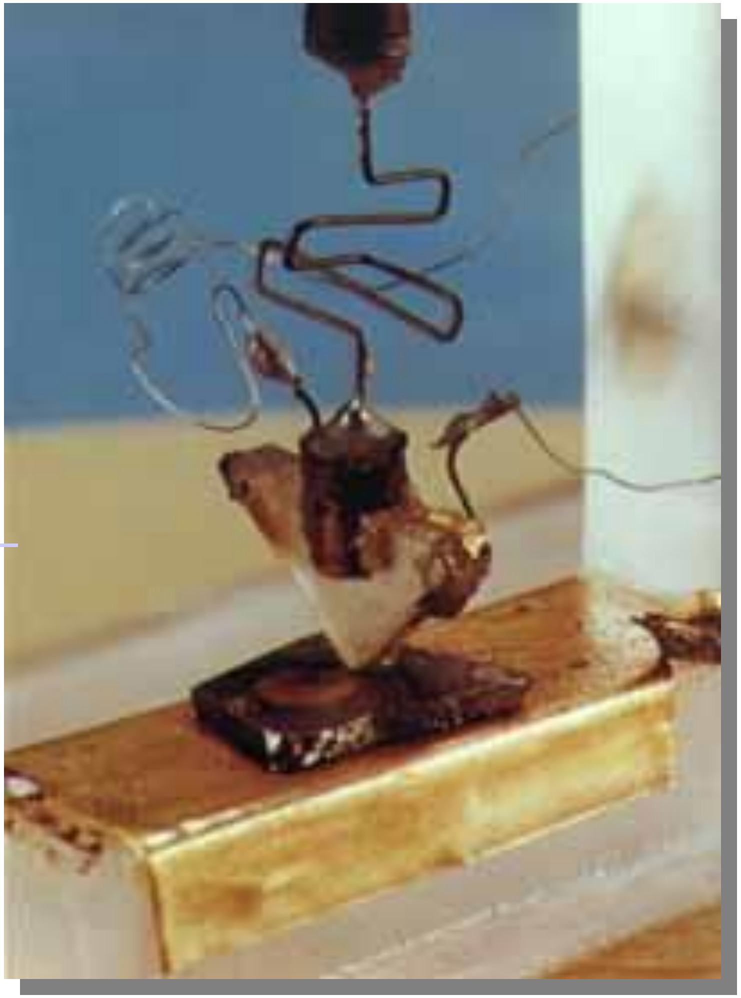
Digital IC konstruktion

Viktor Öwall

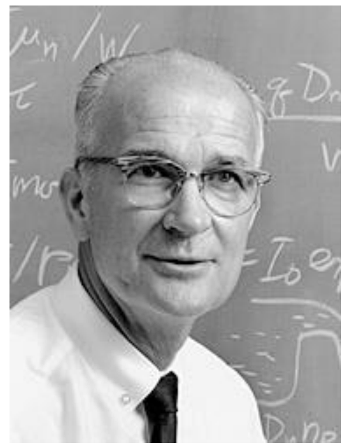
Professor i Elektronikkonstruktion

Den första transistorn, 1947



Nobelpris i fysik 1956

William Shockley

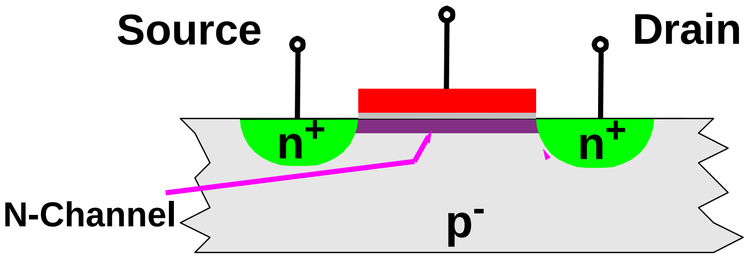


Walter Brattain

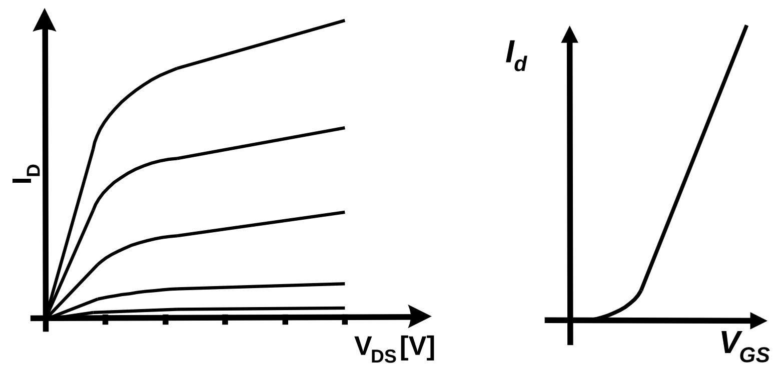
John Bardeen

även 1972

Vad är en transistor?

