

## Design of Digital Circuits

EE4143 Design of Digital Circuits

## What is this course is about?

- **Design of digital microelectronic circuits.**
  - » CMOS devices and manufacturing technology.
  - » Digital gates. Propagation delay, noise margins, and power dissipation.
  - » Programmable logic arrays and FPGAs.
  - » Microelectronic circuits, simulation, verification, and specification.
  - » Structural design concepts, design tools.
  - » VHDL language, data types, objects, operators, control statements, concurrent statements, functions, and procedures.
  - » VHDL modeling techniques, algorithmic, RTL, and gate level designs.

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## What is this course is about?

- **Design of digital microelectronic circuits.**
  - » VLSI fabrication process.
  - » Design rules, Design synthesis, Logic design.
  - » Performance estimation, chip engineering.
  - » Emphasis on virtual prototyping, circuit design, optimization, verification, and testing.
- **What will you learn?**
  - » Understanding, designing, and optimizing digital circuits with respect to different quality metrics: cost, speed, power dissipation, and reliability
  - » Hardware programming language
  - » Behavioral and structural design concepts
  - » Design benchmarking and test.

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## Digital Integrated Circuits

- What is meant by VLSI?
- Brief history of evolution
- Today's Chips
- Moore's Law
- Digital circuit applications
- Design challenges
- Machines Making Machines



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## What is a VLSI Circuit?


<p><u>VERY LARGE SCALE</u></p> <p>↓</p> <p>A circuit that has 10k ~ 1Bln transistors on a single chip</p> <ul style="list-style-type: none"> <li>• Still growing as number of transistors on chip quadruple every 24 months (Moore's law!)</li> </ul>	<p><u>INTEGRATED CIRCUIT</u></p> <p>↓</p> <p>Technique where many circuit components and the wiring that connects them are manufactured simultaneously on a compact chip (die)</p>
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[Adapted from Rabaey's *Digital Integrated Circuits*, ©2002, J. Rabaey et al.]

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## Brief History

### The First Computer: Babbage Difference Engine (1832)



- Executed basic operations (add, sub, mult, div) in arbitrary sequences
- Operated in two-cycle sequence, "Store", and "Mill" (execute)
- Included features like pipelining to make it faster.
- Complexity: 25,000 parts.
- Cost: £17,470 (in 1834!)

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## The Electrical Solution

- More cost effective
  - Early systems used relays to make simple logic devices
  - Still used today in some train safety systems
- The Vacuum Tube
  - Originally used for analog processing
  - Later, complete digital computers realized

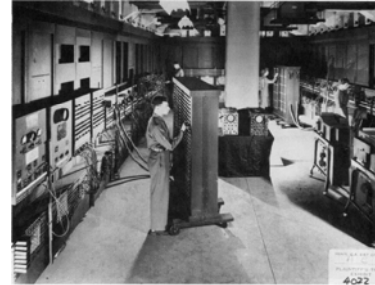
High Point of Tubes: The ENIAC

- 18,000 vacuum tubes
- 80 ft long, 8.5 ft high, several feet wide

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## ENIAC - The first electronic computer (1946)



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## Dawn of the Transistor Age



1947: Bardeen and Brattain create point-contact transistor w/two PN junctions. Gain = 18

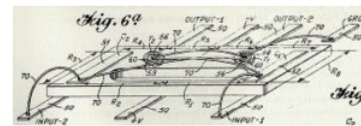
1951: Shockley develops junction transistor which can be manufactured in quantity.



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## Early Integration



Jack Kilby, working at Texas Instruments, invented a monolithic "integrated circuit" in July 1959.

He had constructed the flip-flop shown in the patent drawing above.

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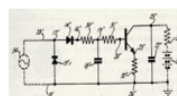


## Early Integration



In mid 1959, Noyce develops the first true IC using planar transistors,

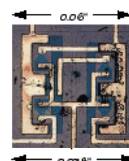
- back-to-back pn junctions for isolation
- diode-isolated silicon resistors and
- SiO<sub>2</sub> insulation
- evaporated metal wiring on top



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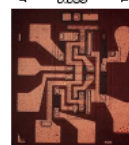


## Practice Makes Perfect



1961: TI and Fairchild introduced first logic IC's

(cost ~ \$50 in quantity!). This is a dual flip-flop with 4 transistors.

