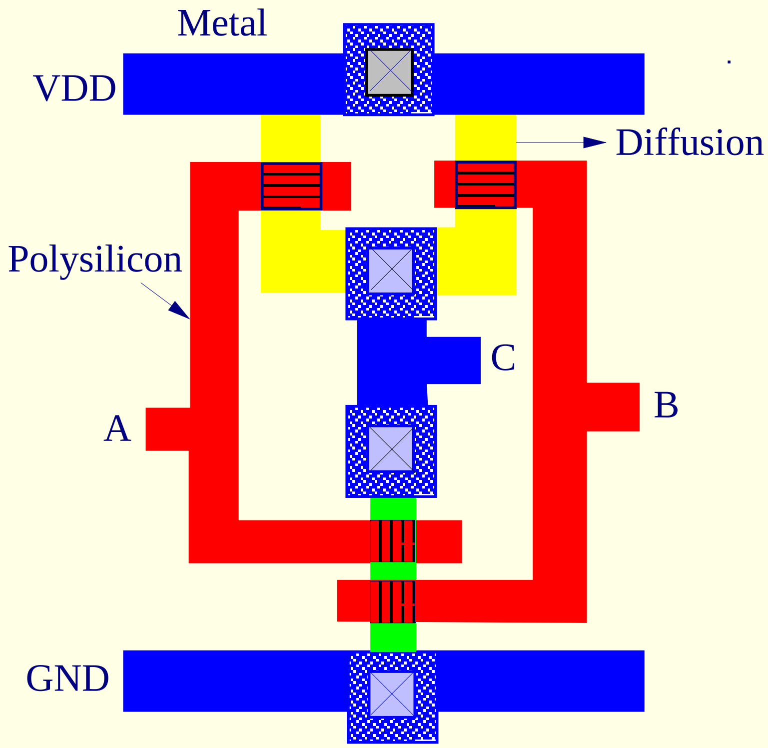


layout

A	B
1	0
0	1

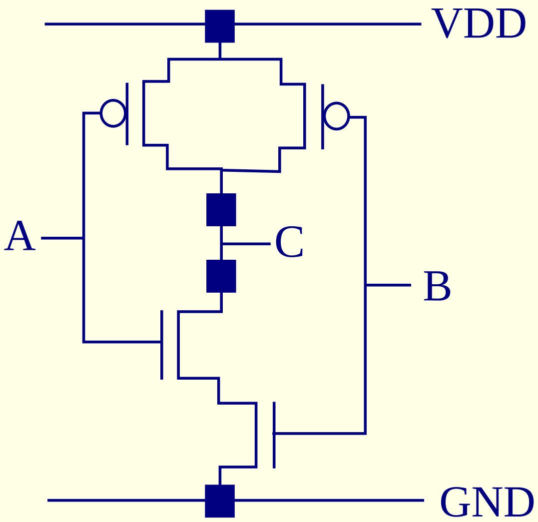


A CMOS NAND Gate

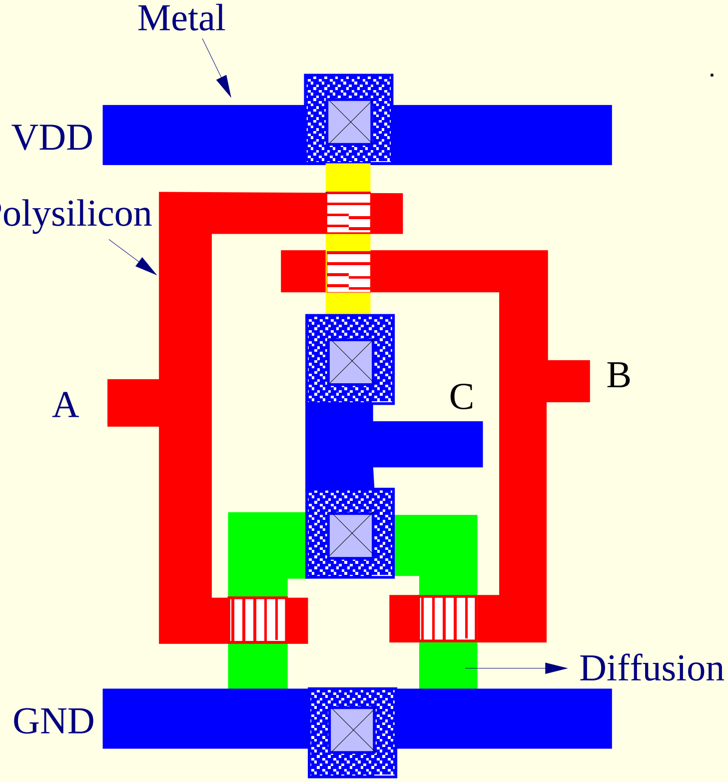


layout

A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

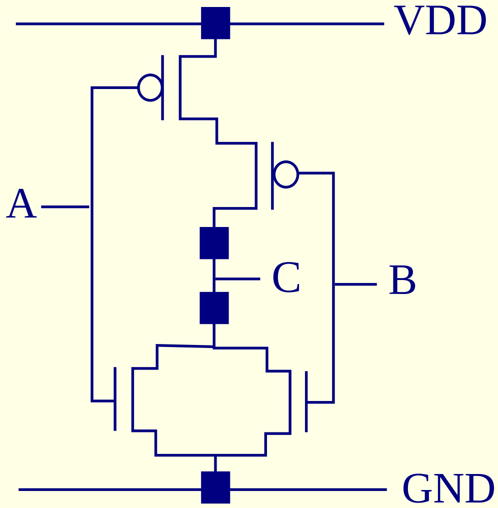


A CMOS NOR Gate



layout

A	B	C
0	0	1
0	1	0
1	0	0
1	1	0



Current VLSI design phases

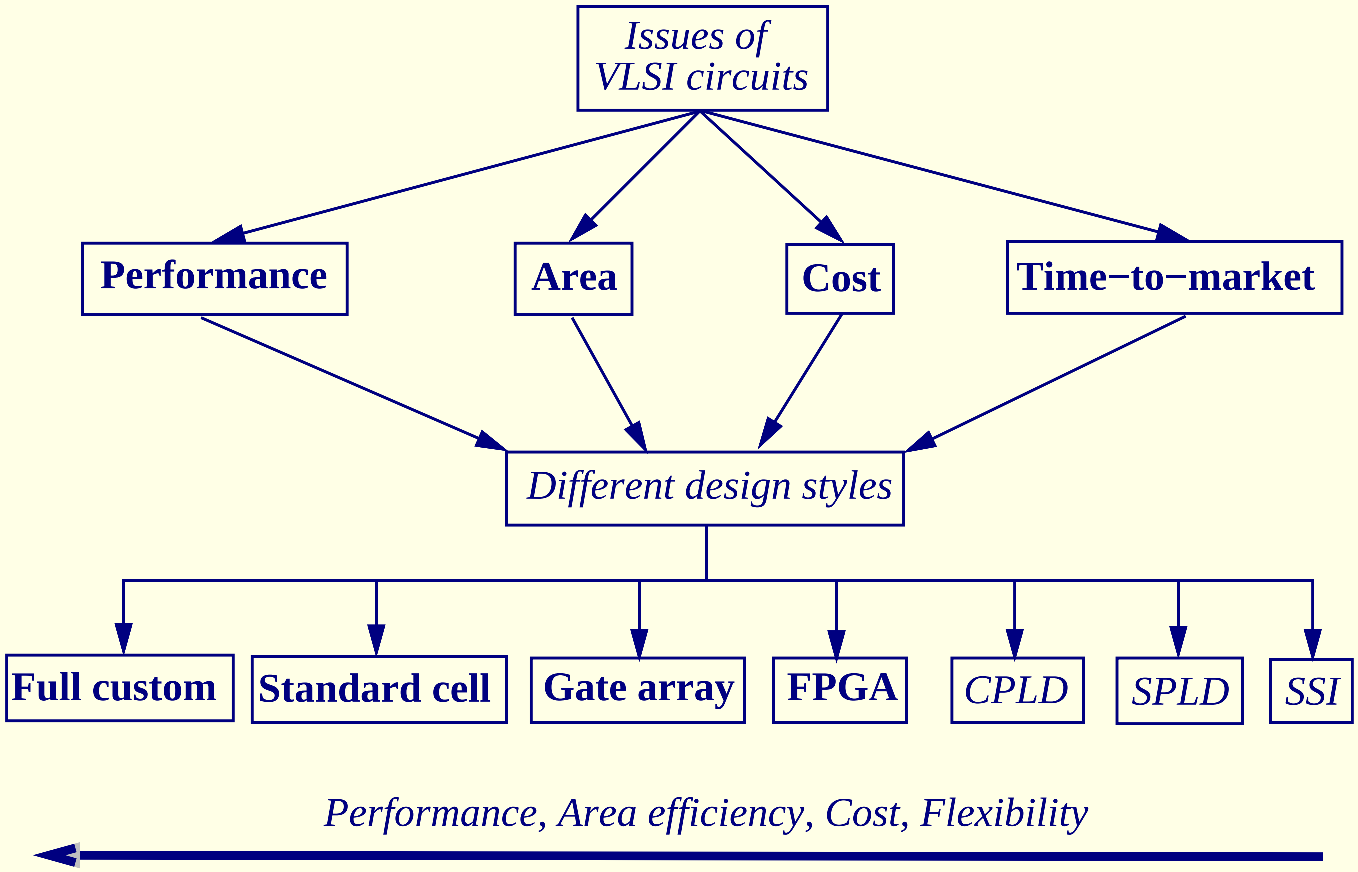
- Synthesis (i.e. specification $\longrightarrow$ implementation)
  1. High level synthesis (459 VLSI Algorithmics)
  2. Logic synthesis (459 VLSI Algorithmics)
  3. Physical design (This course)
- Analysis (implementation $\longrightarrow$ semantics)
  - Verification (design verification, implementation verification)
  - Analysis (timing, function, noise, etc.)
  - Design rule checking, LVS (Layout Vs. Schematic)