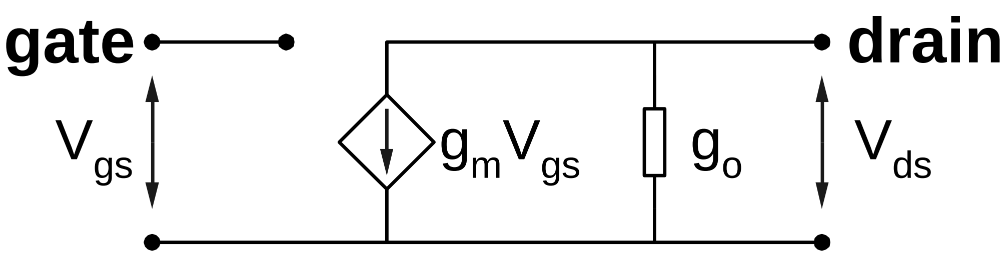


Halvledarkomponent

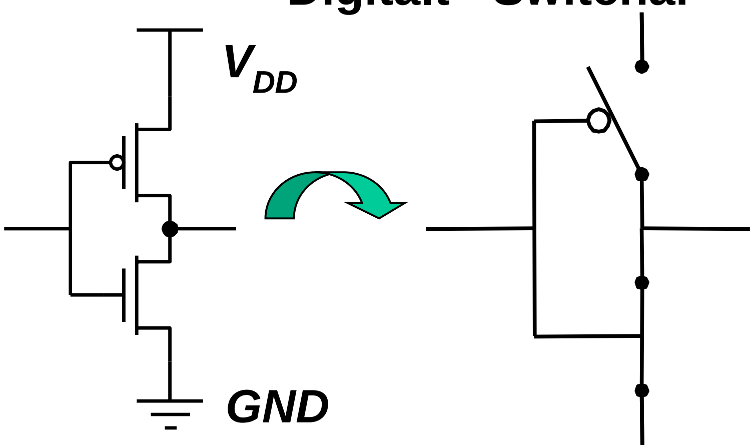


Elektriska förhållanden

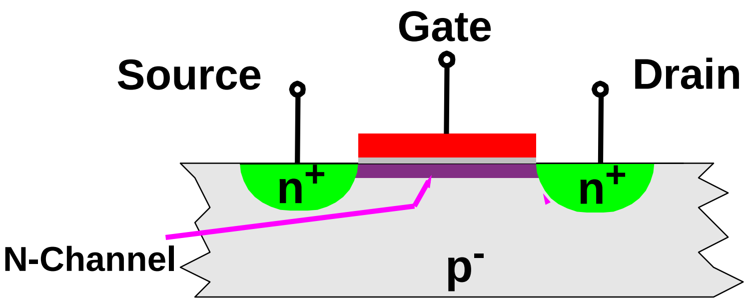
Småsignalmodell



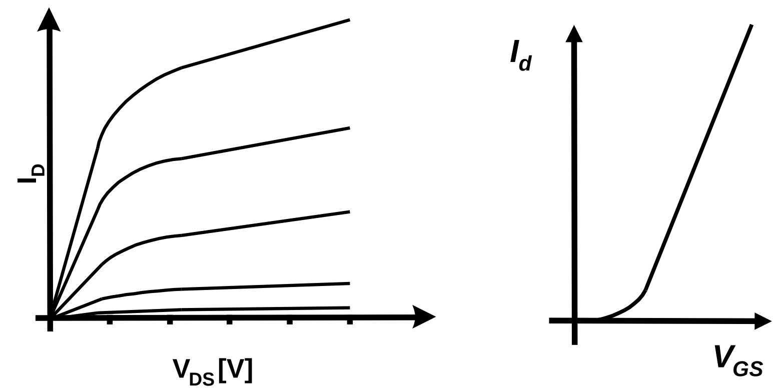
Digitalt - Switchar



Digitalt arbetar vi i stort sätt uteslutande med CMOS transistorer.

