Topics

- Power Dissipation
- Technology Scaling
- Final Project

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Where Does Power Go in CMOS?

- **Dynamic Power Consumption**

  Charging and Discharging Capacitors

- **Short Circuit Currents**

  Short Circuit Path between Supply Rails during Switching

- **Leakage**

  Leaking diodes and transistors

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Power dissipation

- Static power dissipation
  - In theory, CMOS has no static power dissipation
  - There is a slight current (subthreshold leakage current and gate leakage current) on the order of .1-.5nA per device
  - At 5V supply voltage, .5-2.5 nW static power dissipation per device
  - Million gate chip will have .5-2.5 mW static power dissipation

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Power dissipation

- Dynamic power dissipation
  - Proportional to load capacitance and frequency
  - Proportional to square of the supply voltage
    - Current trend is to reduce supply voltages to reduce power
    - Reduced supply voltage will increase delays however
  - Not dependent on device parameters

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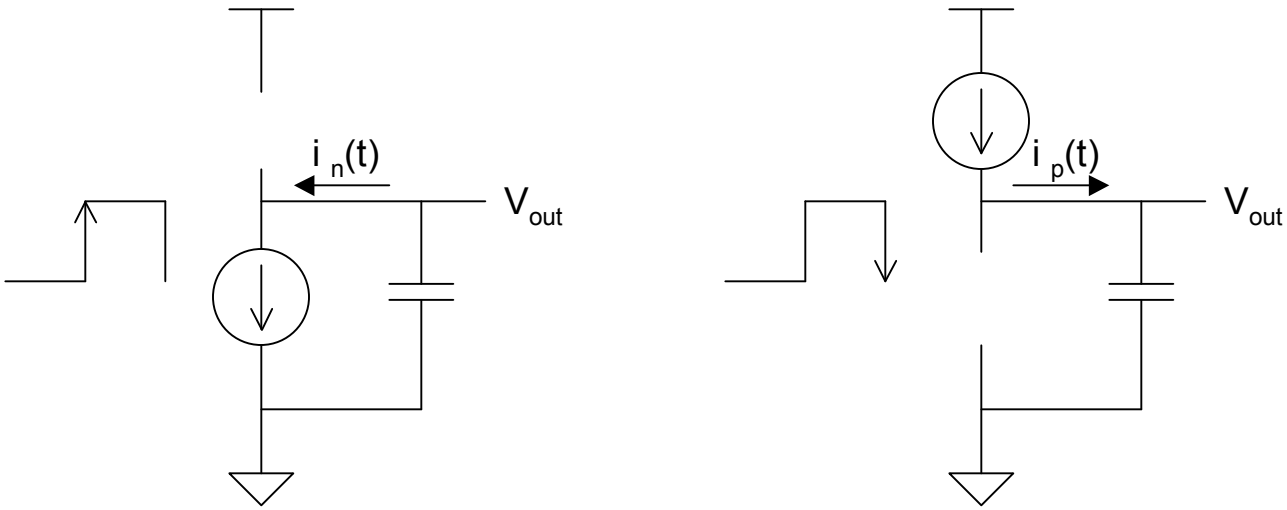
Power dissipation

- Dynamic power dissipation
  - Switching causes short bursts of current flow which will cause power dissipation



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Power dissipation

- Dynamic power dissipation

$$
\begin{aligned}
P &= \frac{1}{T}\left[\int_0^{\frac{T}{2}} i_n(t)V_{out}dt + \int_{\frac{T}{2}}^{T} i_p(t)\left(V_{DD} - V_{out}\right)\right] \\
&= \frac{1}{T}\left[-C_L\int_{V_{DD}}^{0} V_{out}dV_{out} + C_L\int_0^{V_{DD}} \left(V_{DD} - V_{out}\right)dV_{out}\right] \\
&= \frac{C_L}{T}\left[\frac{{V_{DD}}^2}{2} + \frac{{V_{DD}}^2}{2}\right] \\
&= C_L{V_{DD}}^2 f
\end{aligned}
$$

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Power dissipation

- Example

$$
\begin{aligned}
V_{DD} &= 5V \\
f &= 1GHz \\
C_L &= 1pF \\
P &= C_L V_{DD}^2 f \\
&= 1pf \cdot 5^2 \cdot 1GHz \\
&= 25mW
\end{aligned}
$$

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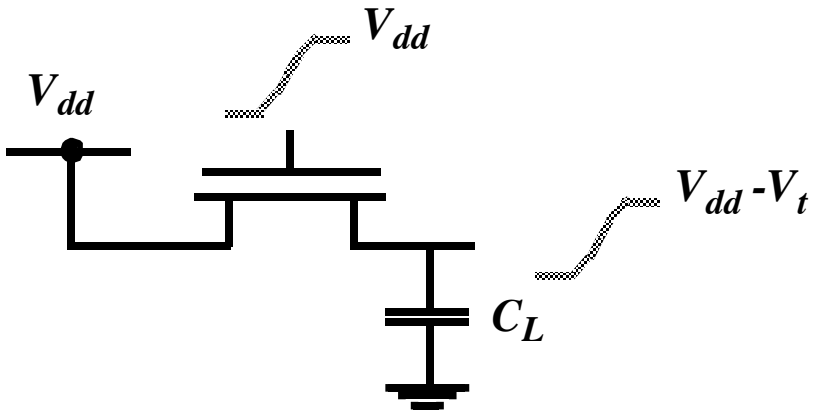
Modification for Circuits with Reduced Swing



$$E_{01\rightarrow} = C_L \cdot V_{dd} \cdot (V_{dd} - V_t)$$

- Can exploit reduced swing to lower power (e.g., reduced bit-line swing in memory)

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Power dissipiation

- Short circuit current dissipation
  - Short circuit current occurs when both transistors are on temporarily
  - Proportional to the ratio of rise time to T
  - Since the rise time is usually much less than T, it can be usually ignored