Physical Design

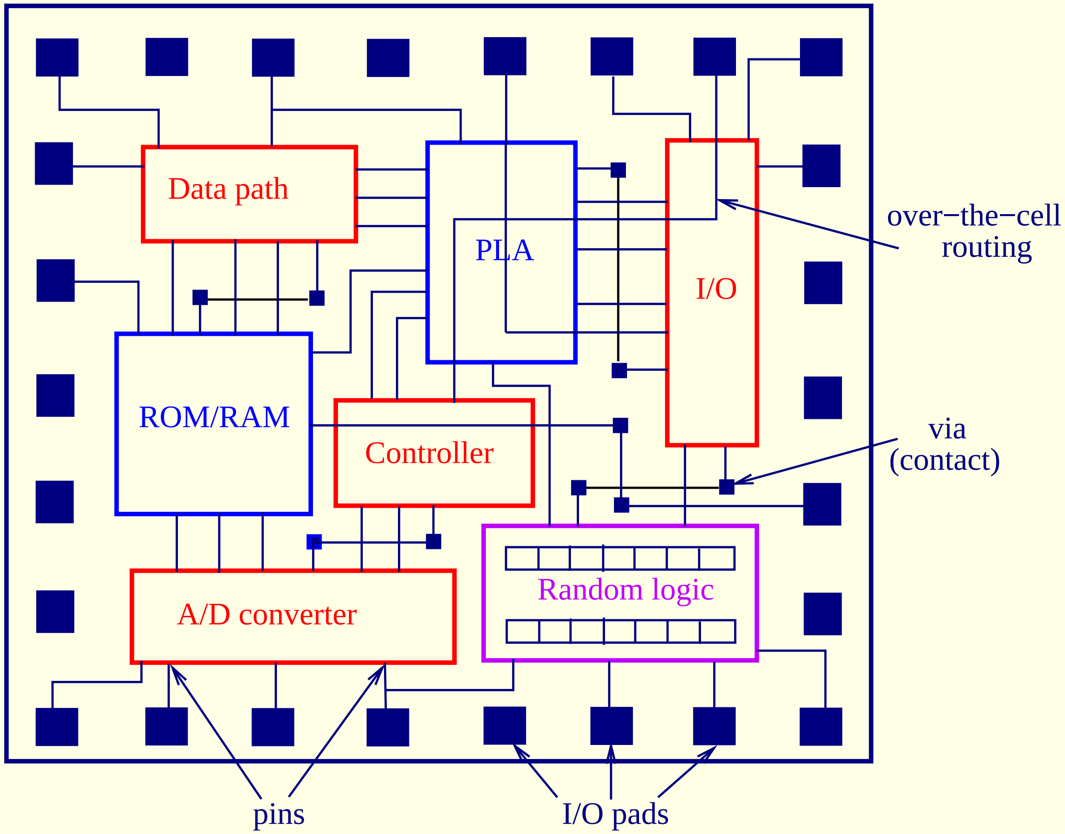
- Physical design converts a structural description into a geometric description.
- Physical design cycle:

  1. Circuit partitioning
  2. Floorplanning
  3. placement, and pin assignment
  4. Routing (global and detailed)
  5. Compaction

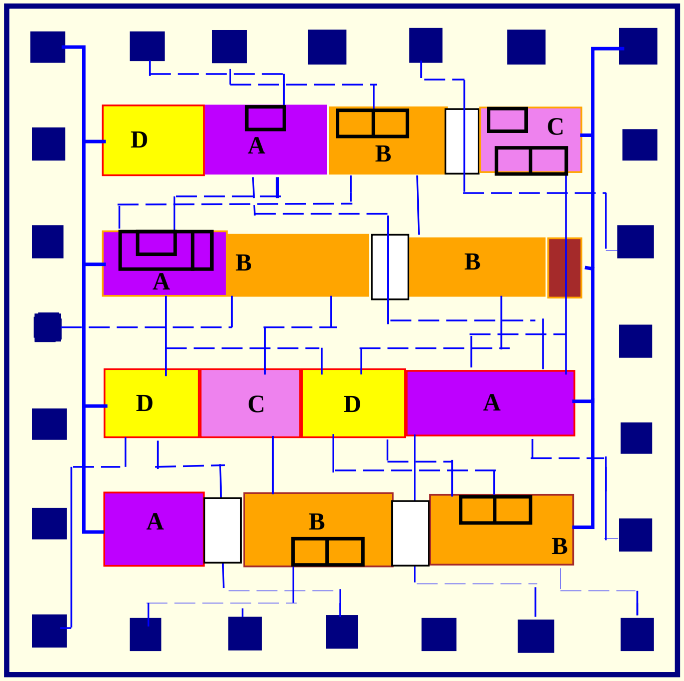
Design Styles

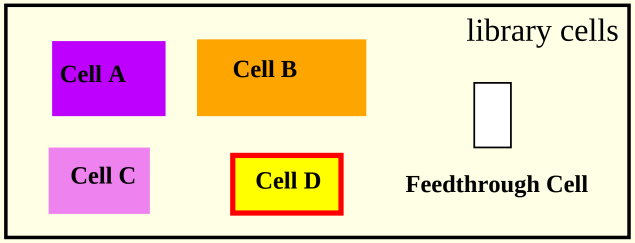


Full Custom Design Style

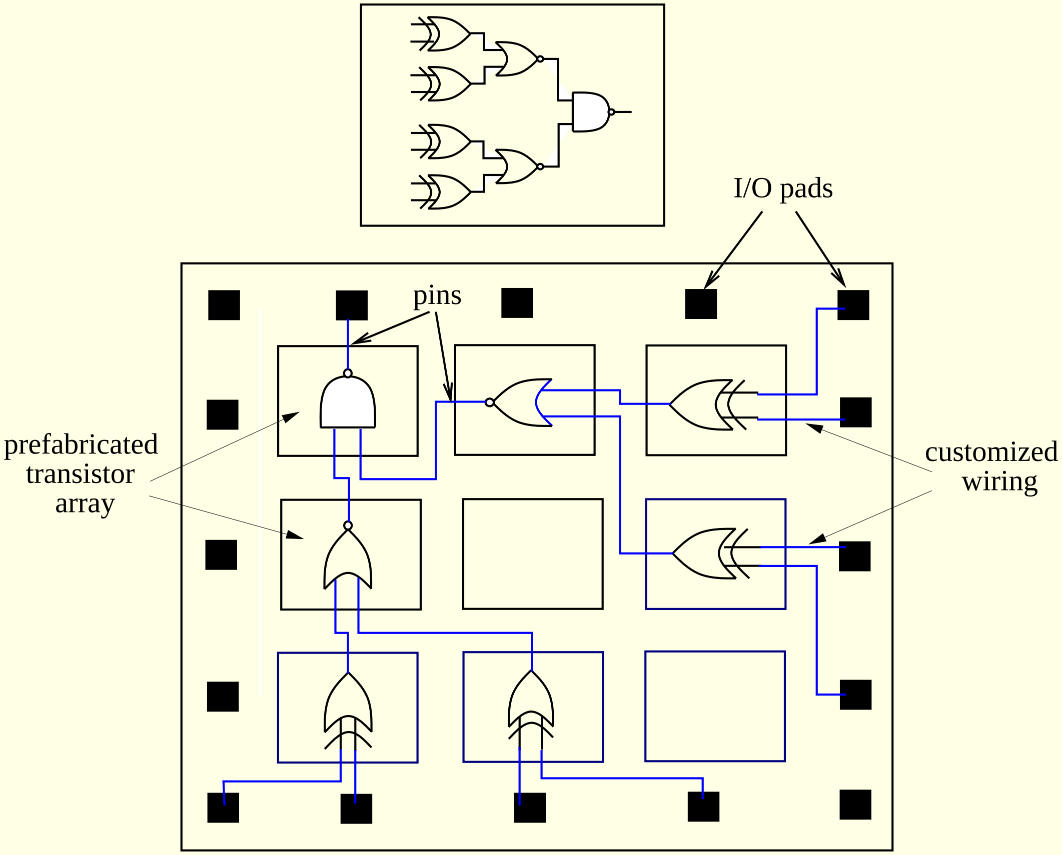


Standard Cell Design Style

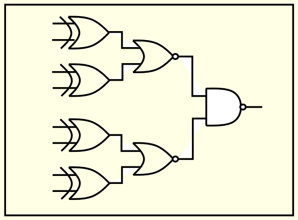


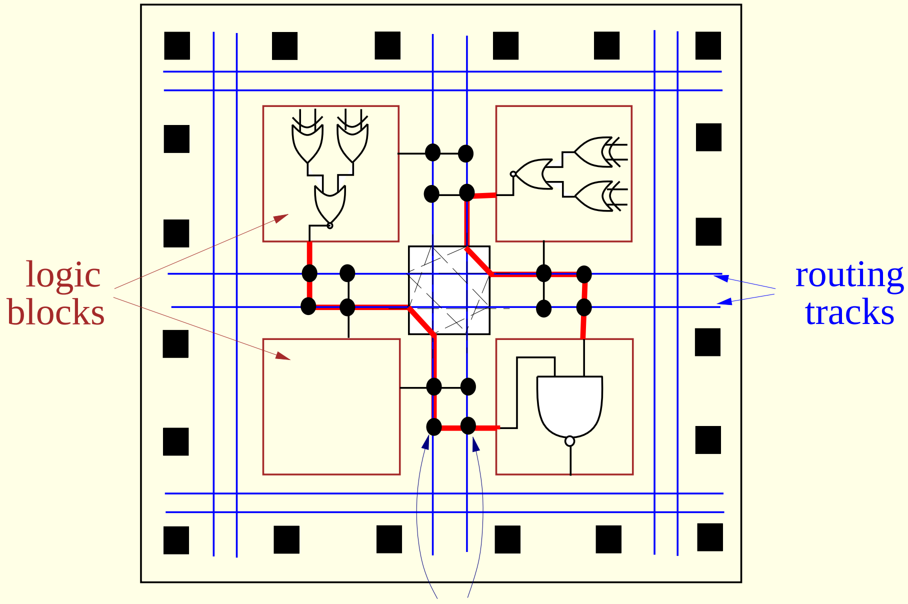


Gate Array Design Style



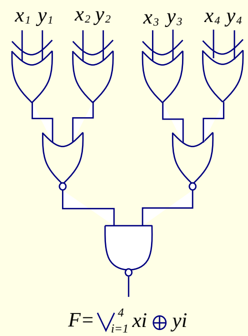
FPGA Design Style



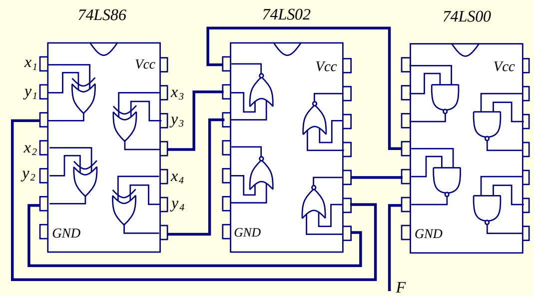