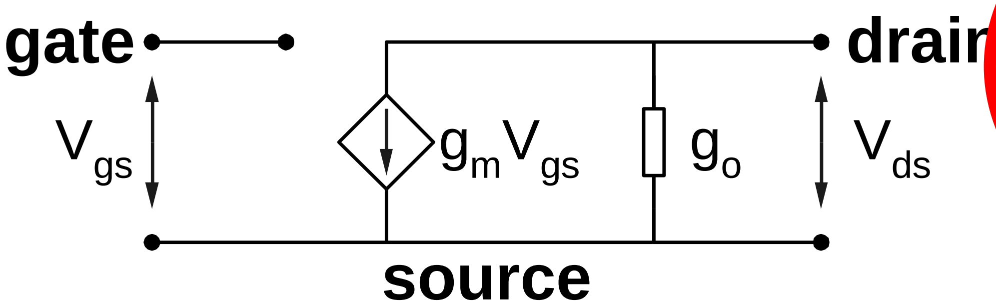


Solid State Physics

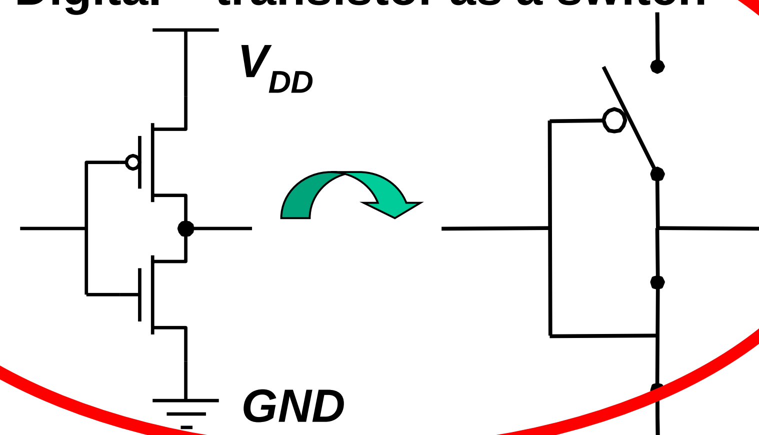


Electrical Characteristics

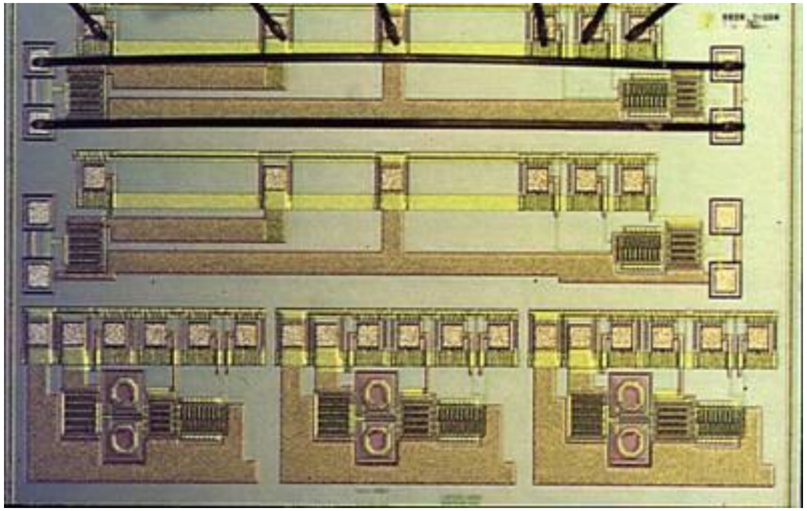
Small Signal Model (amplifier design)