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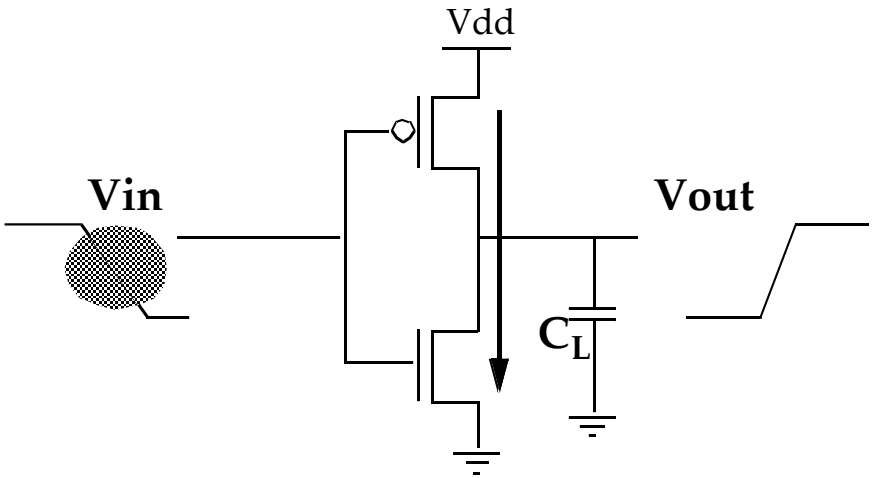
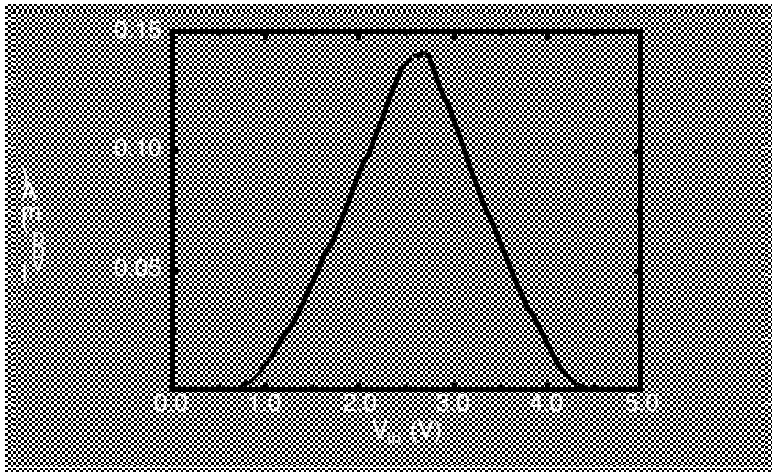
Short Circuit Currents





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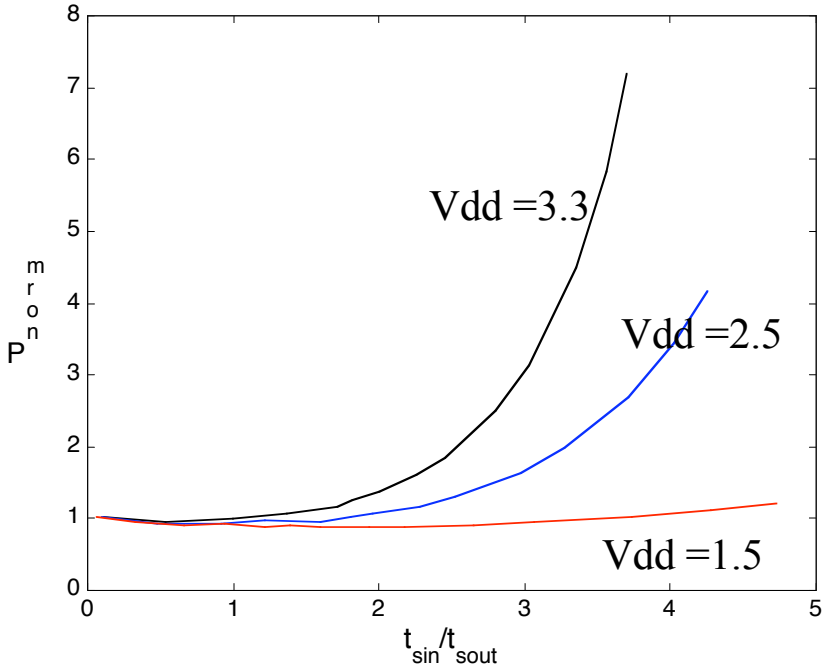
Minimizing Short-Circuit Power



- Keep the input and output rise/fall times the same (< 10% of Total Consumption)

  from [Veendrick84]

  (*IEEE Journal of Solid-State Circuits*, August 1984)

- If $V_{dd} < V_{tn} + |V_{tp}|$ then short-circuit power can be *eliminated*!

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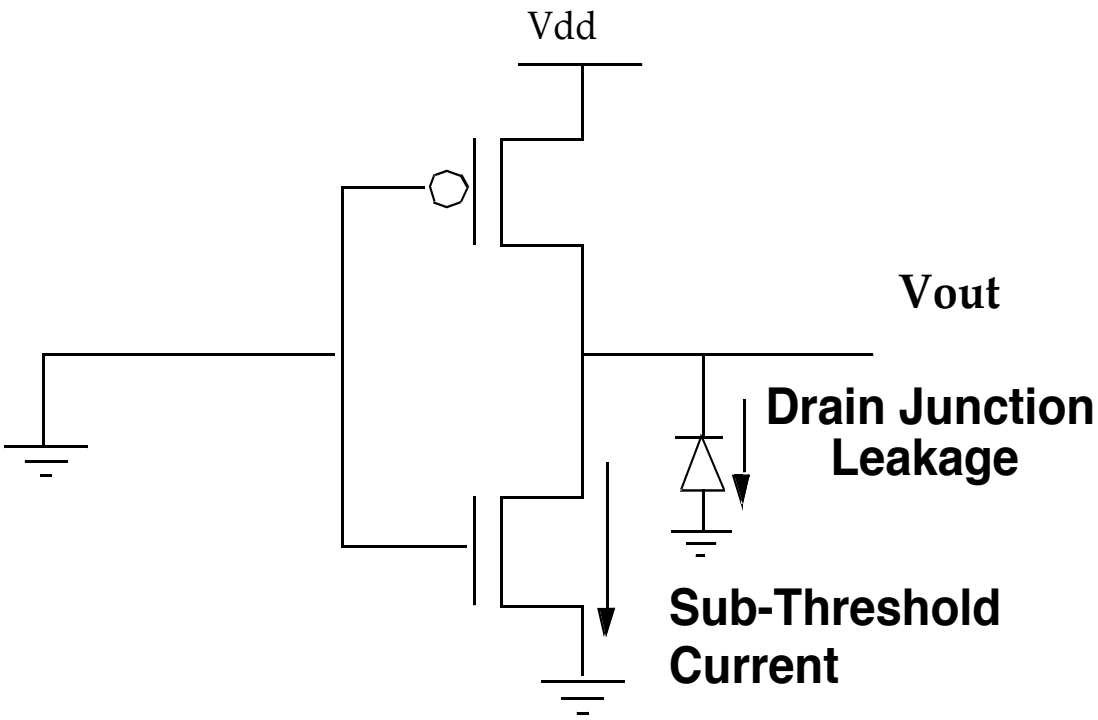
Leakage



Sub-threshold current one of most compelling issues in low-energy circuit design!

