Evolution of Implementation Technologies

- Discrete devices: relays, transistors (1940s-50s)
- Discrete logic gates (1950s-60s)
- Integrated circuits (1960s-70s)
  - e.g. TTL packages: Data Book for 100’s of different parts
  - Map your circuit to the Data Book parts
- Gate Arrays (IBM 1970s)
  - "Custom" integrated circuit chips
  - Design using a library (like TTL)
  - Transistors are already on the chip
  - Place and route software puts the chip together automatically
  - + Large circuits on a chip
  - + Automatic design tools (no tedious custom layout)
  - - Only good if you want 1000’s of parts

Gate Array Technology (IBM - 1970s)

- Simple logic gates
  - Use transistors to implement combinational and sequential logic
- Interconnect
  - Wires to connect inputs and outputs to logic blocks
- I/O blocks
  - Special blocks at periphery for external connections
- Add wires to make connections
  - Done when chip is fabed
  - "mask-programmable"
  - Construct any circuit
Programmable Logic

- Disadvantages of the Data Book method
  - Constrained to parts in the Data Book
  - Parts are necessarily small and standard
  - Need to stock many different parts

- Programmable logic
  - Use a single chip (or a small number of chips)
  - Program it for the circuit you want
  - No reason for the circuit to be small

Programmable Logic Technologies

- Fuse and anti-fuse
  - Fuse makes or breaks link between two wires
  - Typical connections are 50-300 ohm
  - One-time programmable (testing before programming?)
  - Very high density

- EPROM and EEPROM
  - High power consumption
  - Typical connections are 2K-4K ohm
  - Fairly high density

- RAM-based
  - Memory bit controls a switch that connects/disconnects two wires
  - Typical connections are .5K-1K ohm
  - Can be programmed and re-programmed in the circuit
  - Low density
Programmable Logic

- Program a connection
  - Connect two wires
  - Set a bit to 0 or 1

- Regular structures for two-level logic (1960s-70s)
  - All rely on two-level logic minimization
  - PROM connections - permanent
  - EPROM connections - erase with UV light
  - EEPROM connections - erase electrically
  - PROMs
    - Program connections in the ____________ plane
  - PALs
    - Program the connections in the ____________ plane
  - PLAs
    - Program the connections in the ____________ plane

PAL Logic Building Block

- Programmable AND gates
- Fixed OR/NOR gate
- Flipflop/Registered Output
- Feedback to Array
- Tri-state
XOR PALs

- Useful for comparator logic, arithmetic sums, etc.
  - Use of XOR gates can dramatically reduce the number of AND plane inputs needed to realize certain functions.
Another Variation: Synchronous vs. Asynchronous Outputs

Making Large Programmable Logic Circuits

- Alternative 1: “CPLD”
  - Put a lot of PLDs on a chip
  - Add wires between them whose connections can be programmed
  - Use fuse/EEPROM technology

- Alternative 2: “FPGA”
  - Emulate gate array technology
  - Hence Field Programmable Gate Array
  - You need:
    - A way to implement logic gates
    - A way to connect them together
Field-Programmable Gate Arrays

- PALs, PLAs = 10s - 100s Gate Equivalents
- Field Programmable Gate Arrays = FPGAs
  - Altera MAX Family
  - Actel Programmable Gate Array
  - Xilinx Logical Cell Array
- 1000s - 100000(s) of Gate Equivalents!

Field-Programmable Gate Arrays

- Logic blocks
  - To implement combinational and sequential logic
- Interconnect
  - Wires to connect inputs and outputs to logic blocks
- I/O blocks
  - Special logic blocks at periphery of device for external connections

Key questions:
- How to make logic blocks programmable?
- How to connect the wires?
- After the chip has been fabbed
Tradeoffs in FPGAs

- Logic block - how are functions implemented: fixed functions (manipulate inputs) or programmable?
  - Support complex functions, need fewer blocks, but they are bigger so less of them on chip
  - Support simple functions, need more blocks, but they are smaller so more of them on chip

- Interconnect
  - How are logic blocks arranged?
  - How many wires will be needed between them?
  - Are wires evenly distributed across chip?
  - Programmability slows wires down - are some wires specialized to long distances?
  - How many inputs/outputs must be routed to/from each logic block?
  - What utilization are we willing to accept? 50%? 20%? 90%?