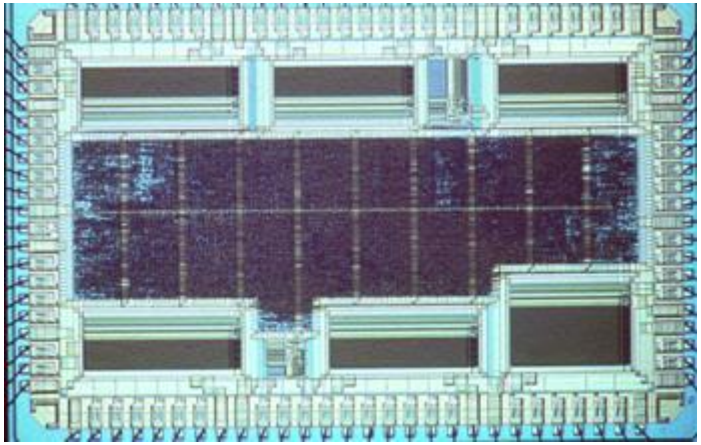
Digital – transistor as a switch



Analogt kontra digitalt



Analogt
- få komponenter
- låg effekt?
- ”verkliga” signaler



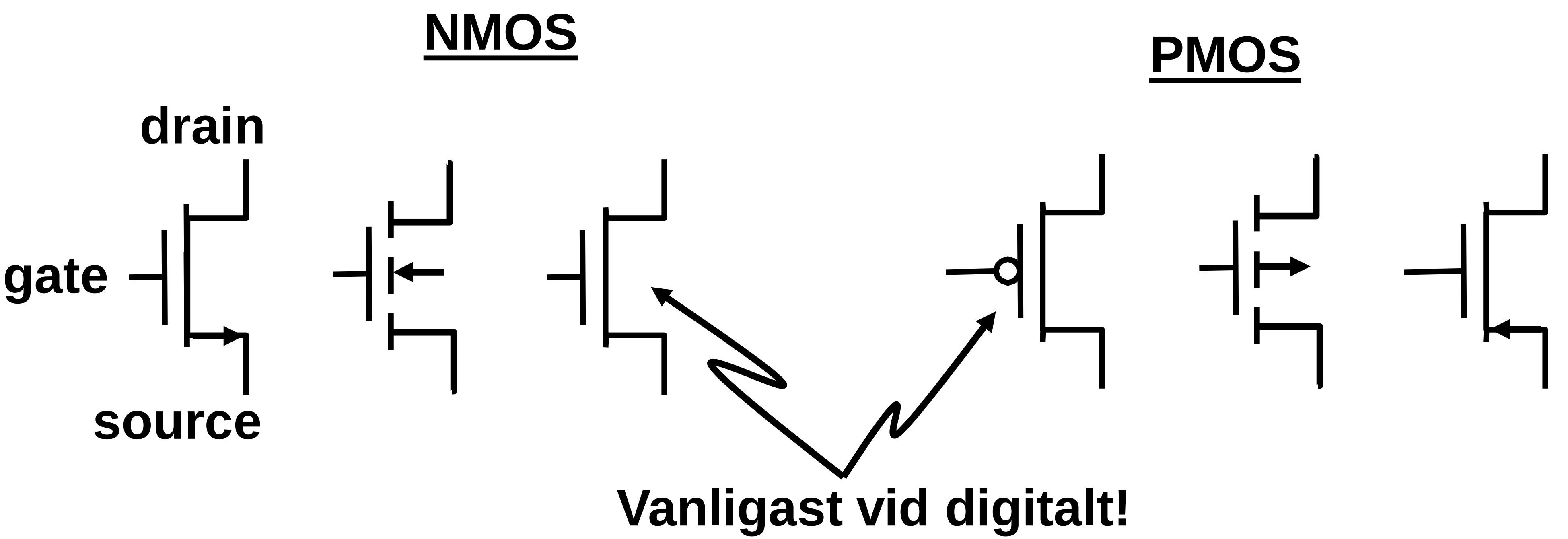
Digitalt
- Hög precision
- Komplexa algoritmer
- Lagringskapacitet

CD/DVD, MP3, Digitalkamera, GSM/4G/5G, datorer, etc, etc

Vad hade vi före det?

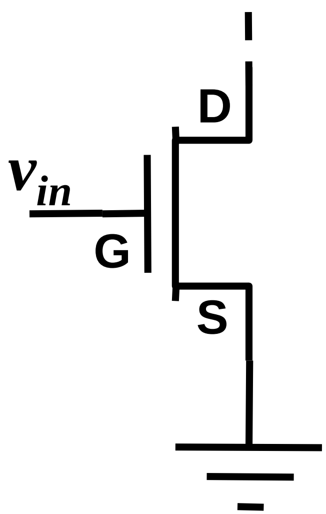
Var används dessa ”rör” idag?

