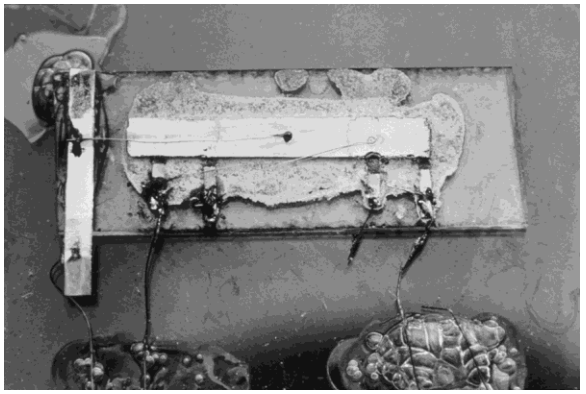
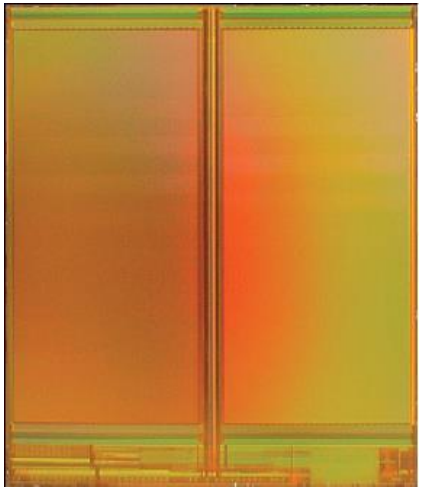
A Brief History

- 1958: First integrated circuit
  - Flip-flop using two transistors
  - Built by Jack Kilby at Texas Instruments
- 2010
  - Intel Core i7 μprocessor
    - » 2.3 billion transistors
  - 64 Gb Flash memory
    - » > 16 billion transistors



Courtesy Texas Instruments



[Trinh09]

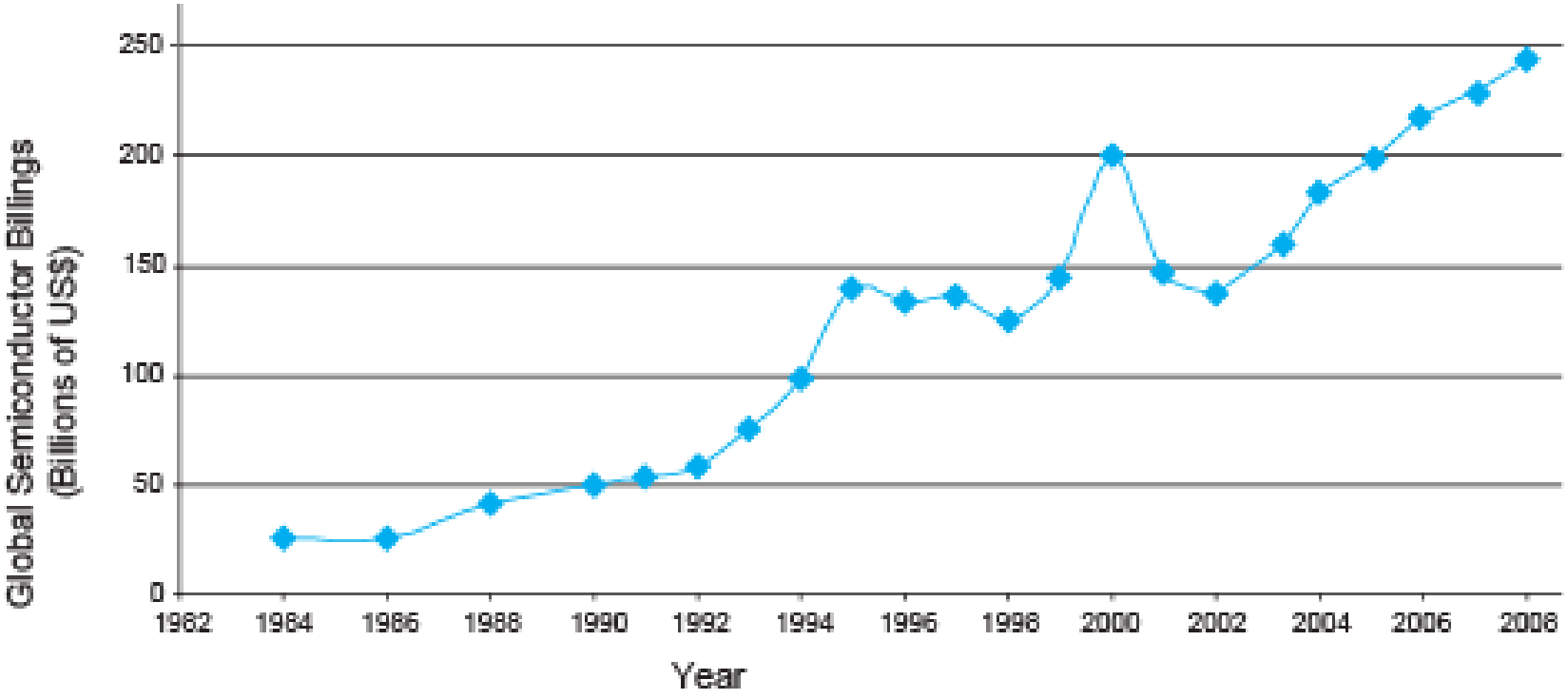
Growth Rate

- 53% compound annual growth rate over 50 years
  - No other technology has grown so fast so long
- Driven by miniaturization of transistors

[Moore65]
Electronics Magazine

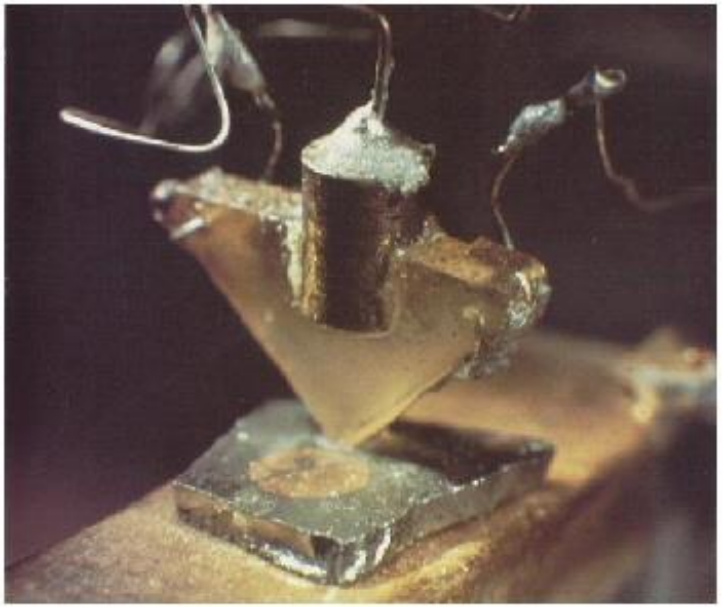
Annual Sales

- $>10^{19}$ transistors manufactured in 2008
  - 1 billion 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
  - See *Crystal Fire*
    by Riordan, Hoddeson



AT&T Archives.
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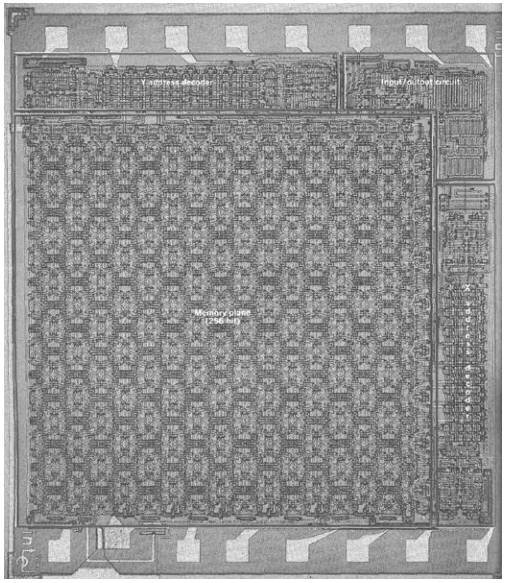
Transistor Types