Altera EPLD (Erasable Programmable Logic Devices)

- Historical Perspective
  - PALs: same technology as programmed once bipolar PROM
  - EPLDs: CMOS erasable programmable ROM (EPROM) erased by UV light

- Altera building block = MACROCELL

![Diagram of Altera EPLD](attachment:altera_epld_diagram.png)
Altera EPLD: Synchronous vs. Asynchronous Mode

Altera EPLDs contain 10s-100s of independently programmed macrocells

Personalized by EPROM bits:

Synchronous Mode
- Flipflop controlled by global clock signal
- Local signal computes output enable

Asynchronous Mode
- Flipflop controlled by locally generated clock signal

+ Seq Logic: could be D, T positive or negative edge triggered
+ Product term to implement clear function

Altera Multiple Array Matrix (MAX)

AND-OR structures are relatively limited
Cannot share signals/product terms among macrocells

Global Routing: Programmable Interconnect Array

EPM5128:
- 8 Fixed Inputs
- 52 I/O Pins
- 8 LABs
- 16 Macrocells/LAB
- 32 Expanders/LAB
LAB Architecture

Expander Terms shared among all macrocells within the LAB
- Efficient way to use AND plane resources

P22V10 PAL

Supports large number of product terms per output
Latches and muxes associated with output pins
Actel Programmable Gate Arrays

Rows of programmable logic building blocks

+ rows of interconnect

Anti-fuse Technology: Program Once

Use Anti-fuses to build up long wiring runs from short segments

8 input, single output combinational logic blocks
FFs constructed from discrete cross coupled gates

Actel Programmable Gate Arrays

Actel Logic Module

Basic Module is a Modified 4:1 Multiplexer

Example: Implementation of S-R Latch
Actel Interconnect

Interconnection Fabric

Actel Routing Example

Jogs cross an anti-fuse

minimize the # of jogs for speed critical circuits

2 - 3 hops for most interconnections
Actel's Next Generation: Axcelerator

C-Cell
- Basic multiplexer logic plus more inputs and support for fast carry calculation
- Carry connections are “direct” and do not require propagation through the programmable interconnect

Actel’s Next Generation: Accelerator

R-Cell
- Core is D flip-flop
- Muxes for altering the clock and selecting an input
- Feed back path for current value of the flip-flop for simple hold
- Direct connection from one C-cell output of logic module to an R-cell input; Eliminates need to use the programmable interconnect

Interconnection Fabric
- Partitioned wires
- Special long wires
Xilinx Programmable Gate Arrays

- CLB - Configurable Logic Block
  - 5-input, 1 output function
  - or 2 4-input, 1 output functions
  - optional register on outputs
- Built-in fast carry logic
- Can be used as memory
- Three types of routing
  - direct
  - general-purpose
  - long lines of various lengths
- RAM-programmable
  - can be reconfigured

Programmable Interconnect

I/O Blocks (IOBs)

Configurable Logic Blocks (CLBs)
The Xilinx 4000 CLB

Figure 1: Simplified Block Diagram of XC4000 Series CLB (RAM and Carry Logic functions not shown)

Two 4-input functions, registered output

Figure 1: Simplified Block Diagram of XC4000 Series CLB (RAM and Carry Logic functions not shown)
5-input function, combinational output

Figure 1: Simplified Block Diagram of XC4000 Series CLB (RAM and Carry Logic functions not shown)

CLB Used as RAM

Figure 4: 16x2 (or 16x1) Edge-Triggered Single-Port RAM
Fast Carry Logic

Xilinx 4000 Interconnect

Figure 28: Single- and Double-Length Lines, with Programmable Switch Matrices (PSMs)
Switch Matrix

Figure 26: Programmable Switch Matrix (PSM)

Xilinx 4000 Interconnect Details
Global Signals - Clock, Reset, Control

Xilinx 4000 IOB
Xilinx FPGA Combinational Logic Examples

- Key: General functions are limited to 5 inputs
  - (4 even better - 1/2 CLB)
  - No limitation on function complexity

- Example
  - 2-bit comparator:
    \[ A \cdot B = C \cdot D \text{ and } A \cdot B > C \cdot D \text{ implemented with 1 CLB} \]
    \[ (GT) \quad F = A \cdot C' + A \cdot B \cdot D' + B \cdot C' \cdot D' \]
    \[ (EQ) \quad G = A' \cdot B \cdot C' \cdot D' + A' \cdot B \cdot C \cdot D + A \cdot B' \cdot C' \cdot D' + A \cdot B \cdot C \cdot D \]

- Can implement some functions of > 5 input

Xilinx FPGA Combinational Logic

- Examples
  - N-input majority function: 1 whenever \( n/2 \) or more inputs are 1
  - N-input parity functions: 5 input/1 CLB; 2 levels yield 25 inputs!
Xilinx FPGA Adder Example