Prefabricated all chip components

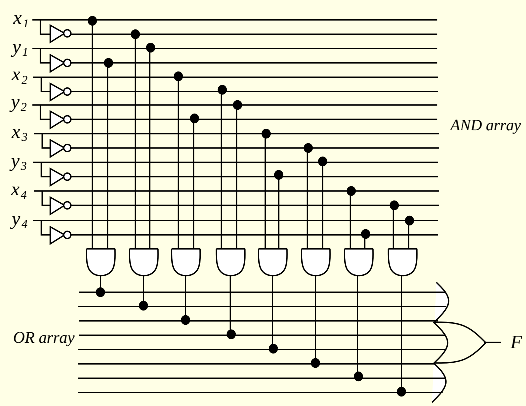
SSI/SPLD Design Style



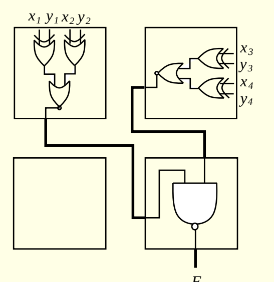
(a) 4−bit comparator.



(b) SSI implementation.



(c) SPLD (PLA) implementation.



(d) Gate array implementation.

Comparisons of Design Styles

	Full custom	Standard cell	Gate array	FPGA	SPLD
Cell size	variable	fixed height*	fixed	fixed	fixed
Cell type	variable	variable	fixed	programmable	programmable
Cell placement	variable	in row	fixed	fixed	fixed
Interconnections	variable	variable	variable	programmable	programmable