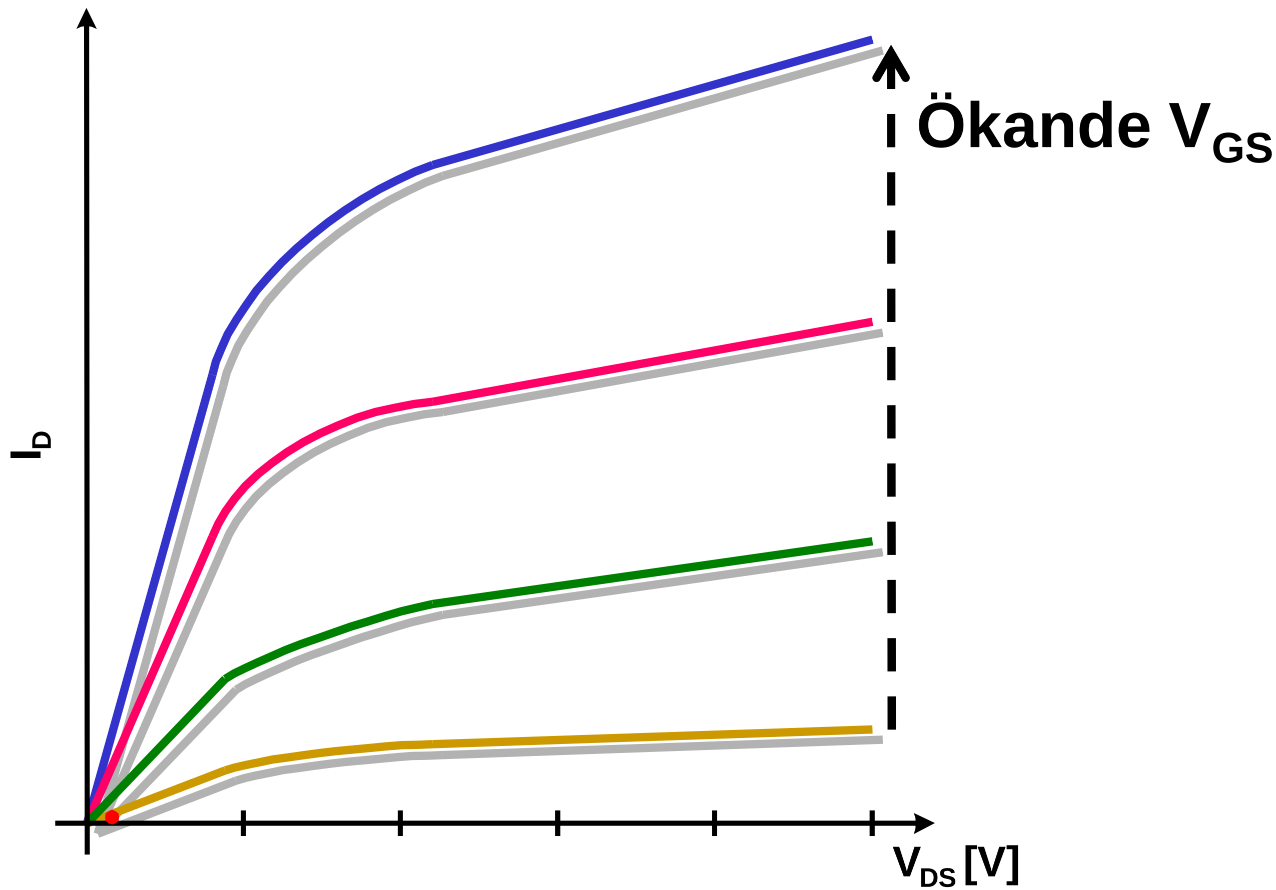
CMOS symboler



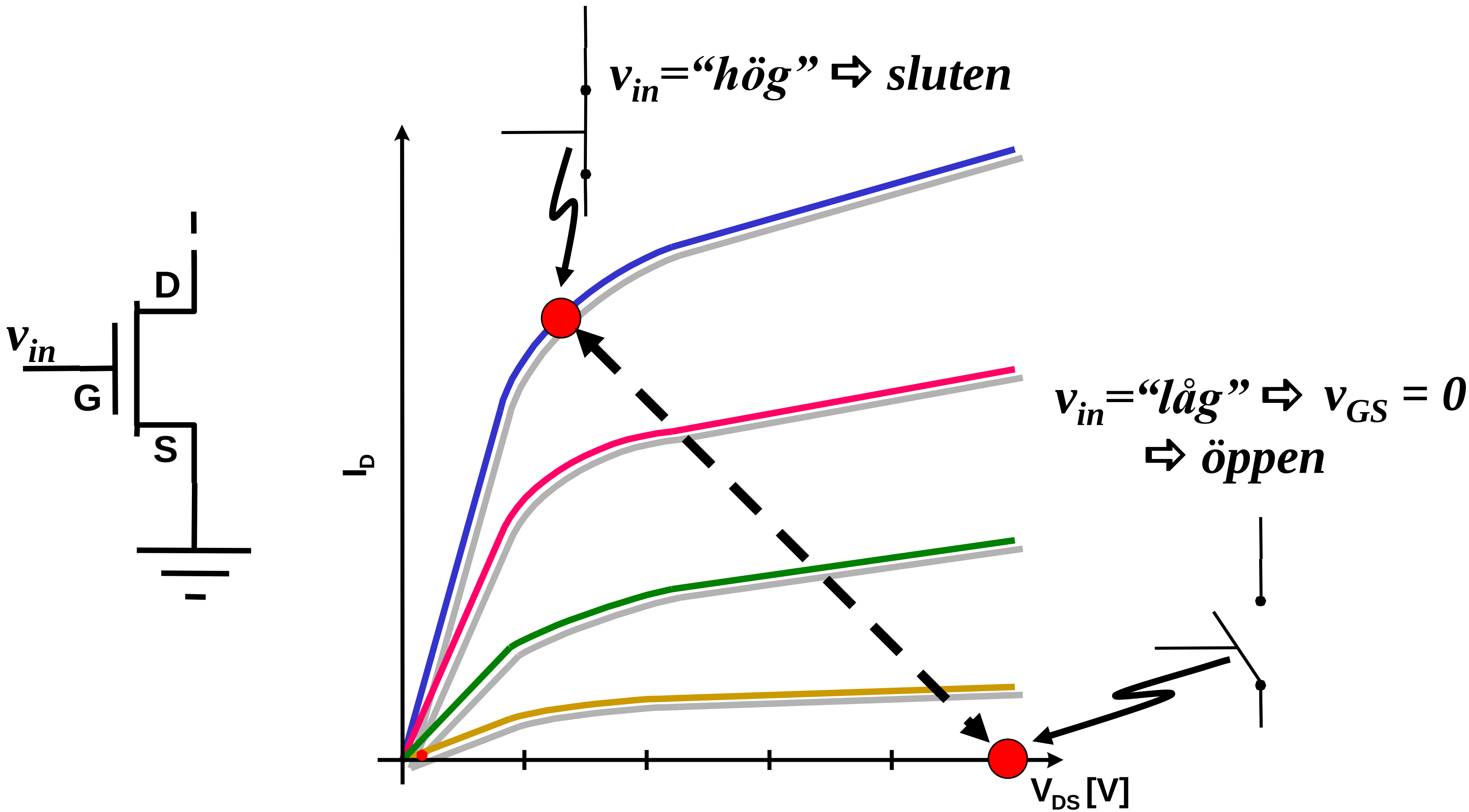
Substratet förutsetts kopplat till GND för NMOS och V_{DD} för PMOS om inget annat anges.