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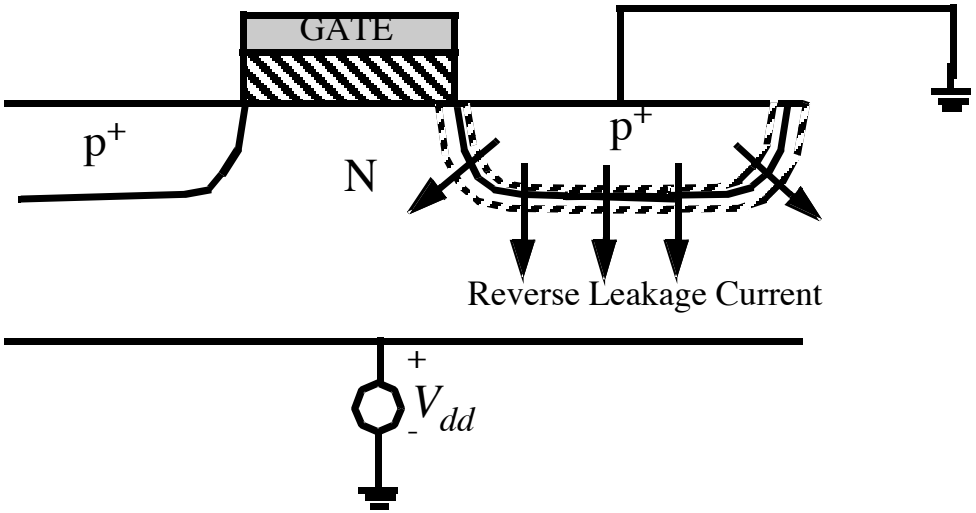
Reverse-Biased Diode Leakage



$$I_{DL} = J_S \times A$$

***JS* = 10-100 pA/μm2 at 25 deg C for 0.25μm CMOS**
***JS* doubles for every 9 deg C!**

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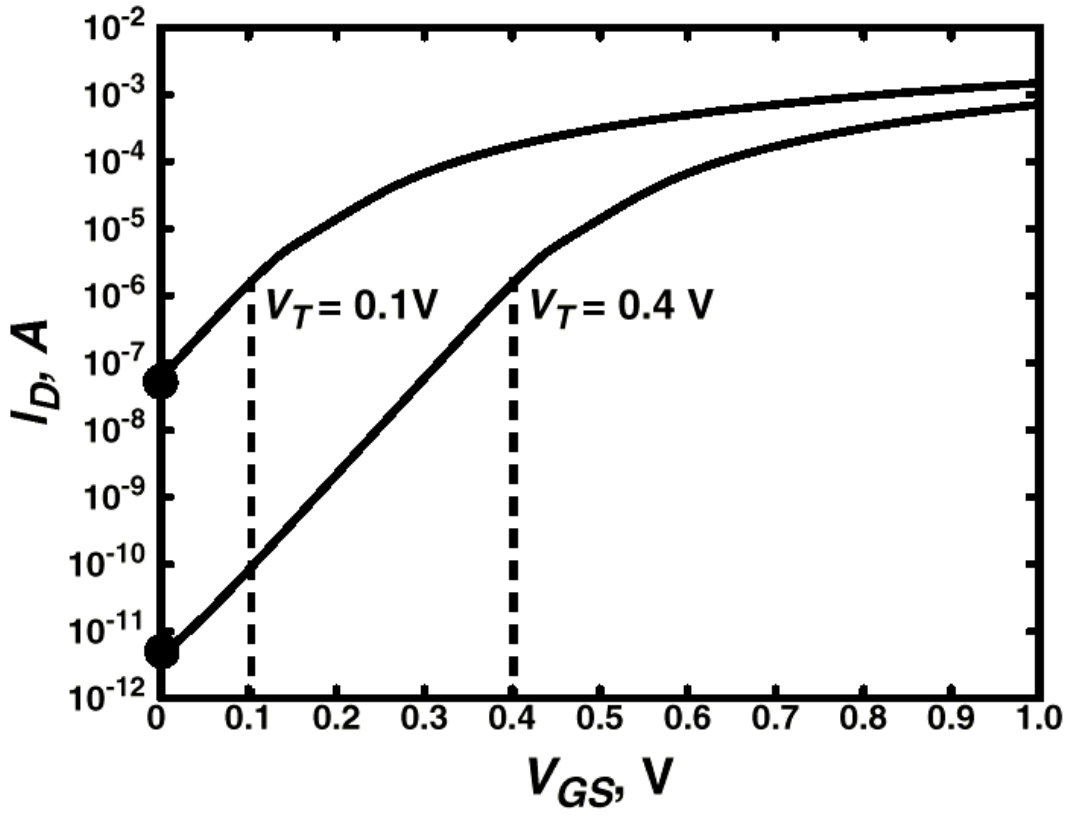
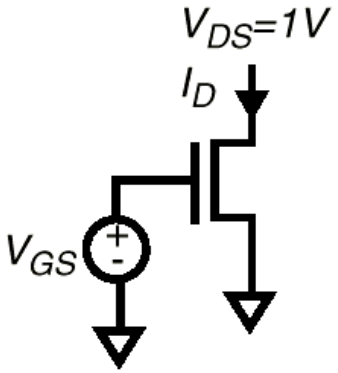
Subthreshold Leakage Component





- **Leakage control is critical for low-voltage operation**

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Principles for Power Reduction

- Prime choice: Reduce voltage!
  - Recent years have seen an acceleration in supply voltage reduction
  - Design at very low voltages still open question (0.6 … 0.9 V by 2010!)
- Reduce switching activity
- Reduce physical capacitance
  - Device Sizing: for F=20
    - f_{opt}(energy)=3.53, f_{opt}(performance)=4.47

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Goals of Technology Scaling

- Make things cheaper:
  - Want to sell more functions (transistors) per chip for the same money
  - Build same products cheaper, sell the same part for less money
  - Price of a transistor has to be reduced
- But also want to be faster, smaller, lower power

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Technology Scaling

- Goals of scaling the dimensions by 30%:
  - Reduce gate delay by 30% (increase operating frequency by 43%)
  - Double transistor density
  - Reduce energy per transition by 30%
- Die size used to increase by 14% per generation
- Technology generation spans 2-3 years

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Technology Scaling Models

- **Full Scaling (Constant Electrical Field)**

  ideal model — dimensions and voltage scale together by the same factor *S*

- **Fixed Voltage Scaling**

  most common model until recently — only dimensions scale, voltages remain constant

- **General Scaling**

  most realistic for todays situation — voltages and dimensions scale with different factors

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Scaling Relationships for Long Channel Devices