- 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

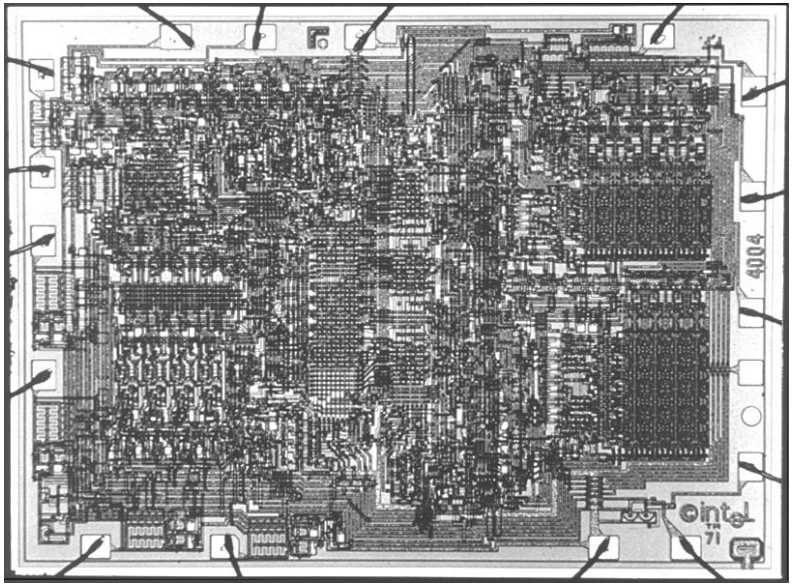
MOS Integrated Circuits

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



[Vadasz69]

Intel 1101 256-bit SRAM



Intel Museum.

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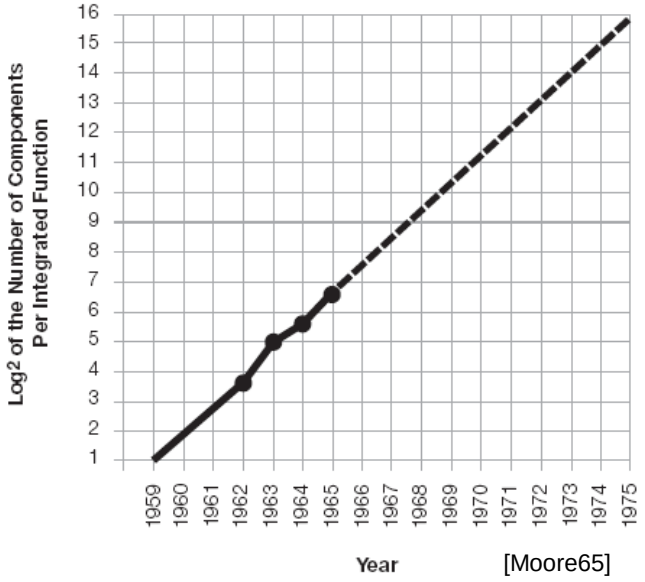
Intel 4004 4-bit μProc