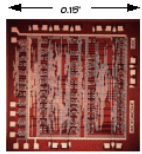


1963: Densities and yields improve. This circuit has four flip-flops.

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## Practice Makes Perfect



1967: Fairchild markets the first semi-custom chip. Transistors (organized in columns) can be easily rewired to create different circuits. Circuit has ~150 logic gates.

1968: Noyce and Moore leave Fairchild to form Intel. By 1971 Intel had 500 employees;

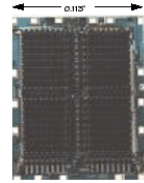
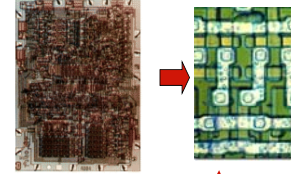
By 2004, 80,000 employees in 55 countries and \$34.2B in sales.

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## The Big Bang

1970: Intel starts selling a 1k bit RAM, the 1103.

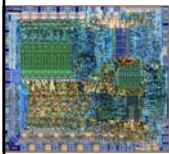


1971: Ted Hoff at Intel designed the first microprocessor. The 4004 had 4-bit busses and a clock rate of 108 KHz. It had 2300 transistors and was built in a 10 um process.

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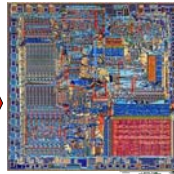
## Exponential Growth



1972: 8080 introduced. Had 3,500 transistors supporting a byte-wide data path.

1974: Introduction of the 8088.

Had 6,000 transistors in a 6 um process. The clock rate was 2 MHz.



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## Today

Many disciplines have contributed to the current state of the art in VLSI Design:

- Solid State Physics
- Materials Science
- Lithography and fab
- Device modeling
- Circuit design and layout
- Architecture design
- Algorithms
- CAD tools

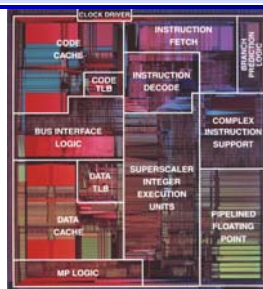
To come up with chips like:

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## Intel Pentium

- Intel® Pentium® 4
- Intel® Celeron® D
- Intel® Pentium® M
- Intel® Itanium® 2
- Intel® Xeon™
- Intel® PCA Cellular
- Intel® IXP465 Network
- Intel® MXP5800 Digital Media

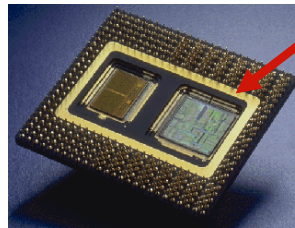


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## Pentium Pro

• Actually a MCM comprising of microprocessor and L2 cache



Why not make it on one chip?

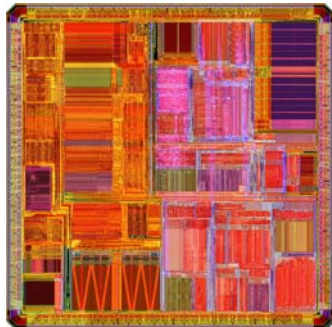
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## Today

Sun UltraSparc

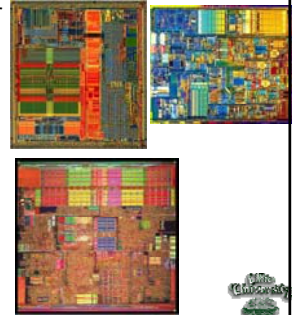
UltraSPARC IV  
UltraSPARC III  
UltraSPARC IIIi  
UltraSPARC IIi  
UltraSPARC IIe