Parameter	Relation	Full Scaling	General Scaling	Fixed Voltage Scaling
W, L, t_{ox}		1/S	1/S	1/S
V_{DD}, V_T		1/S	1/U	1
N_{SUB}	V/W_{depl}^2	S	S^2/U	S^2
Area/Device	WL	$1/S^2$	$1/S^2$	$1/S^2$
C_{ox}	$1/t_{ox}$	S	S	S
C_L	$C_{ox}WL$	1/S	1/S	1/S
k_n, k_p	$C_{ox}W/L$	S	S	S
I_{av}	$k_{n,p} V^2$	1/S	S/U^2	S
t_p (intrinsic)	$C_L V / I_{av}$	1/S	U/S^2	$1/S^2$
P_{av}	$C_L V^2 / t_p$	$1/S^2$	S/U^3	S
PDP	$C_L V^2$	$1/S^3$	$1/SU^2$	1/S

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Transistor Scaling (velocity-saturated devices)

Parameter	Relation	Full Scaling	General Scaling	Fixed-Voltage Scaling
W, L, t_{ox}		$1/S$	$1/S$	$1/S$
V_{DD}, V_T		$1/S$	$1/U$	1
N_{SUB}	V/W_{depl}^2	S	S^2/U	S^2
Area/Device	WL	$1/S^2$	$1/S^2$	$1/S^2$
C_{ox}	$1/t_{ox}$	S	S	S
C_{gate}	$C_{ox}WL$	$1/S$	$1/S$	$1/S$
k_n, k_p	$C_{ox}W/L$	S	S	S
I_{sat}	$C_{ox}WV$	$1/S$	$1/U$	1
Current Density	$I_{sat}/Area$	S	S^2/U	S^2
Ron	V/I_{sat}	1	1	1
Intrinsic Delay	$R_{on}C_{gate}$	$1/S$	$1/S$	$1/S$
P	$I_{sat}V$	$1/S^2$	$1/U^2$	1
Power Density	$P/Area$	1	S^2/U^2	S^2

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Technology Generations

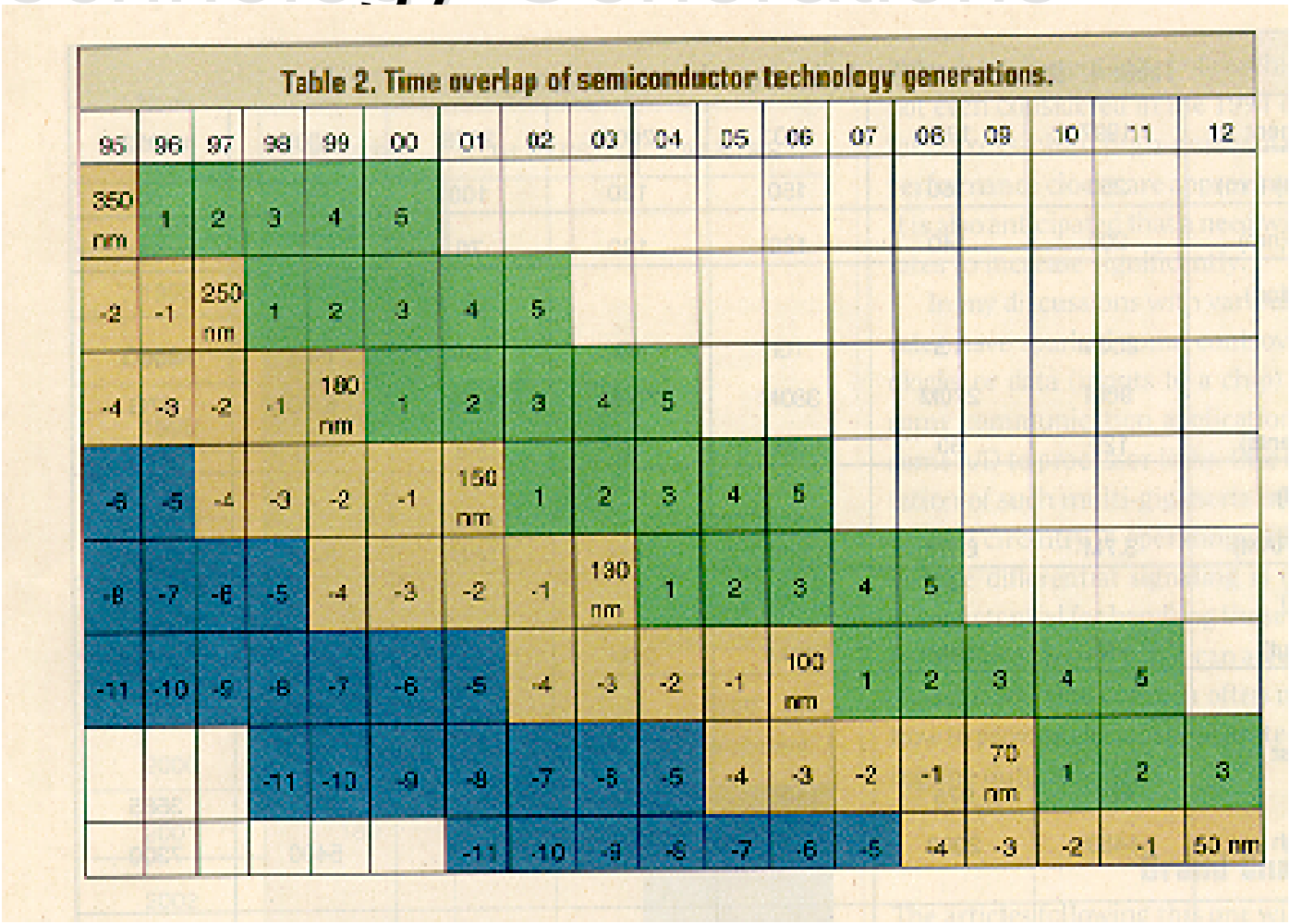

Table 2. Time overlap of semiconductor technology generations.

95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12
350 nm	1	2	3	4	5												
-2	-1	250 nm	1	2	3	4	5										
-4	-3	-2	-1	180 nm	1	2	3	4	5								
-6	-5	-4	-3	-2	-1	150 nm	1	2	3	4	5						
-8	-7	-6	-5	-4	-3	-2	-1	130 nm	1	2	3	4	5				
-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	100 nm	1	2	3	4	5	
			-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	70 nm	1	2	3
						-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	50 nm

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Technology Evolution (2000 data)

International Technology Roadmap for Semiconductors

Year of Introduction	1999	2000	2001	2004	2008	2011	2014
Technology node [nm]	180		130	90	60	40	*30*
Supply [V]	1.5-1.8	1.5-1.8	1.2-1.5	0.9-1.2	0.6-0.9	0.5-0.6	*0.3-0.6*
Wiring levels	6-7	6-7	7	8	9	9-10	*10*
Max frequency [GHz],Local-Global	1.2	1.6-1.4	2.1-1.6	3.5-2	7.1-2.5	11-3	*14.9 -3.6*
Max μP power [W]	90	106	130	160	171	177	*186*
Bat. power [W]	1.4	1.7	2.0	2.4	2.1	2.3	*2.5*

