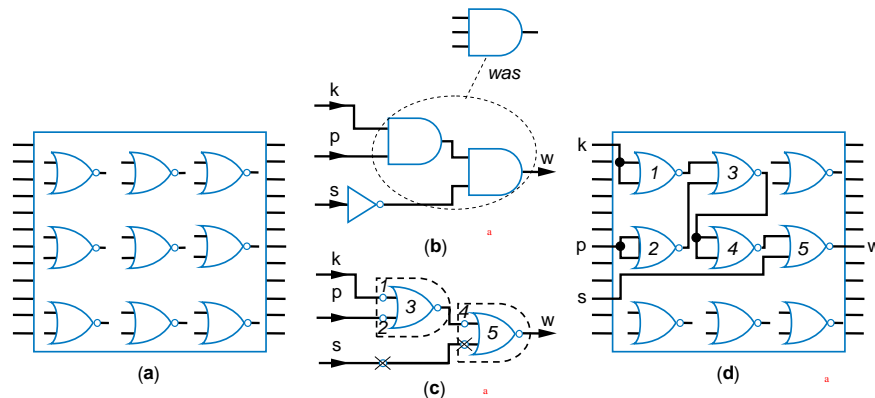


## Implementing Circuits Using NOR Gates Only

- Example: Seat belt warning light on a NOR-based gate array
  - Note: if using 2-input NOR gates, first convert AND/OR gates to 2-inputs



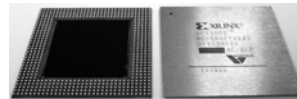
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## Programmable IC Technology – FPGA

7.3

- Manufactured IC technologies require weeks to months to fabricate
  - And have large (hundred thousand to million dollar) initial costs
- Programmable ICs are pre-manufactured
  - Can implement circuit *today*
  - Just download bits into device
  - Slower/bigger/more-power than manufactured ICs
    - But get it today, and no fabrication costs
- Popular programmable IC – FPGA
  - "Field-programmable gate array"
    - Developed late 1980s
    - Though no "gate array" inside
      - Named when gate arrays were very popular in the 1980s
    - Programmable in seconds

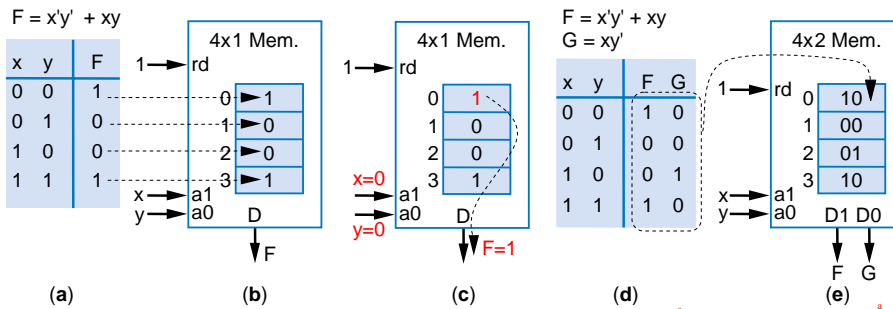


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## FPGA Internals: Lookup Tables (LUTs)

- Basic idea: Memory can implement combinational logic
  - e.g., 2-address memory can implement 2-input logic
  - 1-bit wide memory – 1 function; 2-bits wide – 2 functions
- Such memory in FPGA known as Lookup Table (LUT)

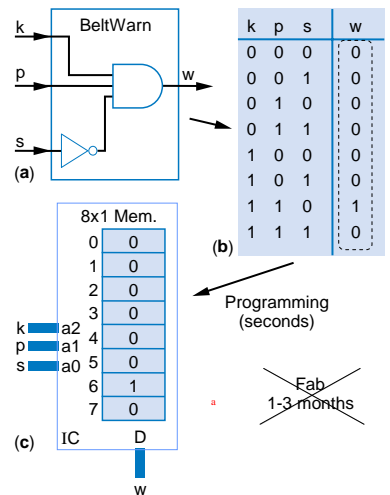


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## FPGA Internals: Lookup Tables (LUTs)

- Example: Seat-belt warning light (again)

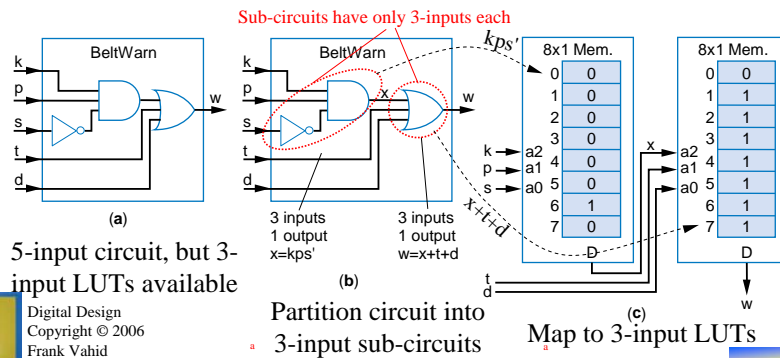


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## FPGA Internals: Lookup Tables (LUTs)