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## Pentium 4

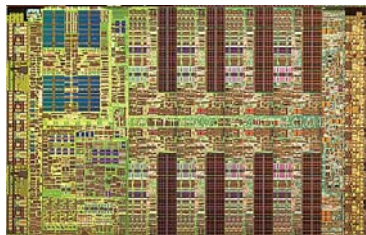
- » Introduction date: November 20, 2000
  - 1.4 GHz clock
  - fabricated in 180 nm process,
  - 42 mln transistors
- » In 2002 (2 GHz in 130 nm, 55 mln transistors)
- » **In 2005 (3.8 GHz in 90 nm, 125 mln transistors)**
- » Typical Use: Desktops and entry-level workstations



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## Supercomputer for Sony's PlayStation 3

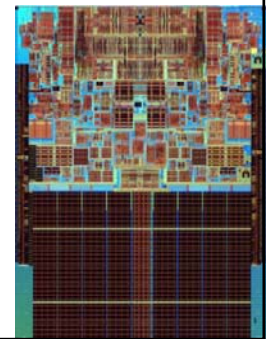
- IBM chip has nine processor cores
- 192 billion floating-point operations per second (192 G)
- Typical Use: multimedia



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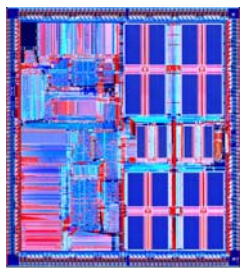
## Intel Core 2 Microprocessor

- In 2006
- 143 mm<sup>2</sup>
- 3 GHZ operation
- 65 nm CMOS technology
- 291 mln transistors



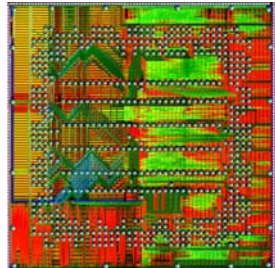
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## Other chips



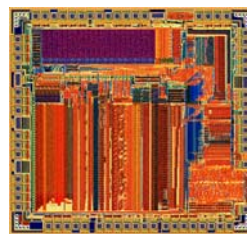
IDT R5000

EE4143 Design of Digital Circuits from <http://micro.magnet.fsu.edu/chipshots/index.html>

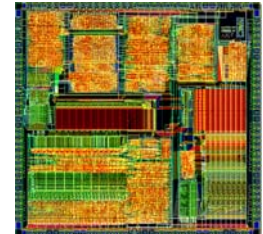


IBM Power PC 601

## Other chips



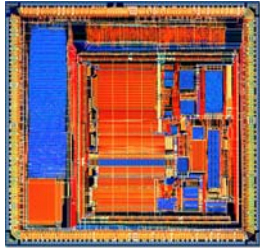
cyrix\_math\_coprocessor\_83587



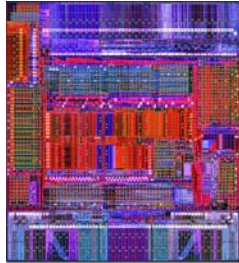
Fairchild Clipper C100

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## Other chips



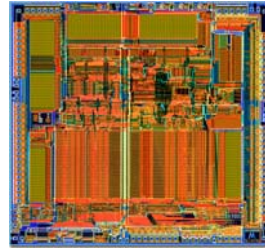
Fujitsu 68903



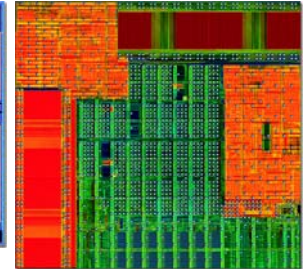
HP PA8000

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## Other chips



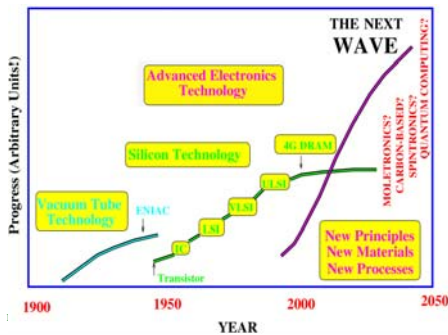
Motorola MC68020



IBM/Motorola Power PC620

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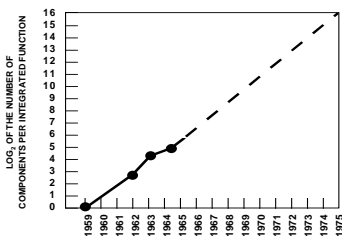
## Evolution of Electronics



## Moore's Law

- In 1965, Gordon Moore noted that the number of transistors on a chip doubled every 12 months.
- He made a prediction that semiconductor technology will double its effectiveness every 18 months

## Moore's Law



Electronics, April 19, 1965.