Node years: 2007/65nm, 2010/45nm, 2013/33nm, 2016/23nm

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Technology Evolution (1999)

Year of Introduction	1994	1997	2000	2003	2006	2009
Channel length (μm)	0.4	0.3	0.25	0.18	0.13	0.1
Gate oxide (nm)	12	7	6	4.5	4	4
V_{DD} (V)	3.3	2.2	2.2	1.5	1.5	1.5
V_T (V)	0.7	0.7	0.7	0.6	0.6	0.6
NMOS I_{Dsat} (mA/μm) (@ $V_{GS} = V_{DD}$)	0.35	0.27	0.31	0.21	0.29	0.33
PMOS I_{Dsat} (mA/μm) (@ $V_{GS} = V_{DD}$)	0.16	0.11	0.14	0.09	0.13	0.16

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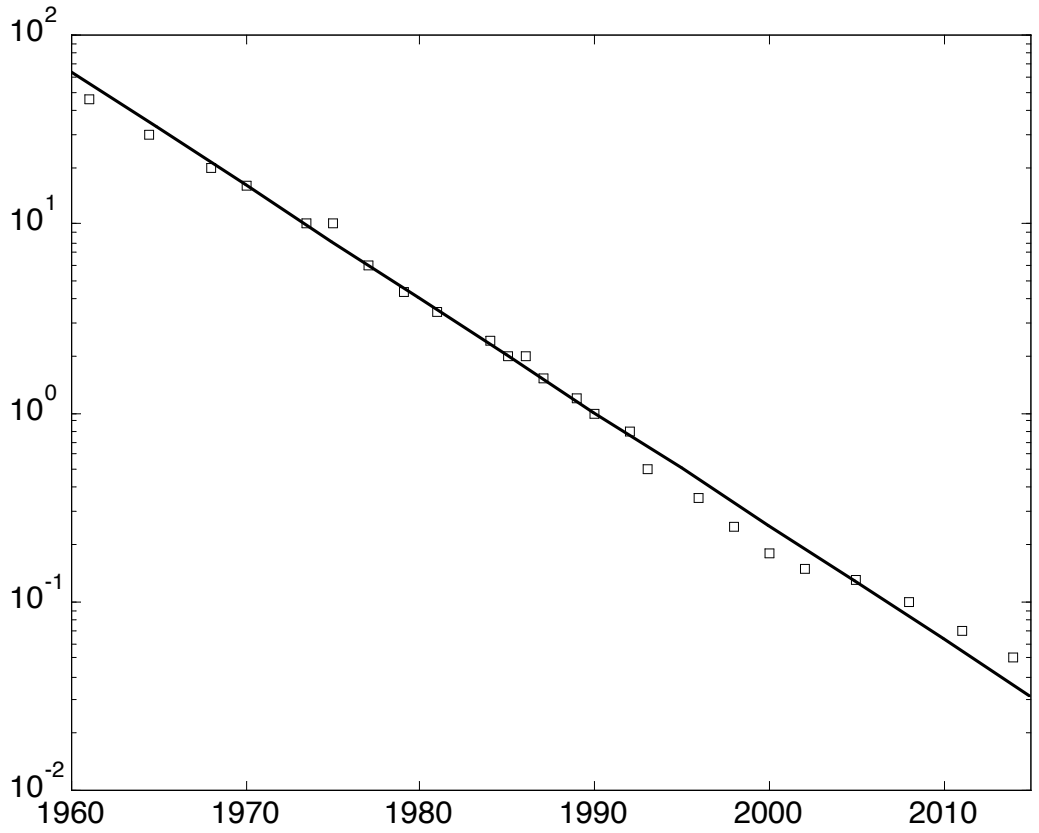
Technology Scaling (1)



Minimum Feature Size

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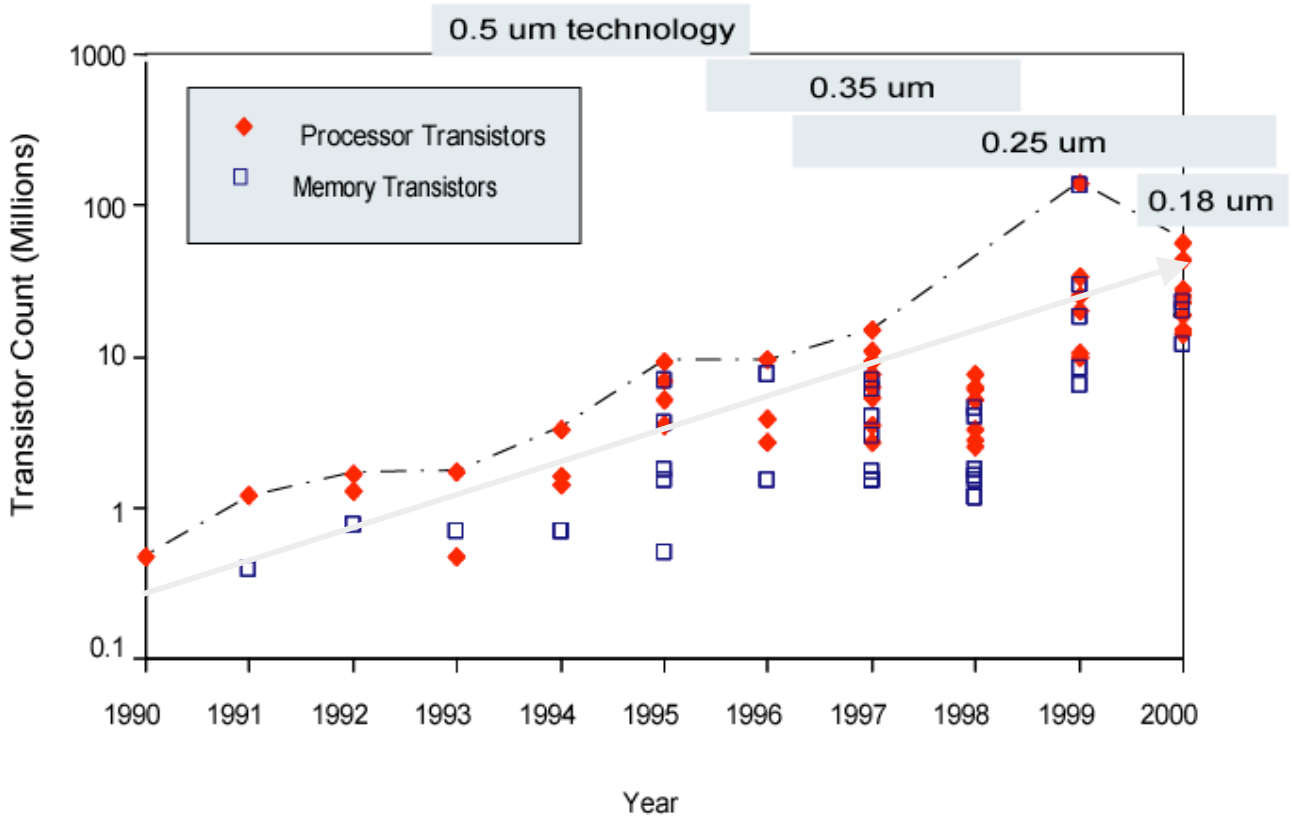
Technology Scaling (2)