NMOS: utgångsdiagram

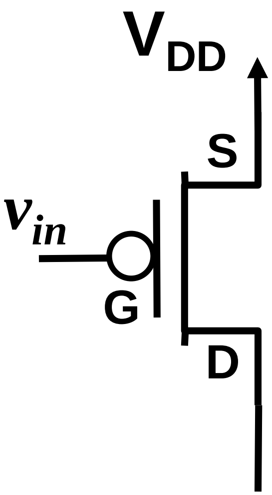


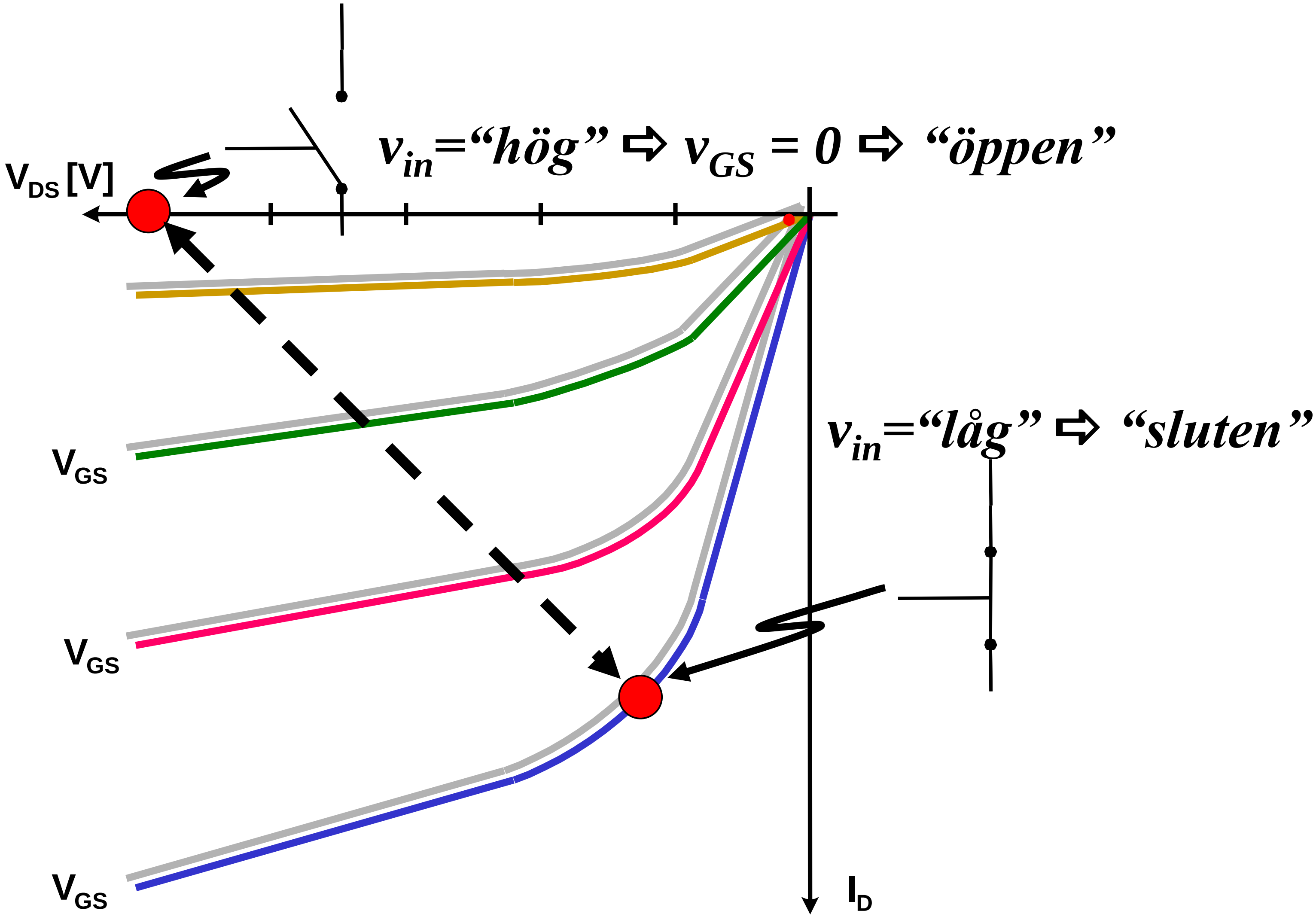