- Lookup tables become inefficient for more inputs
  - 3 inputs  $\rightarrow$  only 8 words
  - 8 inputs  $\rightarrow$  256 words; 16 inputs  $\rightarrow$  65,536 words!
- FPGAs thus have numerous small (3, 4, 5, or even 6-input) LUTs
  - If circuit has more inputs, must partition circuit among LUTs
  - Example: Extended seat-belt warning light system:

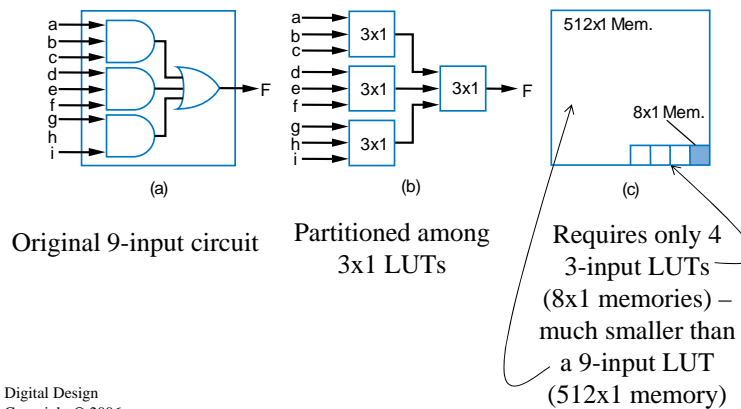


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## FPGA Internals: Lookup Tables (LUTs)

- Partitioning among smaller LUTs is more size efficient
  - Example: 9-input circuit

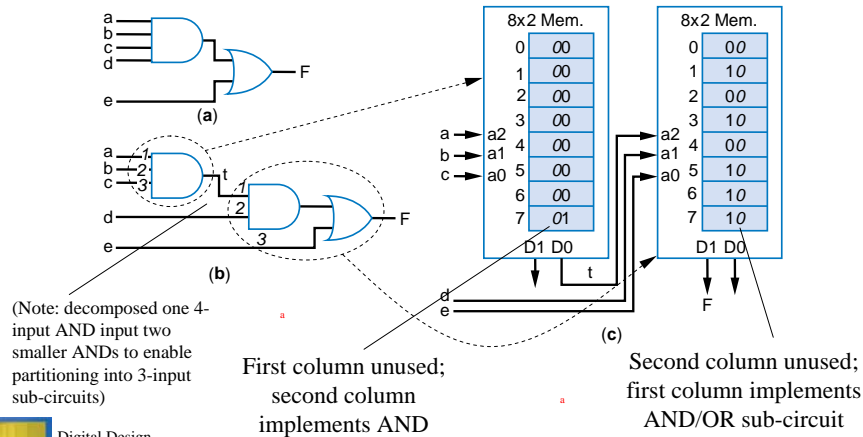


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## FPGA Internals: Lookup Tables (LUTs)

- LUT typically has 2 (or more) outputs, not just one
- Example: Partitioning a circuit among 3-input 2-output lookup tables

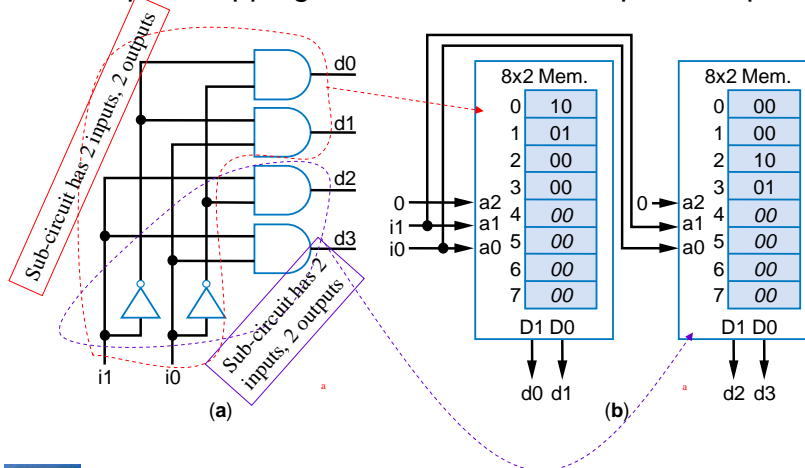


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## FPGA Internals: Lookup Tables (LUTs)