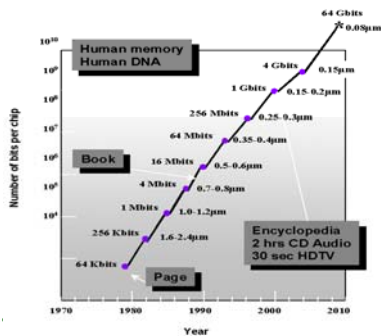
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## Technology Directions: SIA Roadmap

Year	1999	2002	2005	2008	2011	2014
Feature size (nm)	180	130	100	70	50	35
Logic trans/cm <sup>2</sup>	6.2M	18M	39M	84M	180M	390M
Cost/trans (mc)	1.735	.580	.255	.110	.049	.022
#pads/chip	1867	2553	3492	4776	6532	8935
Clock (MHz)	1250	2100	3500	6000	10000	16900
Chip size (mm <sup>2</sup> )	340	430	520	620	750	900
Wiring levels	6-7	7	7-8	8-9	9	10
Power supply (V)	1.8	1.5	1.2	0.9	0.6	0.5
High-perf pow (W)	90	130	160	170	175	183

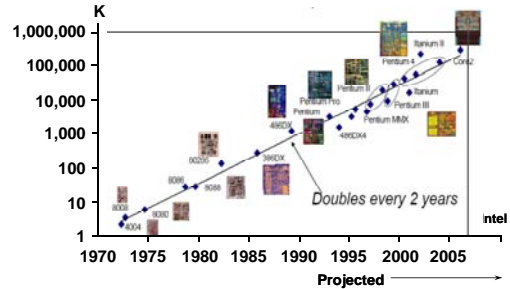
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## Evolution in Complexity



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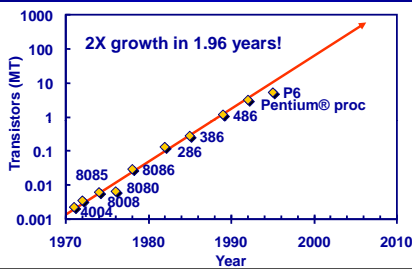
## Transistor Counts



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Courtesy, Intel

## Moore's law in Microprocessors

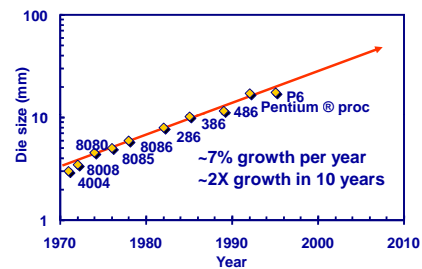


Transistors on Lead Microprocessors double every 2 years

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Courtesy, Intel

## Die Size Growth

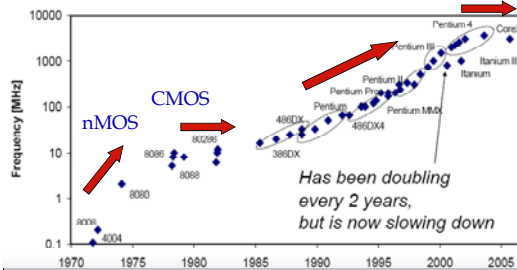


Die size grows by 14% to satisfy Moore's Law

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Courtesy, Intel

## Frequency

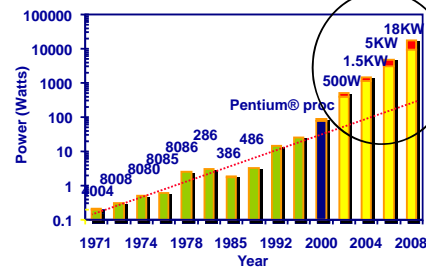


Lead Microprocessors frequency doubles every 2 years

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Courtesy, Intel

## Power dissipation warning in 2000

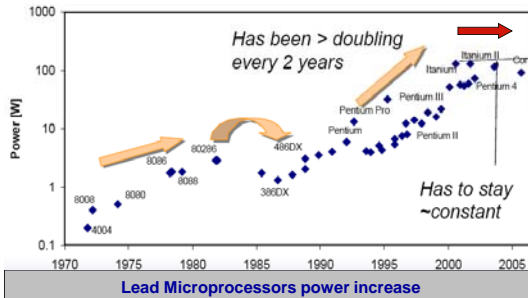


Did this really happen?