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

Moore's Law: Then

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



[Moore65]
Electronics Magazine

Integration Levels

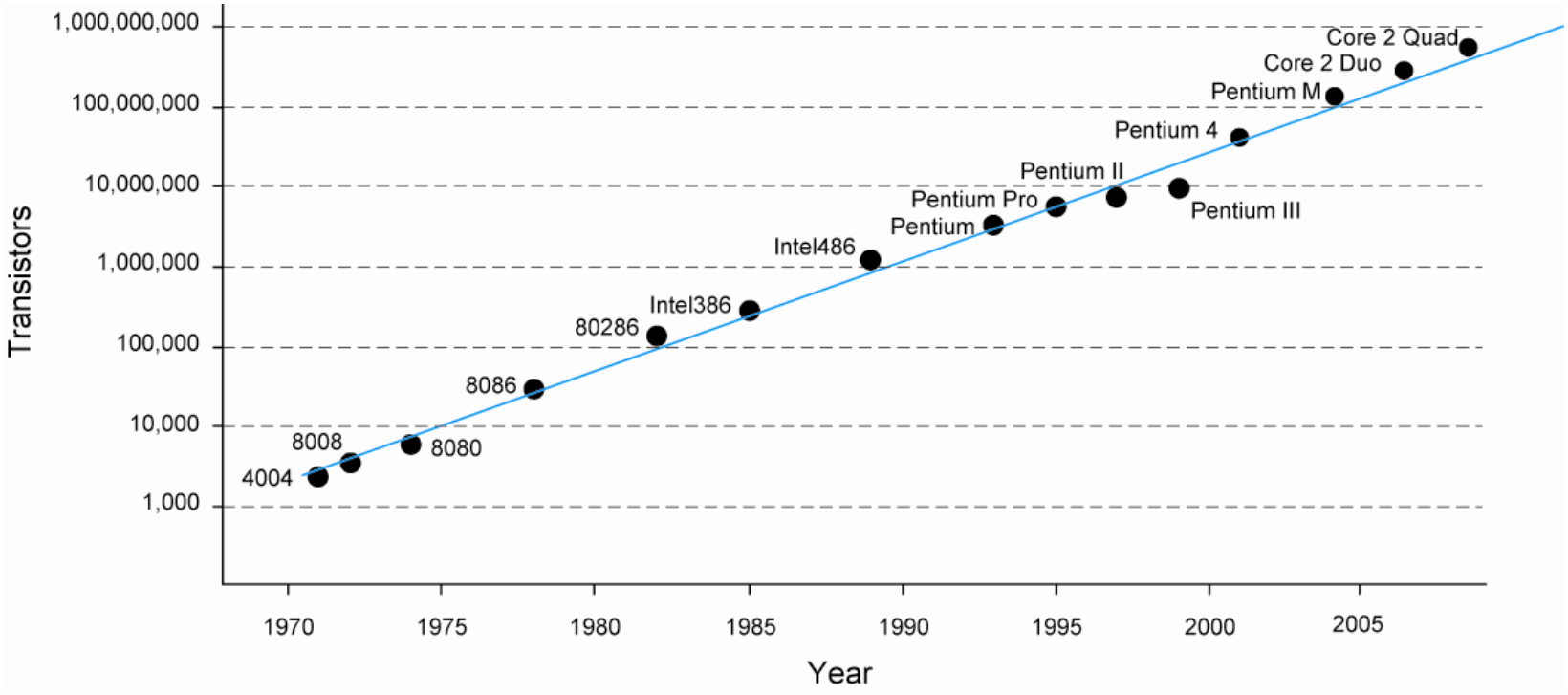
SSI: 10 gates

MSI: 1000 gates

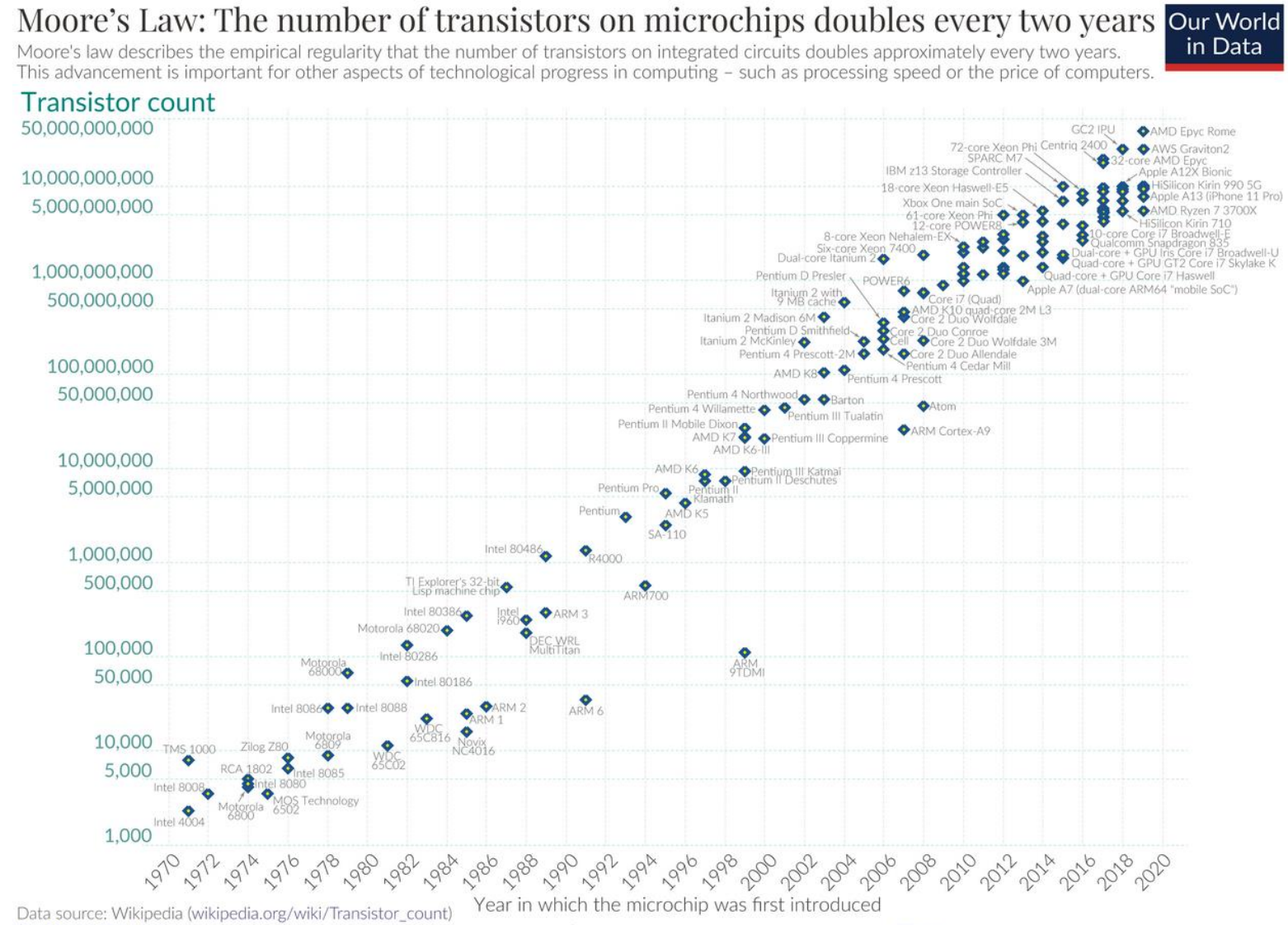
LSI: 10,000 gates

VLSI: > 10k gates

Fifteen years back…



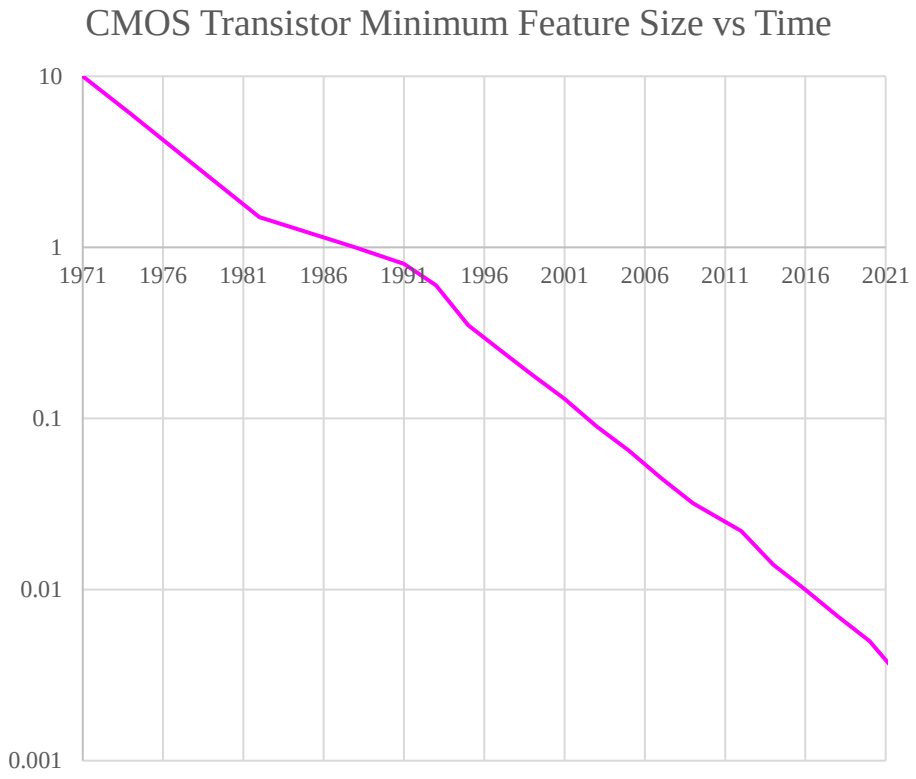
And Now…



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems.

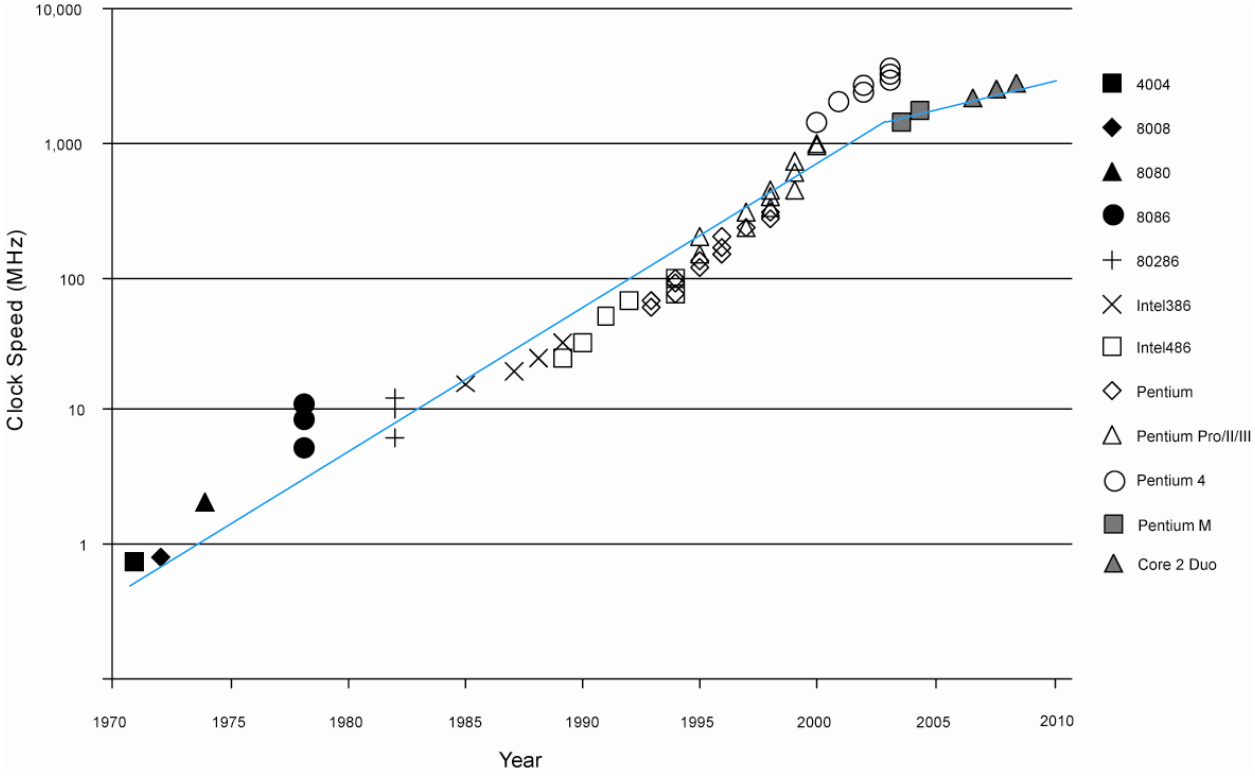
Feature Size

- Minimum feature size shrinking 30% every 2-3 years: Feature size in μm.