Number of components per chip

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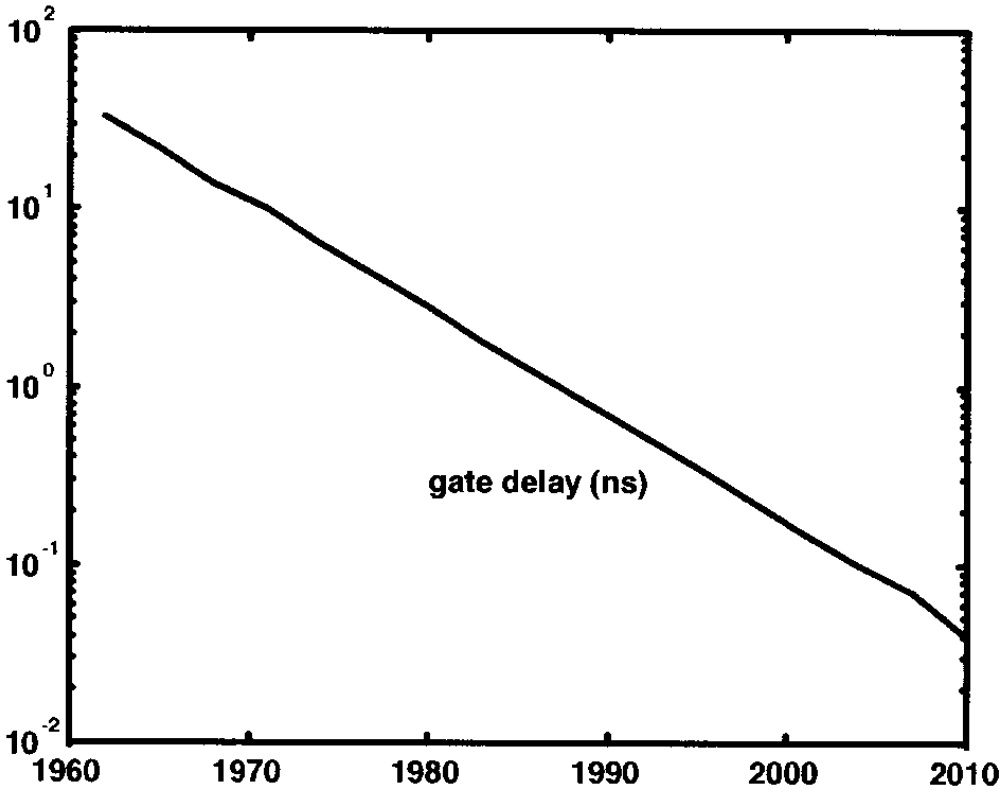
Technology Scaling (3)



t_p decreases by 13%/year
50% every 5 years!

Propagation Delay

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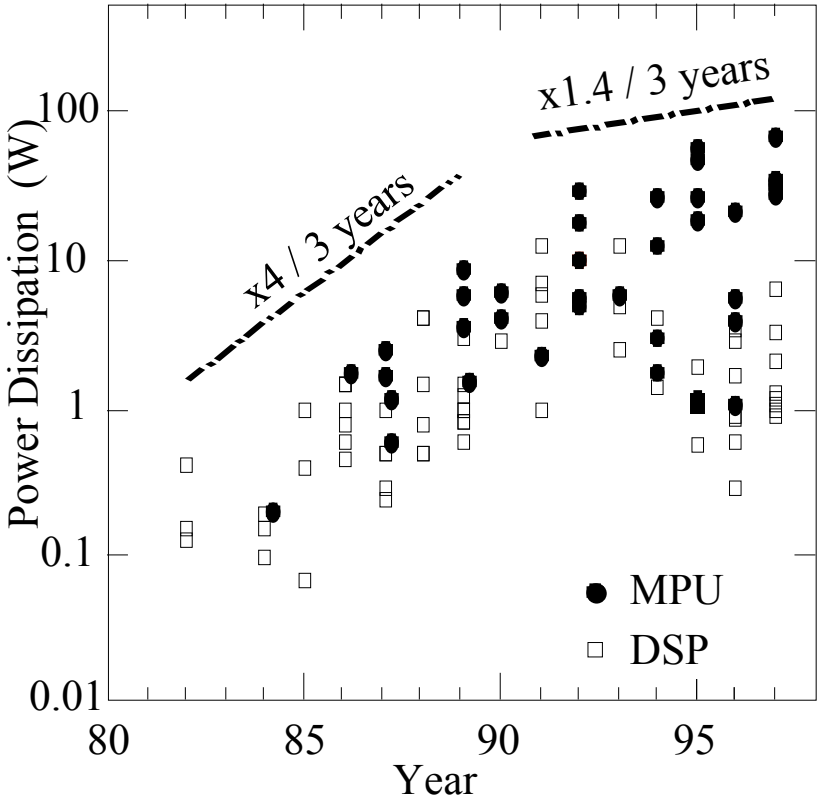
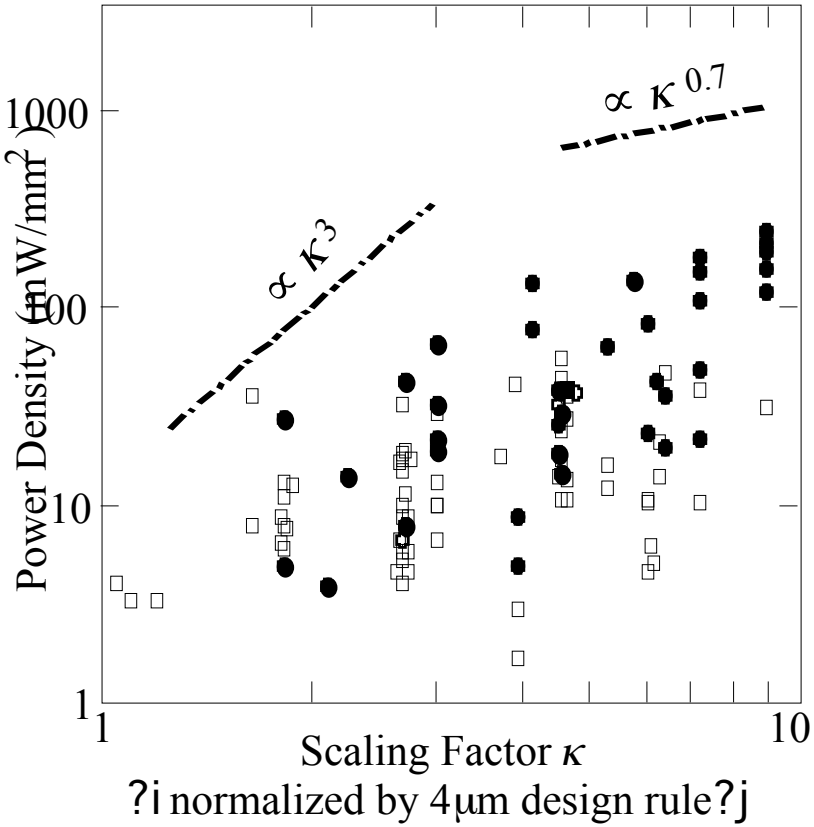
Technology Scaling (4)