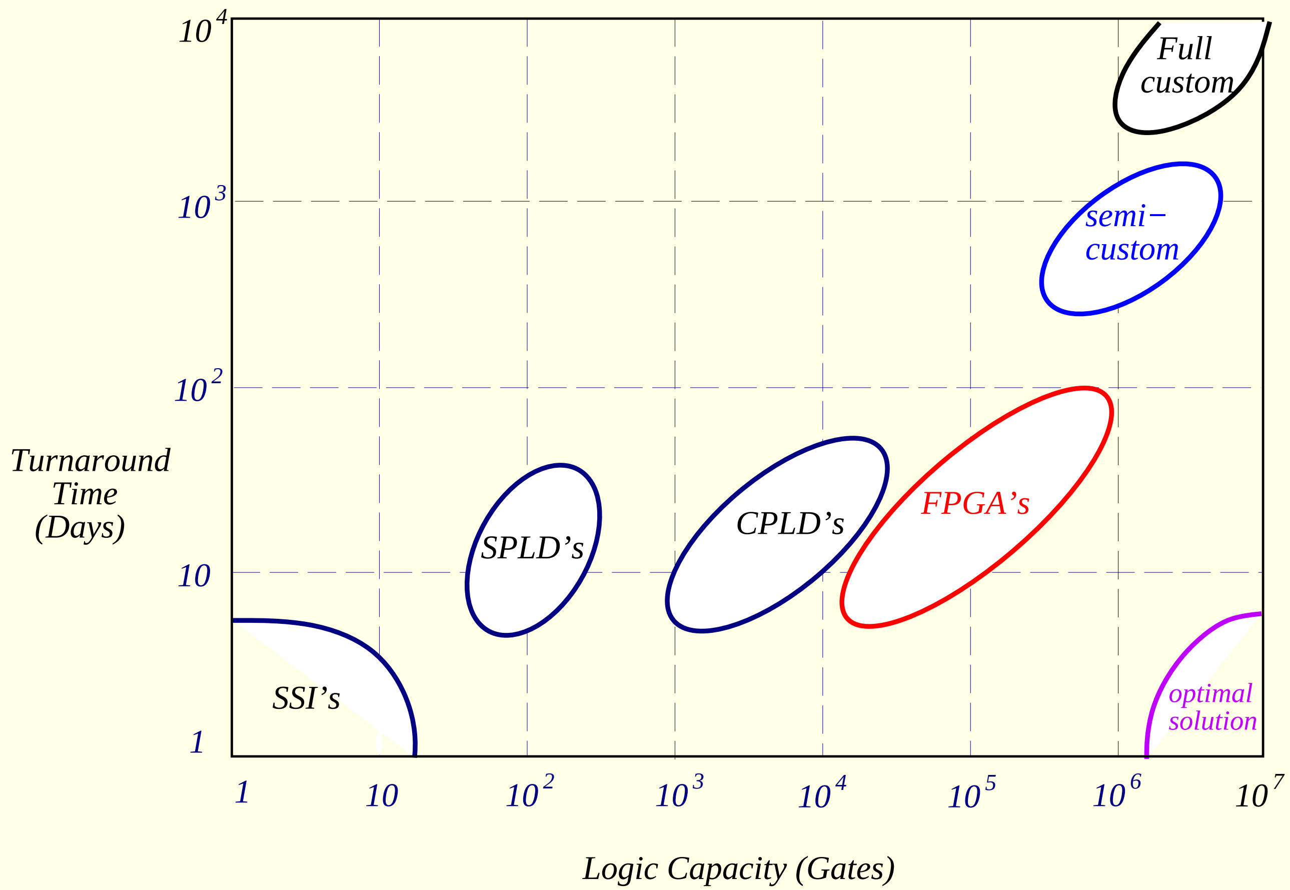
* Uneven height cells are also used.

Comparisons of Design Styles

	Full custom	Standard cell	Gate array	FPGA	SPLD
Fabrication time	$- - -$	$- -$	$+$	$+++$	$++$
Packing density	$+++$	$++$	$+$	$- -$	$- - -$
Unit cost in large quantity	$+++$	$++$	$+$	$- -$	$-$
Unit cost in small quantity	$- - -$	$- -$	$+$	$+++$	$+$
Easy design and simulation	$- - -$	$- -$	$-$	$++$	$+$
Easy design change	$- - -$	$- -$	$-$	$++$	$++$
Accuracy of timing simulation	$-$	$-$	$-$	$+$	$+$
Chip speed	$+++$	$++$	$+$	$-$	$--$

$+$ desirable
$-$ not desirable

Design-Style Trade-offs



Algorithms 101

- Algorithm: a finite step-by-step procedure to solve a problem
- Requirements:
  - Unambiguity: can even be followed by a machine
  - Basic: each step is among a given primitives
  - Finite: it will terminate for every possible input

A game

- An ECE major is sitting on the Northwestern beach and gets thirsty, she knows that there is an ice-cream booth along the shore of Lake Michigan but does not know where–not even north or south. How can she find the booth in the shortest distance?

- Primitives: walking a distance, turning around, etc.

A first solution

- Select a direction, say north, and keep going until find the booth

- Suppose the booth is to the south, she will never stop... of course, with the assumption she follows a straight line, not lake shore or on earth

Another solution

- Set the place she is sitting as the origin
- Search to south 1 yard, if not find, turn to north
- Search to north 1 yard, if not find, turn to south
- Search to south 2 yard, if not find, turn to north
- Search to north 2 yard, if not find, turn to south
- ... (follow the above pattern in geometric sequence 1, 2, 4, 8, ...)

OR

- $n = -1$;
- While (not find) do
  - $n = n + 1$;
  - Search to south 2^n, and turn;
  - Search to north 2^n, and turn;

Correctness proof

- Each time when the while loop is finished, the range from south 2^n to north 2^n is searched. Based on the fact that the booth is at a constant distance x from the origin, it will be within a range from south 2^N to north 2^N for some N. With n to increment in each loop, we will find the booth in finite time.