Corollaries

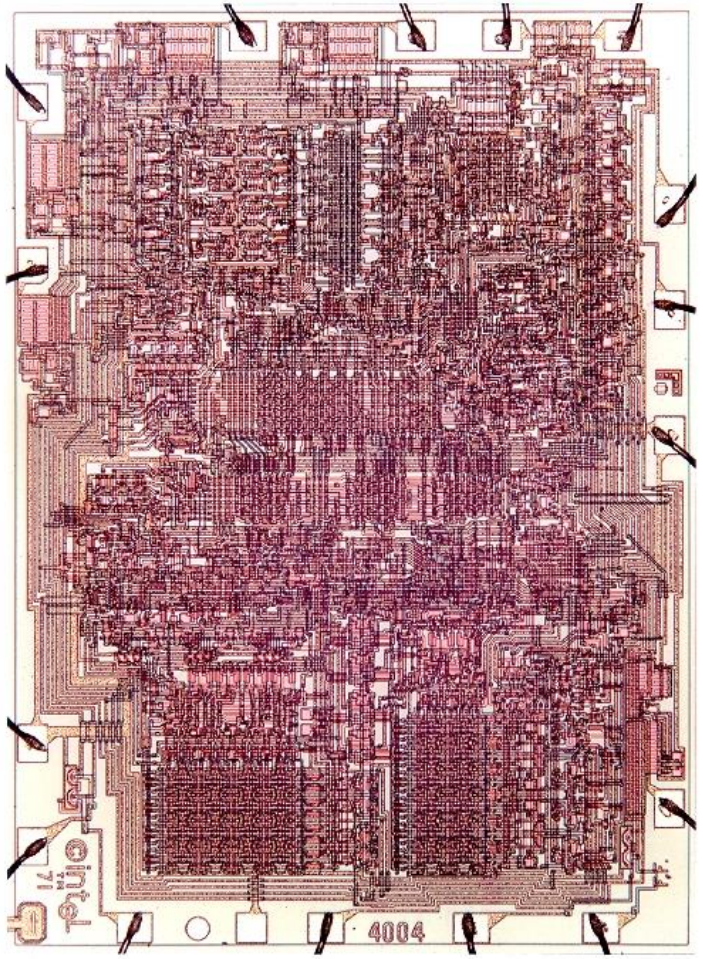
- Many other factors grow exponentially
  - Ex: clock frequency, processor performance



4004

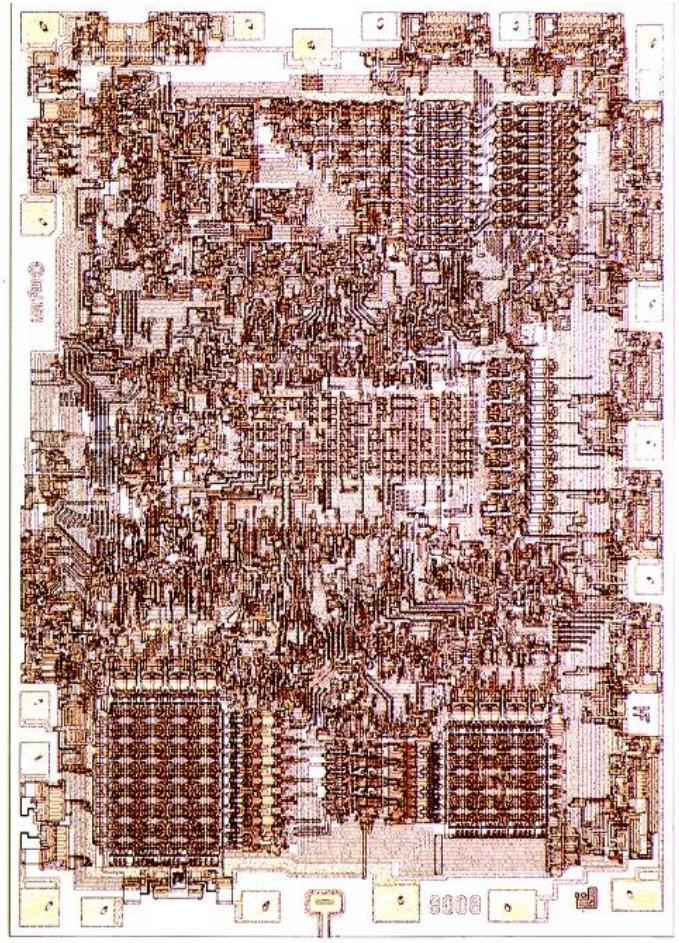
- First microprocessor (1971)
  - For Busicom calculator
- Characteristics
  - 10 μm process
  - 2300 transistors
  - 400 – 800 kHz
  - 4-bit word size
  - 16-pin DIP package

  (Dual Inline Package)
- Masks hand cut from Rubylith
  - Drawn with color pencils
  - 1 metal, 1 poly (jumpers)
  - Diagonal lines (!)



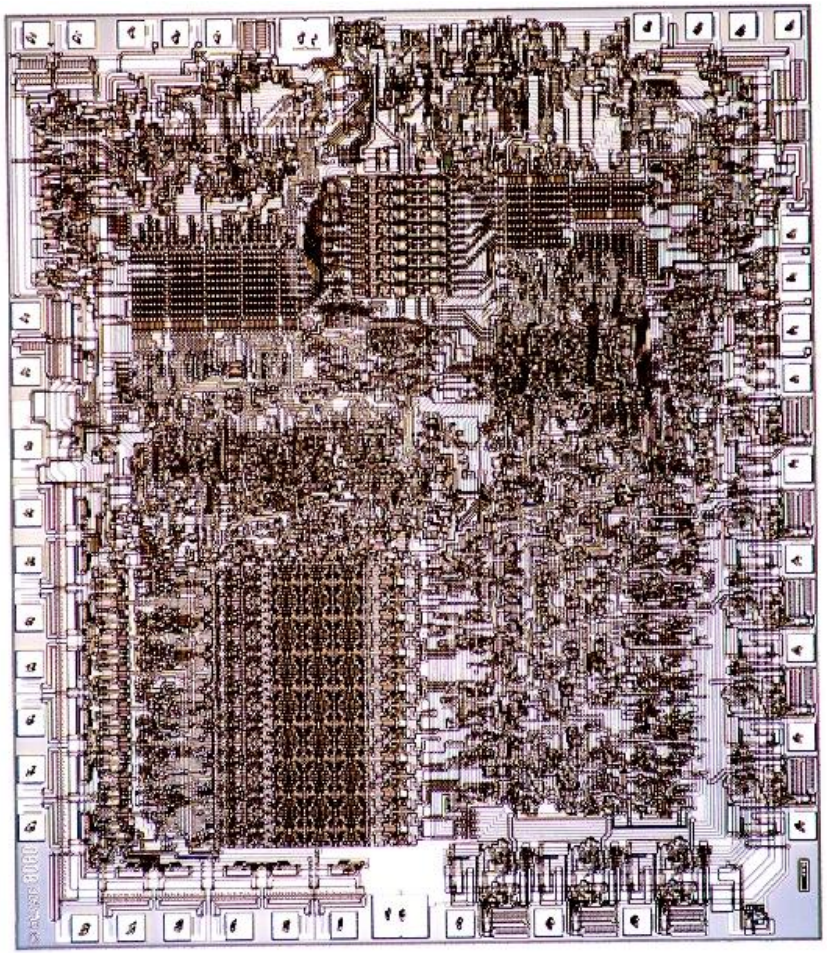
8008

- 8-bit follow-on (1972)
  - Dumb terminals
- Characteristics
  - 10 μm process
  - 3500 transistors
  - 500 – 800 kHz
  - 8-bit word size
  - 18-pin DIP package
- Note 8-bit datapaths
  - Individual transistors visible