NMOS som switch

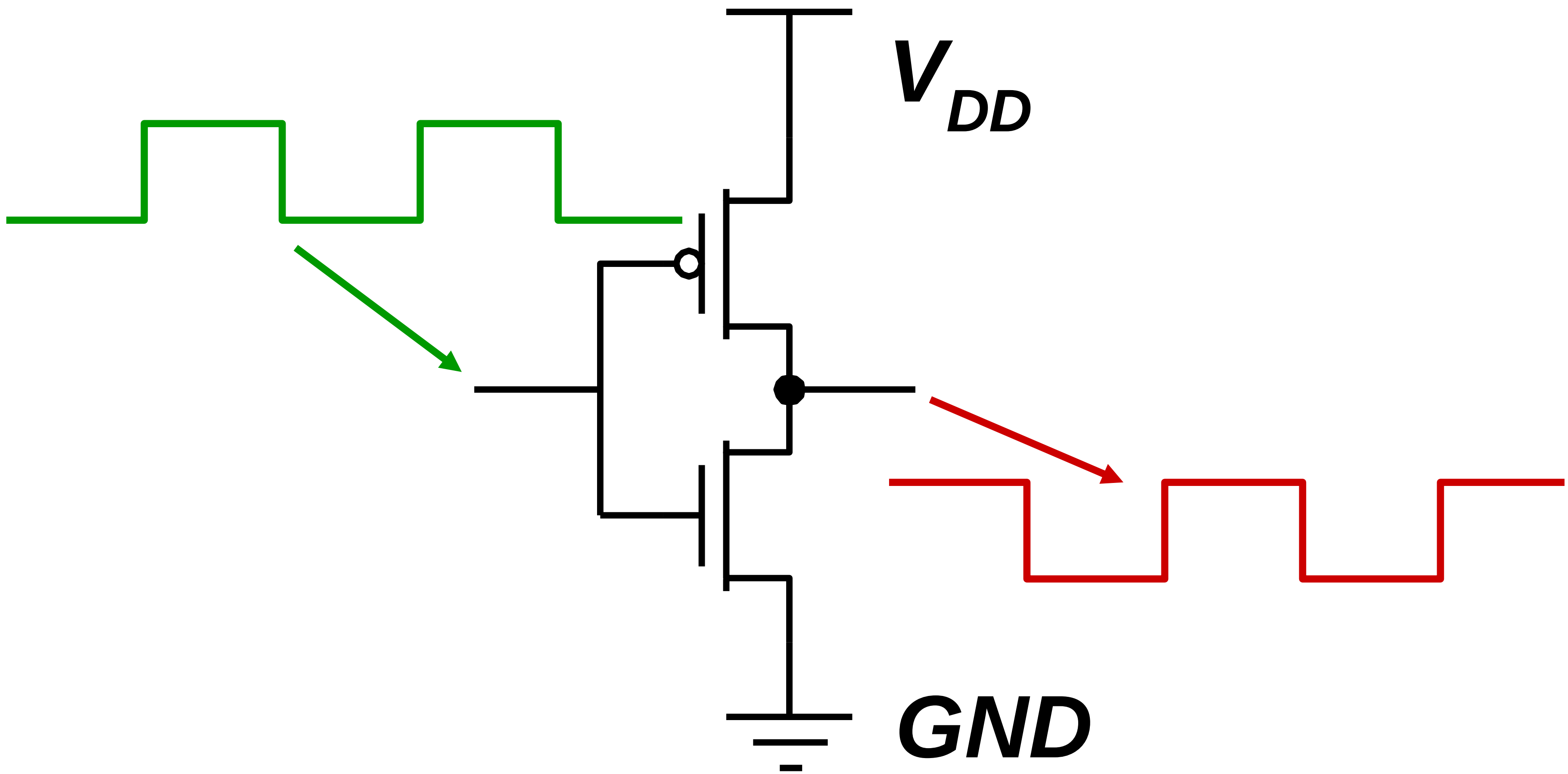


PMOS transistor as a switch