- Example: Mapping a 2x4 decoder to 3-input 2-output LUTs

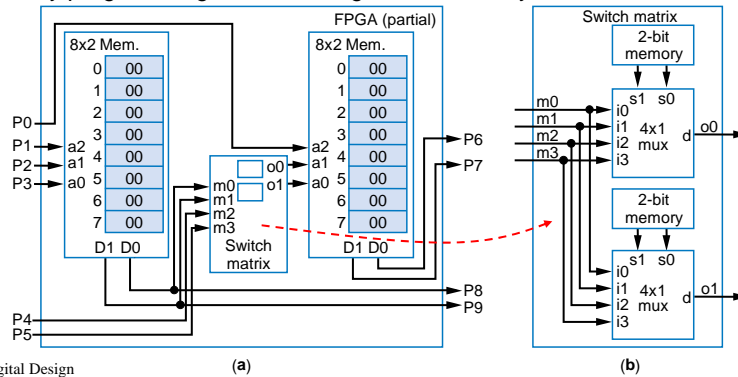


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## FPGA Internals: Switch Matrices

- Previous slides had hardwired connections between LUTs
- Instead, want to program the connections too
- Use switch matrices (also known as programmable interconnect)
  - Simple mux-based version – each output can be set to any of the four inputs just by programming its 2-bit configuration memory

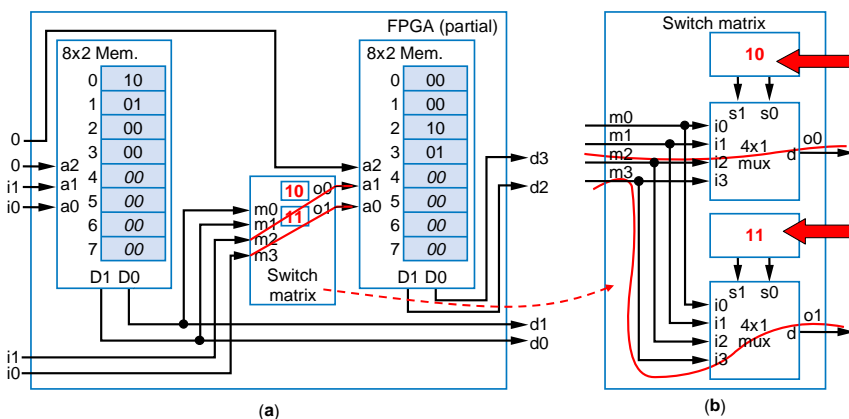


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## FPGA Internals: Switch Matrices

- Mapping a 2x4 decoder onto an FPGA with a switch matrix



These bits establish the desired connections

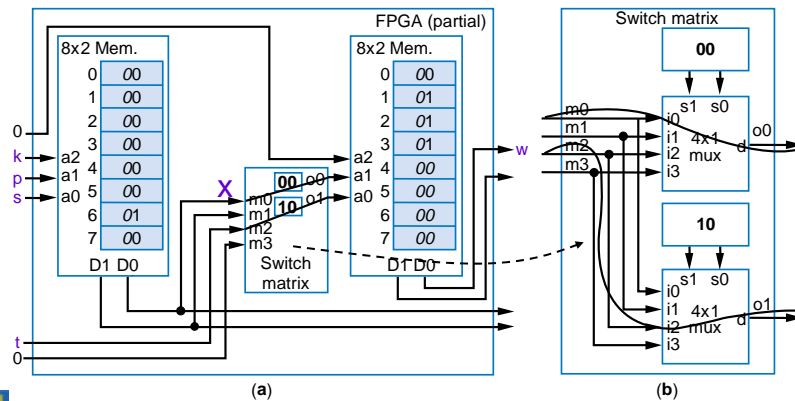
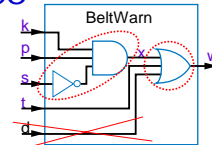


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## FPGA Internals: Switch Matrices

- Mapping the extended seatbelt warning light onto an FPGA with a switch matrix
  - Recall earlier example (let's ignore d input for simplicity)

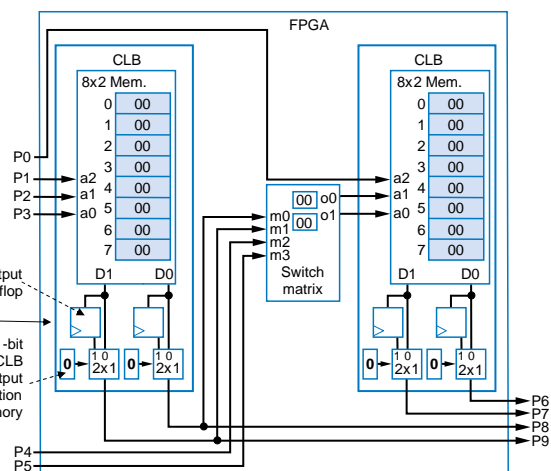


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## FPGA Internals: Configurable Logic Blocks (CLBs)