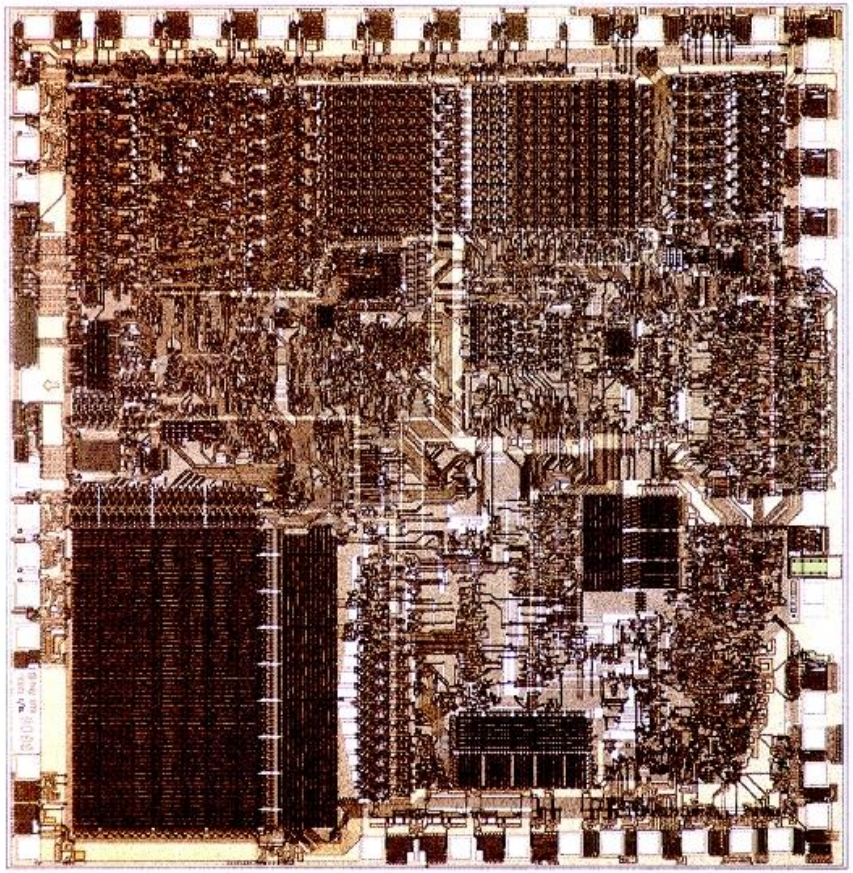
8080

- 16-bit address bus (1974)
  - Used in Altair computer
    - » (early hobbyist PC)
- Characteristics
  - 6 μm process
  - 4500 transistors
  - 2 MHz
  - 8-bit word size
  - 40-pin DIP package



8086 / 8088

- 16-bit processor (1978-9)
  - IBM PC and PC XT
  - Revolutionary products
  - Introduced x86 ISA
- Characteristics
  - 3 μm process
  - 29k transistors
  - 5-10 MHz
  - 16-bit word size
  - 40-pin DIP package
- Microcode ROM

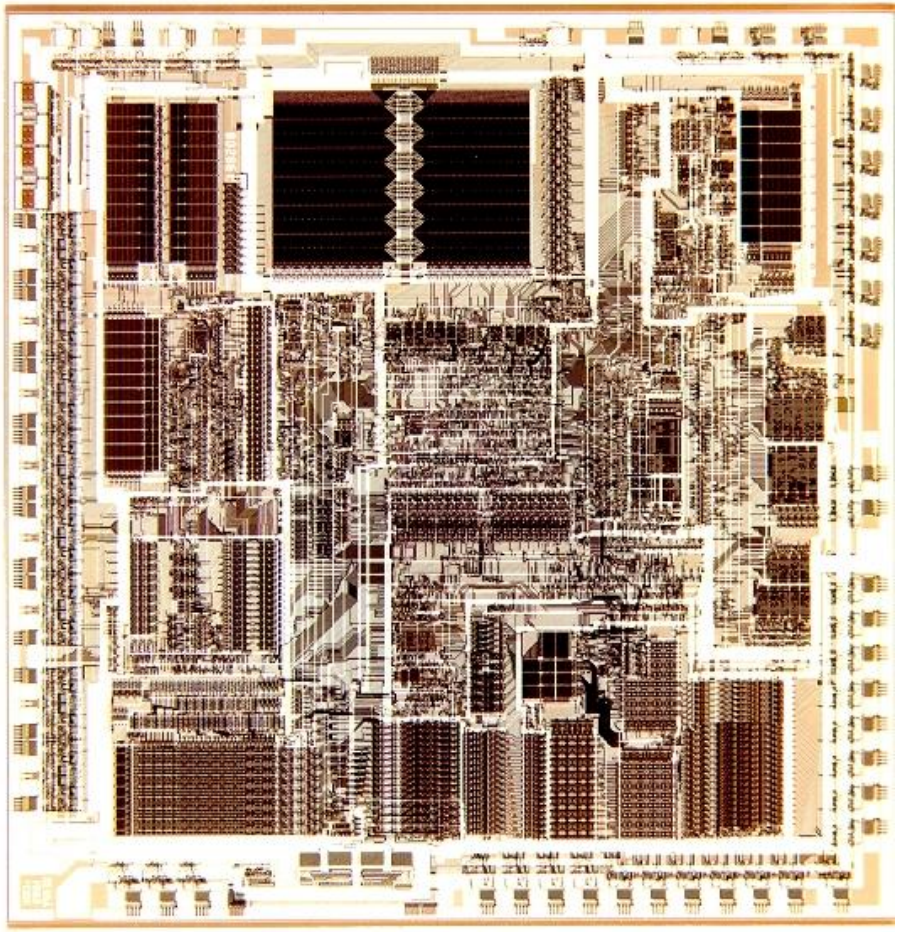


translates machine instructions, state machine data, or other input into sequences of detailed circuit-level operations.

80286

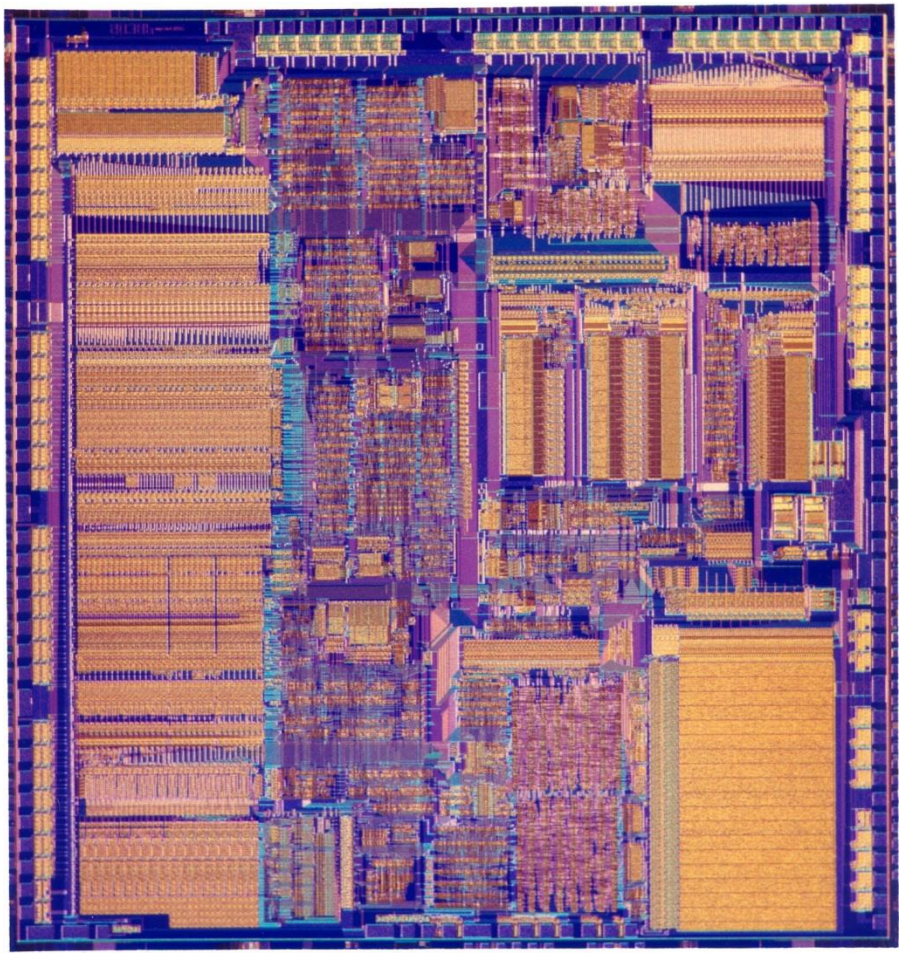
- Virtual memory (1982)
  - IBM PC AT
- Characteristics
  - 1.5 μm process
  - 134k transistors
  - 6-12 MHz
  - 16-bit word size
  - 68-pin PGA: Pin Grid Array
- Regular datapaths and ROMs