**Example**

- 2-bit binary adder - inputs: A1, A0, B1, B0, CIN
- outputs: S0, S1, Cout

![Adder Diagram]

Full Adder, 4 CLB delays to final carry out

2 x Two-bit Adders (3 CLBs each) yields 2 CLBs to final carry out

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Xilinx Vertex-II Family

- 88-1000+ pins
- 64-10000+ CLBs
  - Combinational and sequential logic using lookup tables and flip-flops
  - Random-access memory
  - Shift registers for use as buffer storage
- Multipliers regularly placed throughout the CLB array to accelerate digital signal processing applications
- E.g., the XC2V8000: 11,648 CLBs, 1108 IOBs, 90,000+ FFs, 3Mbits RAM (168 x 18Kbit blocks), 168 multipliers
  - Equivalent to eight million two-input gates!
Xilinx Vertex-II Family IOB

- Tri-state/bidirectional driver
- Registers for each of three signals involved: input, output, tri-state enable.
- Two registers to latch values with separate clocks.
- For large pinouts, separate clocks stagger signals changes to avoid large current spikes.
- FFs used for synchronization as well as latching.

Xilinx Vertex-II Family CLB

- Four basic slices in two groups
- Each has a fast carry-chain
- Local interconnect to wire logic of each slice and connect to the CLB array: switch matrix is large collection of programmable switches.
Xilinx Vertex-II Family CLB Internals

- Just _ of one slice!
- 4-input LUT + FF
- Fast carry logic
- Many programmable interconnections for sync vs. async operation

Xilinx Vertex-II Family Fast Carry Logic

\[(A \oplus B)C_i + AB\]

<table>
<thead>
<tr>
<th></th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Xilinx Vertex-II Family CLB

- Sequential Portion
  - Two positive edge-triggered flip-flops
  - Transparent latches or flip-flops
  - Asynchronous or synchronous sets and resets
  - Initialize to different values at power-up
  - Clocks and load enables complemented or not

Xilinx Vertex-II Family Slice Personality

- 4-input function generator
- OR 16 bits of dual-ported random-access memory (with separate address inputs for read - G1 to G4 - and write - WG1 to WG4)
- OR a 16-bit variable-tap shift register
- With muxes, CLB can implement any function of 8 inputs and some functions of 9 inputs
- Registered and unregistered versions of function block outputs
## Xilinx Vertex-II Family Interconnections

- **Methods of interconnecting CLBs and IOBs:**
  1. Direct fast connections within a CLB
  2. Direct-connections between adjacent CLBs
  3. Double-lines to fanout signals to CLBs one or two away
  4. Hex lines to connect to CLBs three or six away
  5. Long lines that span the entire chip

- **Fast access to neighbors:** vertically and horizontally with direct connections
- **Double and hex lines provide a slightly larger range**
- **Long lines saved for time-critical signals with min signal skew**

<table>
<thead>
<tr>
<th>Interconnections</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 Horizontal Long Lines</td>
<td><img src="image1.png" alt="Diagram 1" /></td>
</tr>
<tr>
<td>24 Vertical Long Lines</td>
<td><img src="image2.png" alt="Diagram 2" /></td>
</tr>
<tr>
<td>120 Horizontal Hex Lines</td>
<td><img src="image3.png" alt="Diagram 3" /></td>
</tr>
<tr>
<td>120 Vertical Hex Lines</td>
<td><img src="image4.png" alt="Diagram 4" /></td>
</tr>
<tr>
<td>40 Horizontal Double Lines</td>
<td><img src="image5.png" alt="Diagram 5" /></td>
</tr>
<tr>
<td>40 Vertical Double Lines</td>
<td><img src="image6.png" alt="Diagram 6" /></td>
</tr>
<tr>
<td>16 Direct Connections (total in all four directions)</td>
<td><img src="image7.png" alt="Diagram 7" /></td>
</tr>
<tr>
<td>8 Fast Connects</td>
<td><img src="image8.png" alt="Diagram 8" /></td>
</tr>
</tbody>
</table>

## Programmable Logic Summary

- **Discrete Gates**
- **Packaged Logic**
- **PLAs**
- **Ever more general architectures of programmable combinational + sequential logic and interconnect**
  - Altera
  - Actel
  - Xilinx—4000 series to Vertex
    - CLBs implementing logic function generators, RAMs, Shift registers, fast carry logic
    - Local, inter-CLB, and long line interconnections