(a) Power dissipation vs. year.



?i normalized by 4μm design rule?j

(b) Power density vs. scaling factor.

From Kuroda

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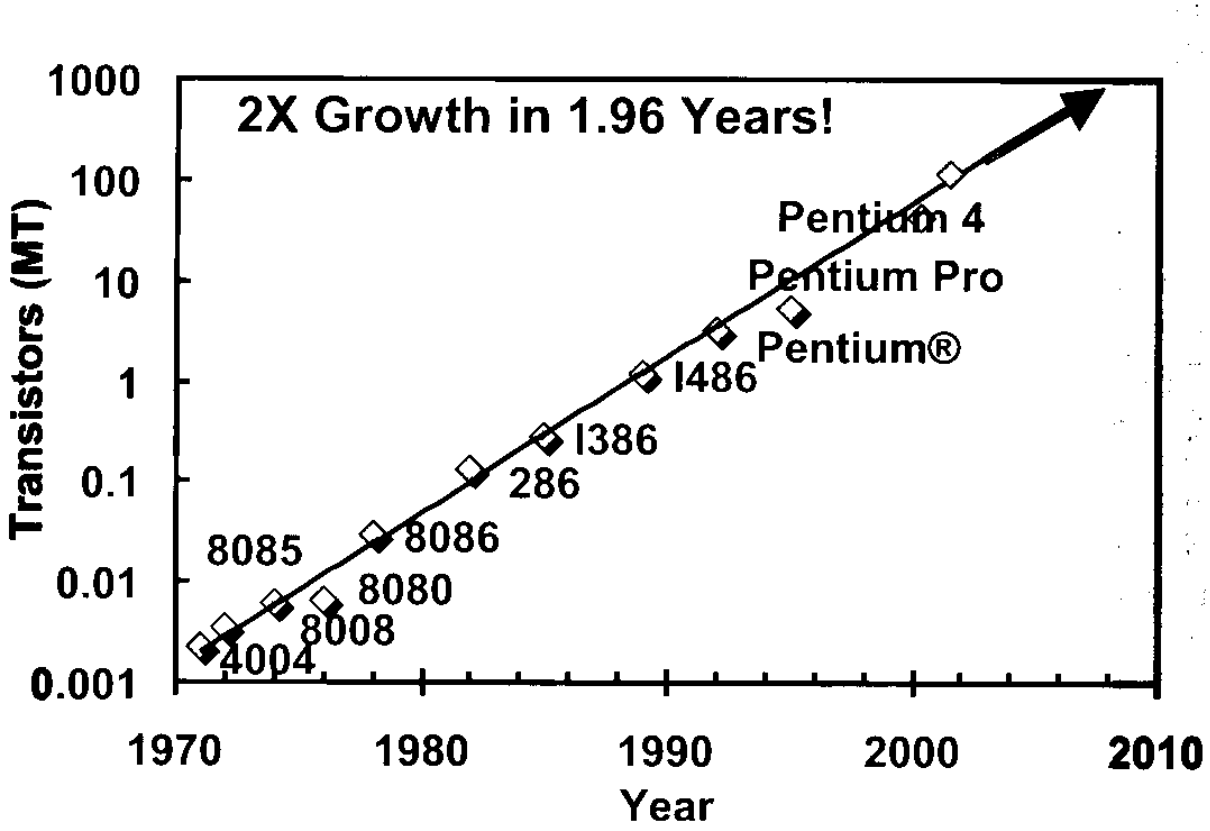
µProcessor Scaling



P.Gelsinger: µProcessors for the New Millenium, ISSCC 2001

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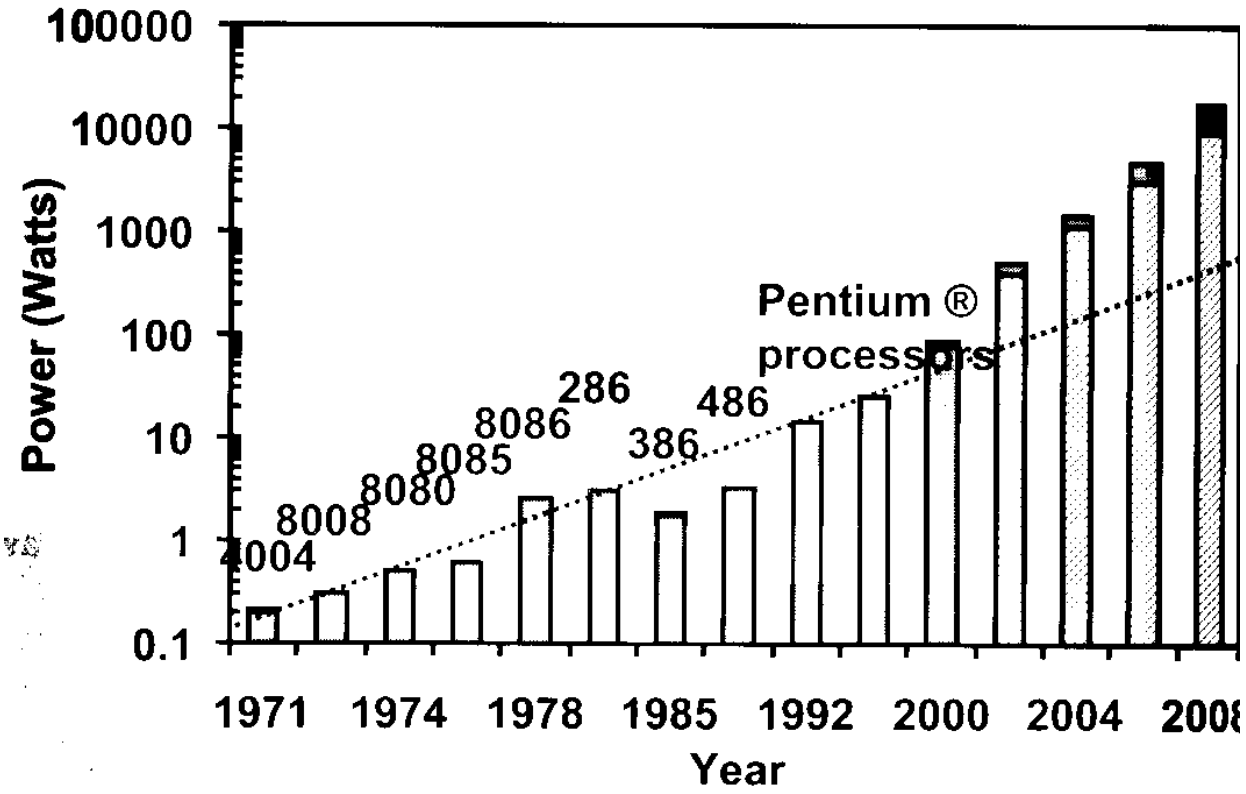
μProcessor Power