  Bitslices clearly visible



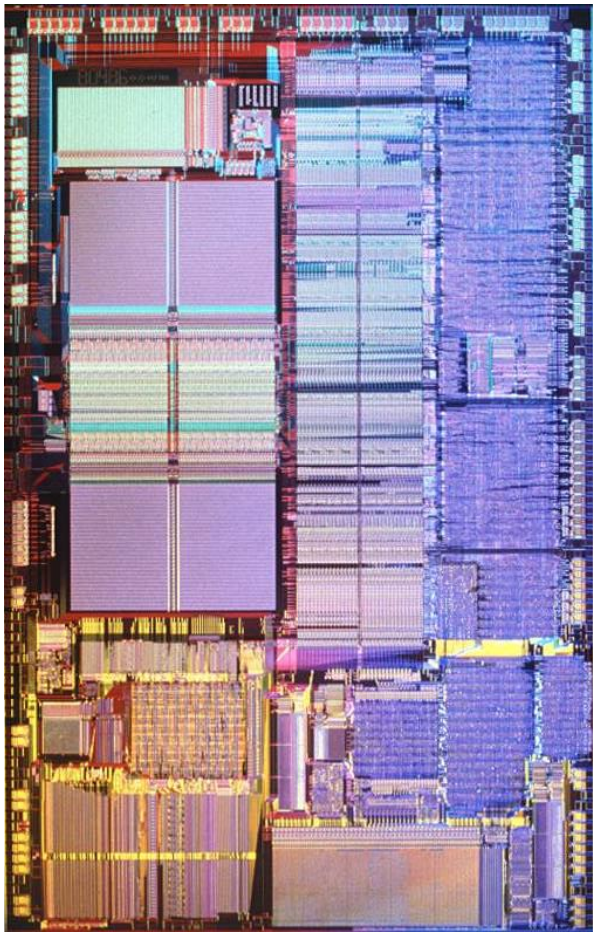
80386

- 32-bit processor (1985)
  - Modern x86 ISA
- Characteristics
  - 1.5-1 μm process
  - 275k transistors
  - 16-33 MHz
  - 32-bit word size
  - 100-pin PGA
- 32-bit datapath, microcode ROM, synthesized control



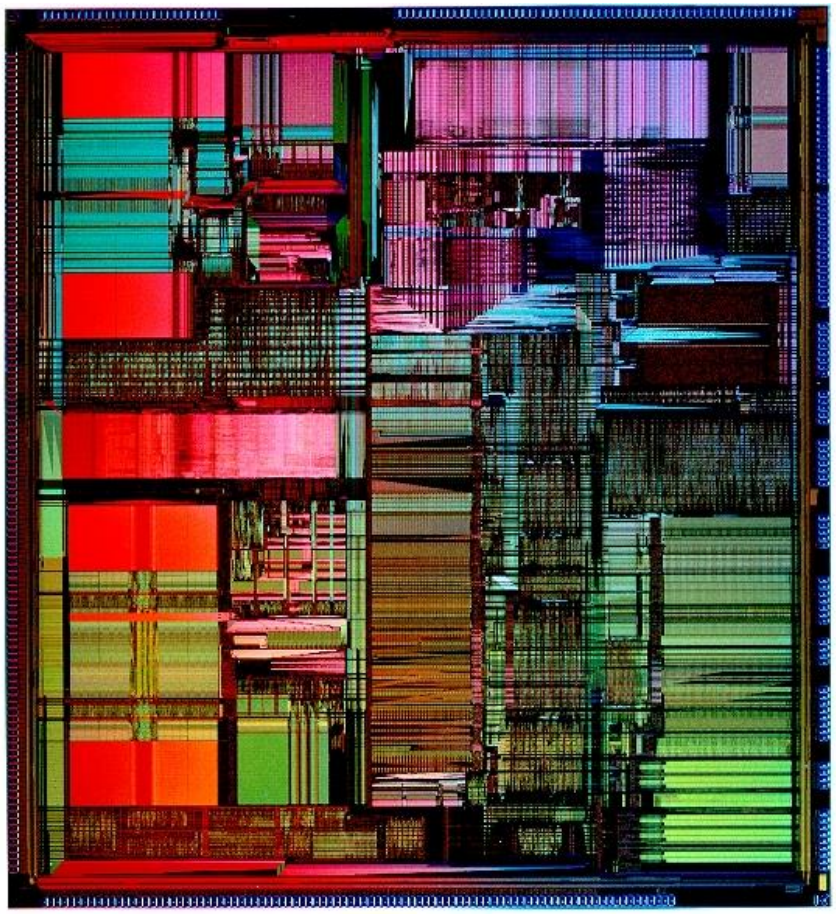
80486

- Pipelining (1989)
  - Floating point unit
  - 8 KB cache
- Characteristics
  - 1-0.6 μm process
  - 1.2M transistors
  - 25-100 MHz
  - 32-bit word size
  - 168-pin PGA
- Cache, Integer datapath, FPU, microcode, synthesized control