- Is this the fastest (or shortest) way to find the booth?

Analysis of algorithm

- Observation: the traveled distance depends on where is the booth
- Suppose the distance between the booth and the origin is x
- When the algorithm stops, we should have $2^n \geq x$ but $2^{n-1} < x$
- The distance traveled is

$$3 \cdot 2^n + 2(2 \cdot 2^{n-1} + 2 \cdot 2^{n-2} + \cdots + 2) \leq 7 \cdot 2^n$$

- which is smaller than $14x$
- We know that the lower bound is x, can we do better?

Complexity of an algorithm

- Two resources: running time and storage
- They are dependent on inputs: expressed as functions of input size
  - Why input size: lower bound (at least read it once)
- **Big-Oh** notation: $f(n) = O(g(n))$ if there exist constants n_0 and c such that for all $n > n_0$, $f(n) \leq c \cdot g(n)$.
  - Make our life easy: is it $13x$ instead of $14x$ in our game
  - The solution is asymptotically optimal for our game

Time complexity of an algorithm

- Run-time comparison: 1000 MIPS (Yr: 200x), 1 instr. /op.

Time	Big-Oh	$n = 10$	$n = 100$	$n = 10^3$	$n = 10^6$
500	$O(1)$	5×10^{-7} sec	5×10^{-7} sec	5×10^{-7} sec	5×10^{-7} sec
$3n$	$O(n)$	3×10^{-8} sec	3×10^{-7} sec	3×10^{-6} sec	0.003 sec
$n \log n$	$O(n \log n)$	3×10^{-8} sec	2×10^{-7} sec	3×10^{-6} sec	0.006 sec
n^2	$O(n^2)$	1×10^{-7} sec	1×10^{-5} sec	0.001 sec	16.7 min
n^3	$O(n^3)$	1×10^{-6} sec	0.001 sec	1 sec	3×10^5 cent.
2^n	$O(2^n)$	1×10^{-6} sec	3×10^{17} cent.	-	-
$n!$	$O(n!)$	0.003 sec	-	-	-

- Polynomial-time complexity: $O(p(n))$, where n is the input size and $p(n)$ is a polynomial function of n.

Complexity of a problem

- Given a problem, what is the running time of the fastest algorithm for it?
- Upper bound: easy–find an algorithm with less time
- Lower bound: hard–every algorithm requires more time
- **P**: set of problems solvable in polynomial time
- **NP**(Nondeterministic P): set of problems whose solution can be proved in polynomial time
- Millennium open problem: $\mathbf{NP} \neq \mathbf{P}$?
  - Fact: there are a set of problems in **NP** resisting any polynomial solution for a long time (40 years)

NP-complete and NP-hard

- Cook 1970: If the problem of boolean satisfiability can be solved in poly. time, so can all problems in **NP**.
- Such a problem with this property is called NP-hard.
- If a NP-hard problem is in **NP**, it is called NP-complete.
- Karp 1971: Many other problems resisting poly. solutions are NP-complete.

How to deal with a hard problem

- Prove the problem is NP-complete:
  1. The problem is in NP (i.e. solution can be proved in poly. time)
  2. It is NP-hard (by polynomial reducing a NP-complete problem to it)
- Solve NP-hard problems:
  - Exponential algorithm (feasible only when the problem size is small)
    - * Pseudo-polynomial time algorithms
  - Restriction: work on a subset of the input space

- Approximation algorithms: get a provable close-to-optimal solution
- Heuristics: get a as good as possible solution
- Randomized algorithm: get the solution with high probability

Algorithmic Paradigms

- Divide and conquer: divide a problem into sub-problems, solve sub-problems, and combine them to construct a solution.
  - Greedy algorithm: optimal solutions to sub-problems will give optimal solution to the whole problem.
  - Dynamic programming: solutions to a larger problem are constructed from a set of solutions to its sub-problems.
- Mathematical programming: a system of optimizing an objective function under constraints functions.
- Simulated annealing: an adaptive, iterative, non-deterministic algorithm that allows "uphill" moves to escape from local optima.

- Branch and bound: a search technique with pruning.
- Exhaustive search: search the entire solution space.