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Courtesy, Intel

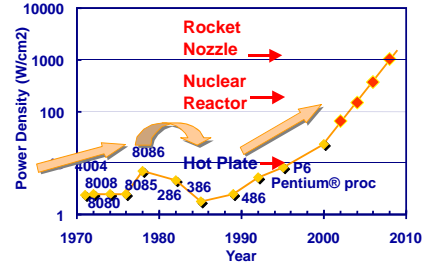
## Power Dissipation



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Courtesy, Intel

## Power density



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Courtesy, Intel

## Not Only Microprocessors



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## Challenges in Digital Design

### "Microscopic Problems"

- Ultra-high speed design
- Interconnect
- Noise, Crosstalk
- Reliability, Manufacturability
- Power Dissipation
- Clock distribution.

Everything Looks a Little Different



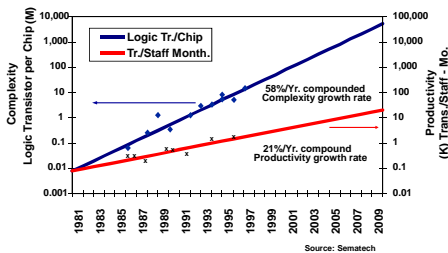
### "Macroscopic Issues"

- Time-to-Market
- Millions of Gates
- High-Level Abstractions
- Reuse & IP: Portability
- Predictability
- etc.

...and There's a Lot of Them!

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## Productivity Trends



Complexity outpaces design productivity

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Courtesy, ITRS Roadmap

## Definitions

- Wafer – a thin circular silicon
- Each wafer holds hundreds of dies
- Transistors and wiring are made from many layers (usually 10 – 15) built on top of one another
  - » the first half-dozen or so layers define transistors
  - » the second define the metal wires between transistors
- Lambda ( $\lambda$ ) – the smallest resolvable feature size imprinted on the IC; it is roughly half the length of the smallest transistor
  - » 0.2 $\mu$ m IC – the smallest transistors are approximately 0.2 $\mu$ m in length ( $\lambda = 0.1\mu$ m)



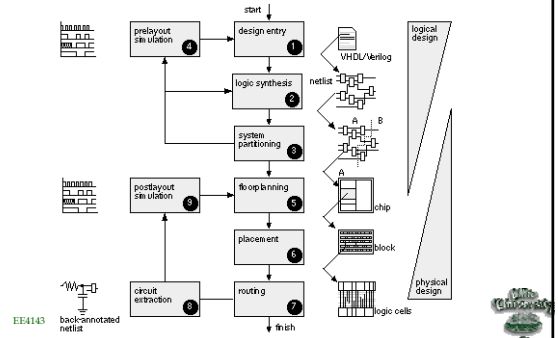
## Why Scaling?

- Technology shrinks by 0.7/generation
- With every generation can integrate 2x more functions per chip for about the same \$/chip
- Cost of a function decreases by 2x
- But ...
  - » How to design chips with more and more functions?
  - » Design engineering population does not double every two years...
- Hence, a need for more efficient design methods
  - » Exploit different levels of abstraction

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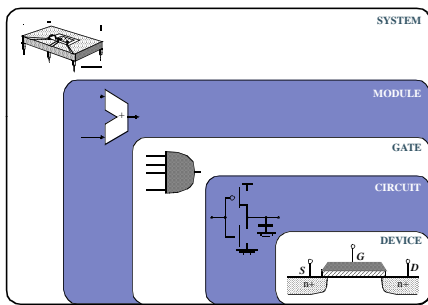
## Design Flow



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## Design Abstraction Levels



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