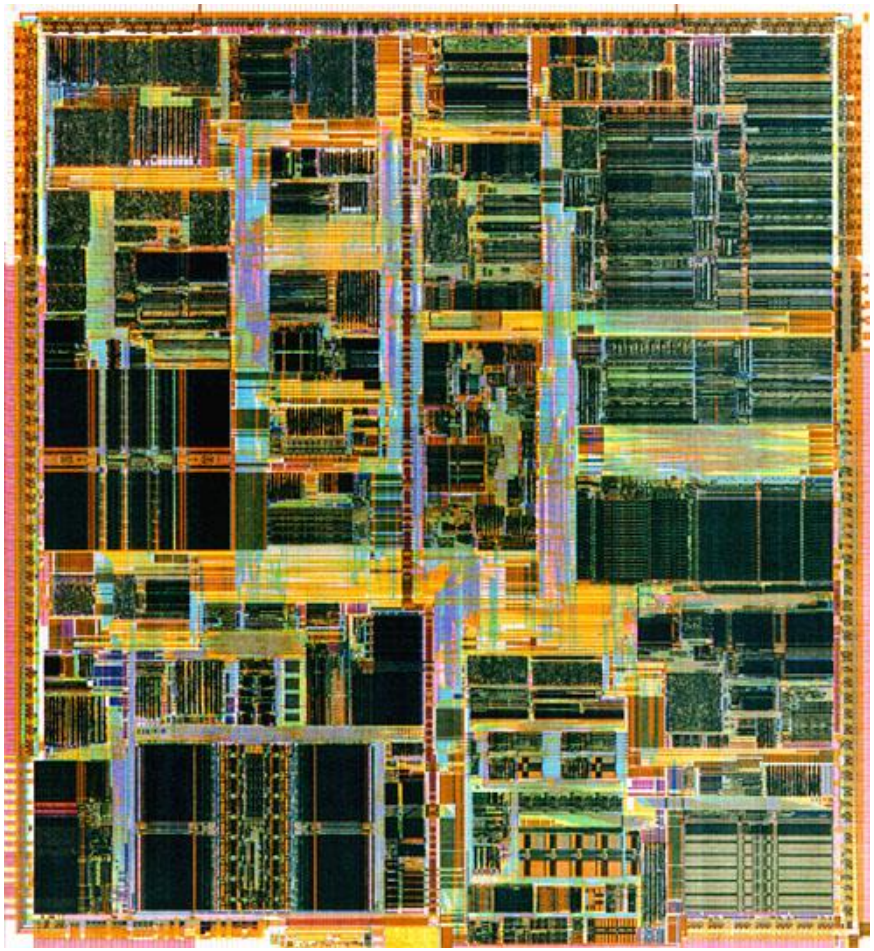
Pentium

- Superscalar (1993)
  - 2 instructions per cycle
  - Separate 8KB I$ & D$
- Characteristics
  - 0.8-0.35 µm process
  - 3.2M transistors
  - 60-300 MHz
  - 32-bit word size
  - 296-pin PGA
- Caches, datapath, FPU, control



Pentium Pro / II / III

- Dynamic execution (1995-9)
  - 3 micro-ops / cycle
  - Out of order execution
  - 16-32 KB I$ & D$
  - Multimedia instructions
  - PIII adds 256+ KB L2$
- Characteristics
  - 0.6-0.18 μm process
  - 5.5M-28M transistors
  - 166-1000 MHz
  - 32-bit word size
  - MCM / SECC



Multi-Chip Module on Single Edge Contact Cartridge

Pentium 4

- Deep pipeline (2001)
  - Very fast clock
  - 256-1024 KB L2$
- Characteristics
  - 180 – 65 nm process
  - 42-125M transistors
  - 1.4-3.4 GHz
  - Up to 160 W
  - 32/64-bit word size
  - 478-pin PGA
- Units start to become invisible on this scale

Pentium 4

- Deep pipeline (2001)
  - Very fast clock
  - 256-1024 KB L2$
- Characteristics
  - 180 – 65 nm process
  - 42-125M transistors
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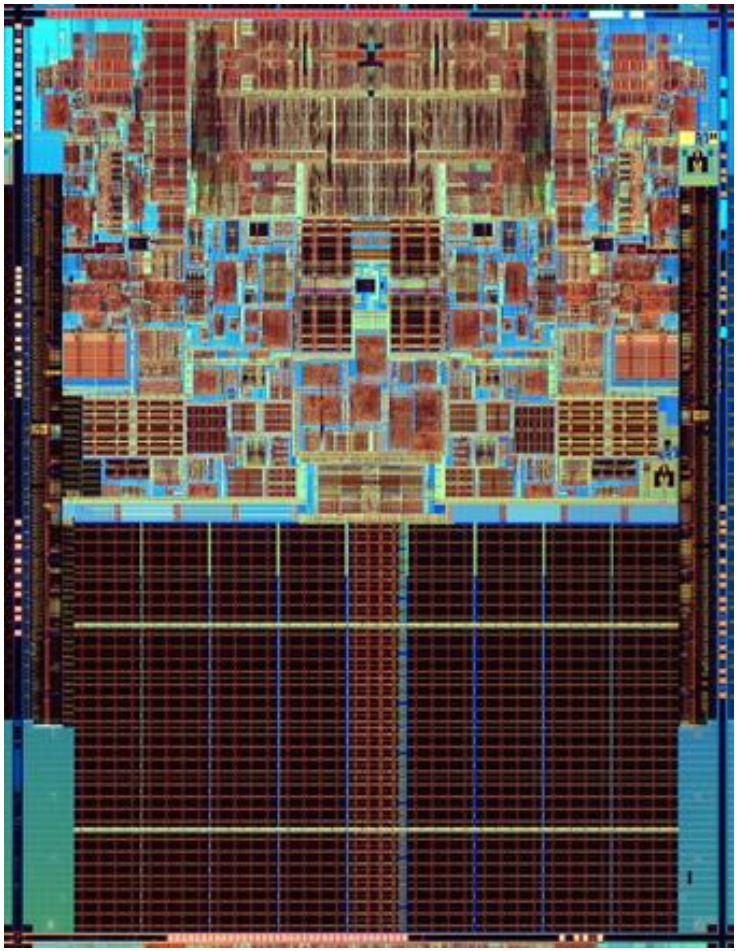
  - Up to 160 W
  - 32/64-bit word size
  - 478-pin PGA
- Units start to become invisible on this scale

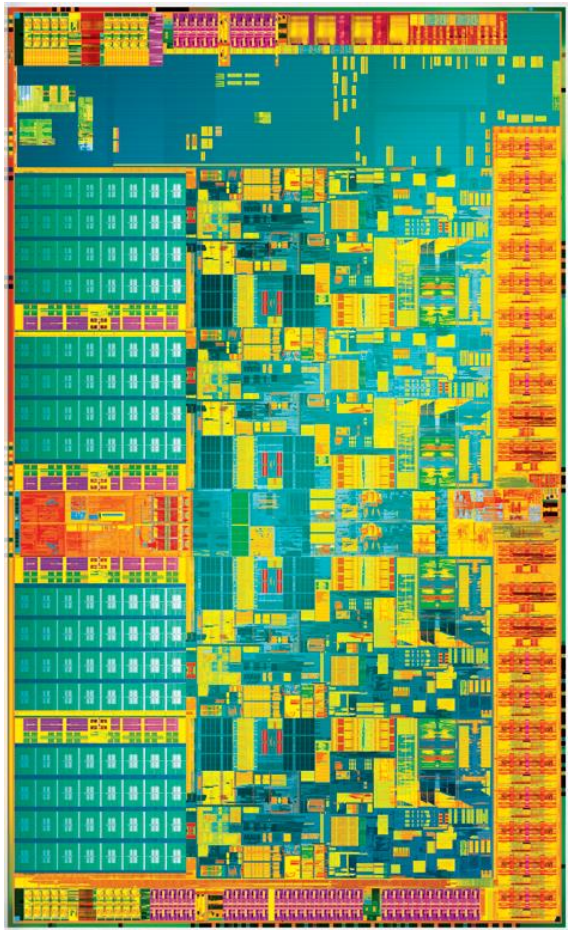
Core2 Duo

- Dual core (2006)
  - 1-2 MB L2$ / core
- Characteristics
  - 65-45 nm process
  - 291M transistors
  - 1.6-3+ GHz
  - 65 W
  - 32/64 bit word size
  - 775 pin LGA: Land Grid Array
- Much better performance/power efficiency



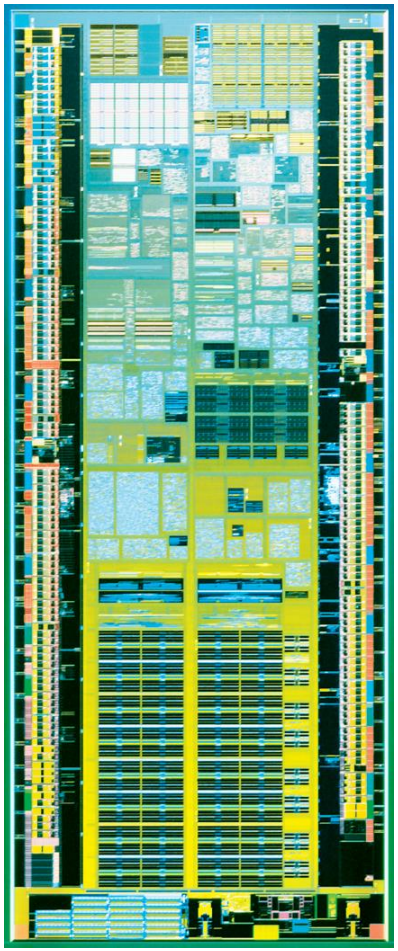
Core i7

- Quad core (& more)
  - Pentium-style architecture
  - 2 MB L3$ / core
- Characteristics
  - 45-32 nm process
  - 731M transistors
  - 2.66-3.33+ GHz
  - Up to 130 W
  - 32/64 bit word size
  - 1366-pin LGA
  - Multithreading
- On-die memory controller