P.Gelsinger: μProcessors for the New Millenium, ISSCC 2001

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2010 Outlook

- Performance 2X/16 months
  - 1 TIP (terra instructions/s)
  - 30 GHz clock
- Size
  - No of transistors: 2 Billion
  - Die: 40*40 mm
- Power
  - 10kW!!
  - Leakage: 1/3 active Power

P.Gelsinger: μProcessors for the New Millenium, ISSCC 2001

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Some interesting questions

- What will cause this model to break?
- When will it break?
- Will the model gradually slow down?
  - Power and power density
  - Leakage
  - Process Variation

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Final Project

- Teams of two
- Choose your own project
- If you want to fabricate chip, you are limited to a 1.5 mm square - roughly 5-10000 transistors

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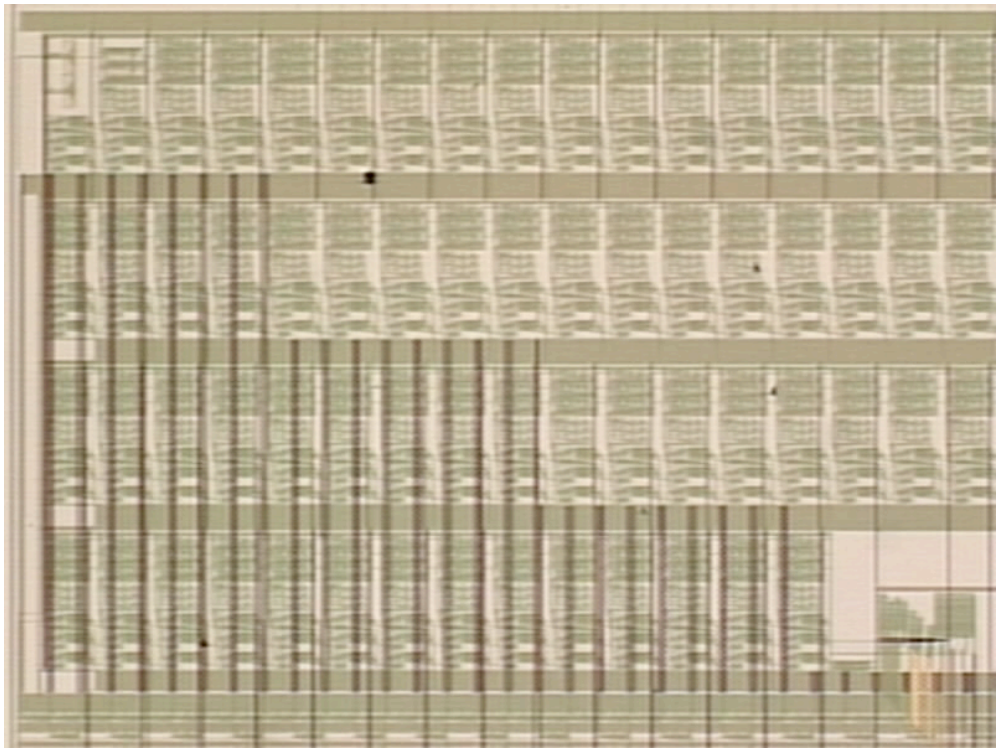
Final Project

- Spring 2003 - Search Engine Processor



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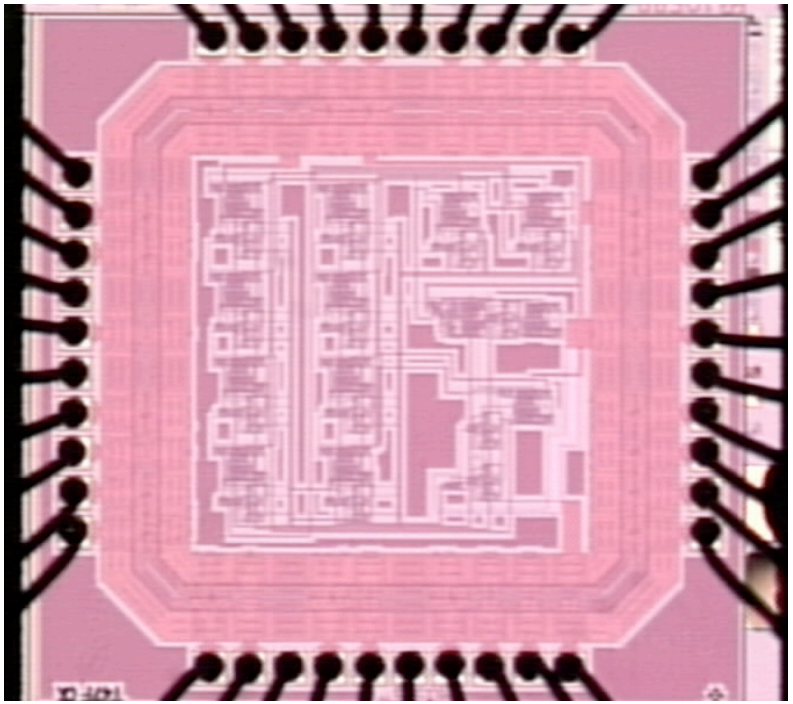
Final Project

- Spring 2004 - Encoder/Decoder



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Final Project

- Important Dates
  - Proposal due March 3rd
  - Architecture due March 17th
  - Logic Design due March 31st
  - Demonstrations April 26-28th
  - Final Project Report due April 29th
  - Presentation April 28th

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Next Class

- Exam 1
  - Lectures 1-10
  - HW1-3
  - Chapters 1-6

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