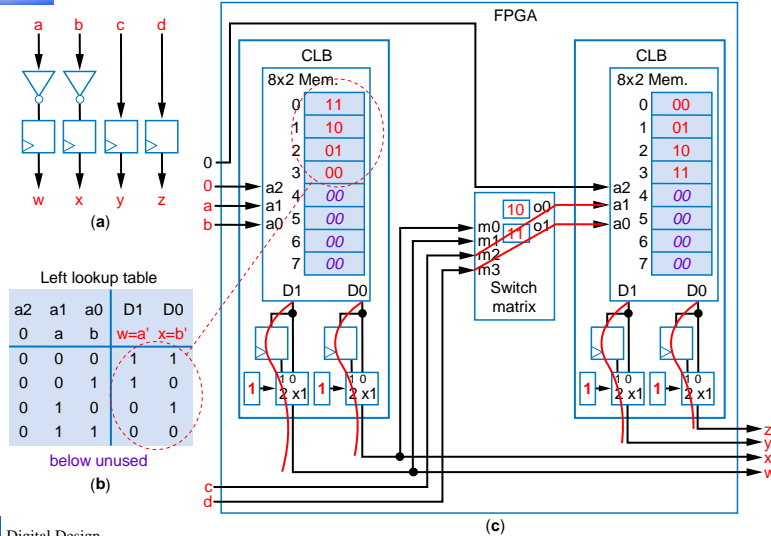
- LUTs can only implement combinational logic
- Need flip-flops to implement sequential logic
- Add flip-flop to each LUT output
  - Configurable Logic Block (CLB)
    - LUT + flip-flops
  - Can program CLB outputs to come from flip-flops or from LUTs directly



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## FPGA Internals: Sequential Circuit Example using CLBs



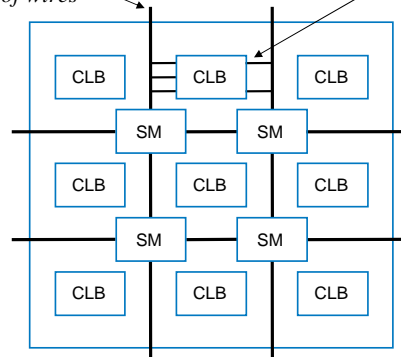
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## FPGA Internals: Overall Architecture

- Consists of hundreds or thousands of CLBs and switch matrices (SMs) arranged in regular pattern on a chip

Represents channel with tens of wires



Connections for just one CLB shown, but all CLBs are obviously connected to channels

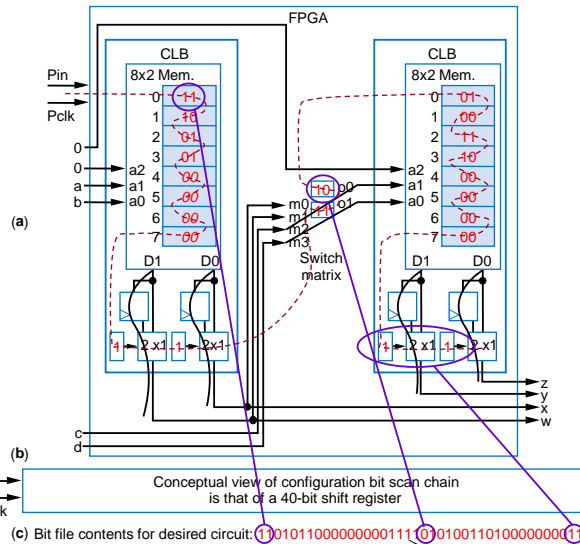


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## FPGA Internals: Programming an FPGA

- All configuration memory bits are connected as one big shift register
  - Known as scan chain
- Shift in "bit file" of desired circuit



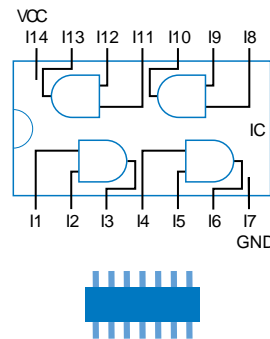
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*This isn't wrong. Although the bits appear as "10" above, note that the scan chain passes through those bits from right to left – so "01" is correct here.*

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## Other Technologies

- Off-the-shelf logic (SSI) IC
  - Logic IC has a few gates, connected to IC's pins
    - Known as Small Scale Integration (SSI)
  - Popular logic IC series: 7400
    - Originally developed 1960s
      - Back then, each IC cost \$1000
      - Today, costs just tens of cents



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