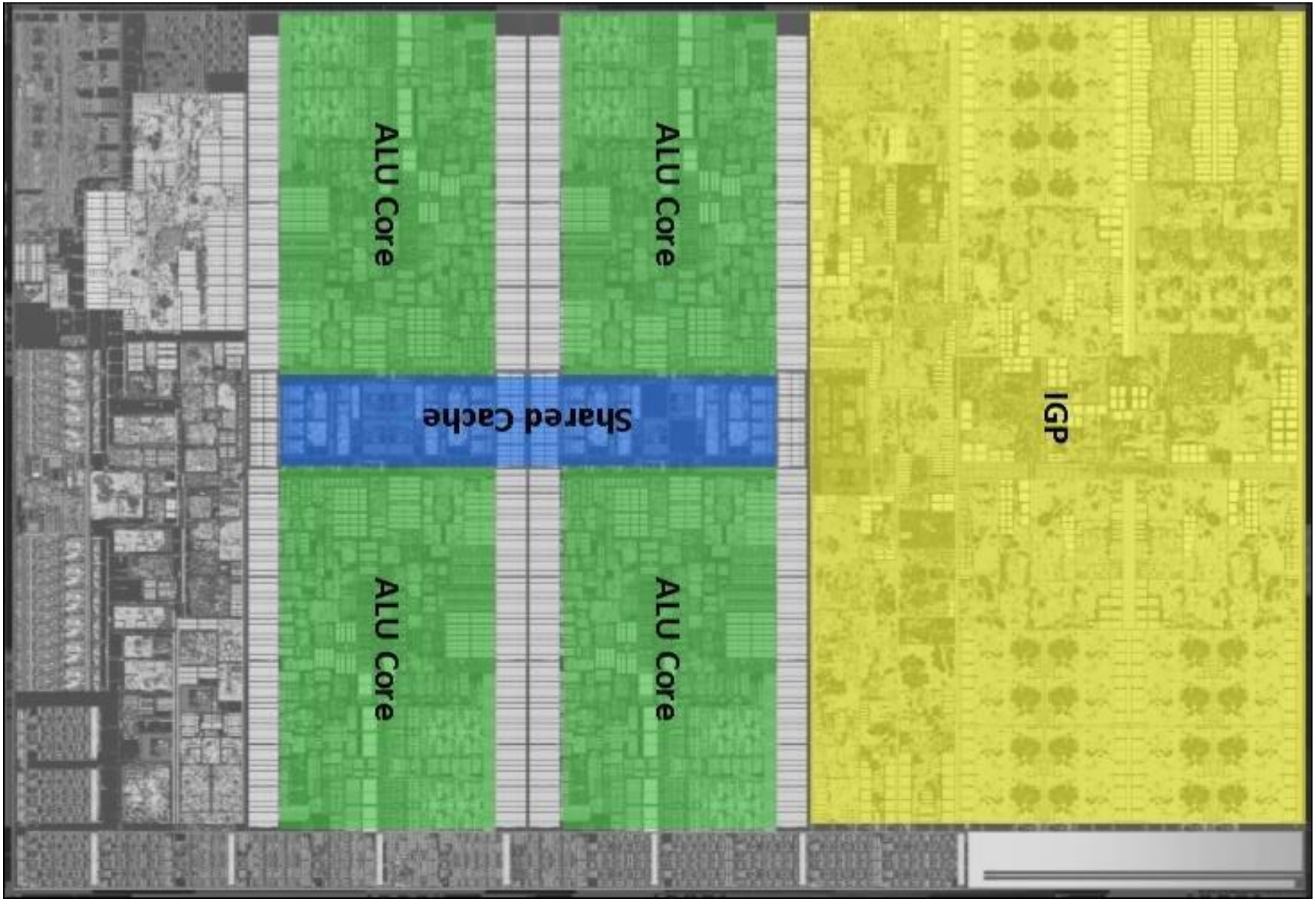


Atom

- Low power CPU for netbooks
  - Pentium-style architecture
  - 512KB+ L2$
- Characteristics
  - 45-32 nm process
  - 47M transistors
  - 0.8-1.8+ GHz
  - 1.4-13 W
  - 32/64-bit word size
  - 441-pin FCBGA
- Low voltage (0.7 – 1.1 V) operation
  - Excellent performance/power



Intel Skylake Processor 2015



Skylake

- Low power CPU for netbooks
  - 6th generation Core processor
  - L1 64KB+ L256 KB/core + L3 2 MB/core
- Characteristics
  - 22 nm process (tri-gate)
  - 1.7 Billion transistors
  - 4.0-4.2 GHz
  - 91 W
  - 64-bit word size
  - 3647 pin LGA
- Low voltage (0.7 V – 1.1) operation

Apple M1

- 4 high performance (Firestorm) + 4 energy efficient cores (Icestorm)
  - 2020
  - High performance core: L1 192KB instruction cache + 128 KB data cache; Share 12 MB L2 cache
  - Energy efficient core: L1 128KB instruction cache + 64 KB data cache; Share 4 MB L2 cache
  - Integrated eight-core GPU; shares 16MB system level cache with CPU
- Characteristics
  - Shares 8/16 GB SDRAM on the chip (system in package)
  - 60 Billion transistors
  - 3.2 GHz
  - 5 nm process

Summary – Processor Case Study

- 10^4 increase in transistor count, clock frequency over 3 decades!

Processor	Year	Feature Size (μm)	Transistors	Frequency (MHz)	Word Size	Power (W)	Cache (L1 / L2 / L3)	Package
4004	1971	10	2.3k	0.75	4	0.5	none	16-pin DIP
8008	1972	10	3.5k	0.5–0.8	8	0.5	none	18-pin DIP
8080	1974	6	6k	2	8	0.5	none	40-pin DIP
8086	1978	3	29k	5–10	16	2	none	40-pin DIP
80286	1982	1.5	134k	6–12	16	3	none	68-pin PGA
Intel386	1985	1.5–1.0	275k	16–25	32	1–1.5	none	100-pin PGA
Intel486	1989	1–0.6	1.2M	25–100	32	0.3–2.5	8K	168-pin PGA
Pentium	1993	0.8–0.35	3.2–4.5M	60–300	32	8–17	16K	296-pin PGA
Pentium Pro	1995	0.6–0.35	5.5M	166–200	32	29–47	16K / 256K+	387-pin MCM PGA
Pentium II	1997	0.35–0.25	7.5M	233–450	32	17–43	32K / 256K+	242-pin SECC
Pentium III	1999	0.25–0.18	9.5–28M	450–1000	32	14–44	32K / 512K	330-pin SECC2
Pentium 4	2000	180–65 nm	42–178M	1400–3800	32/64	21–115	20K+ / 256K+	478-pin PGA
Pentium M	2003	130–90 nm	77–140M	1300–2130	32	5–27	64K / 1M	479-pin FCBGA
Core	2006	65 nm	152M	1000–1860	32	6–31	64K / 2M	479-pin FCBGA
Core 2 Duo	2006	65–45 nm	167–410M	1060–3160	32/64	10–65	64K / 4M+	775-pin LGA
Core i7	2008	45 nm	731M	2660–3330	32/64	45–130	64K / 256K / 8M	1366-pin LGA
Atom	2008	45 nm	47M	800–1860	32/64	1.4–13	56K / 512K+	441-pin FCBGA