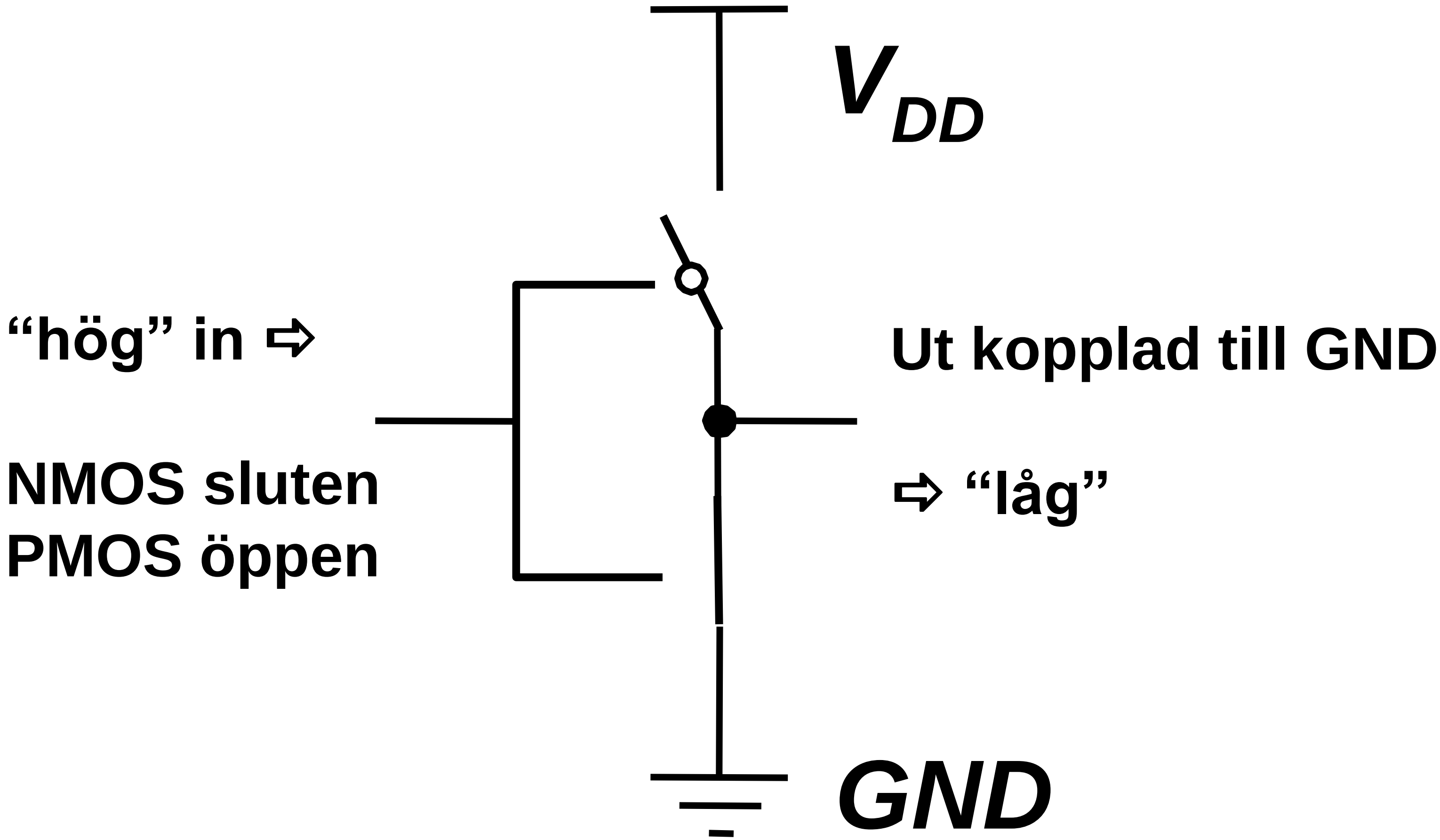




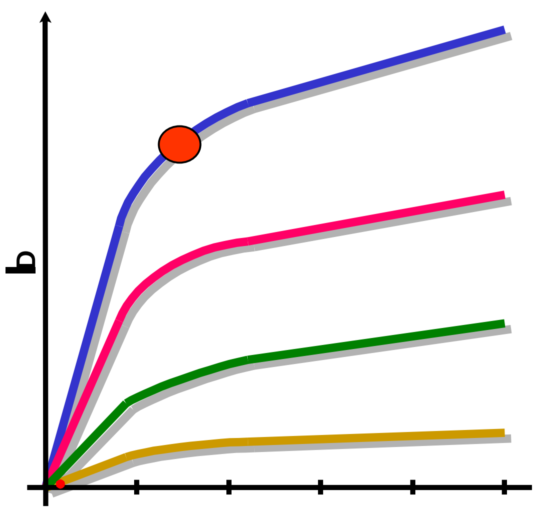
Digitala kretsar
CMOS Inverteraren

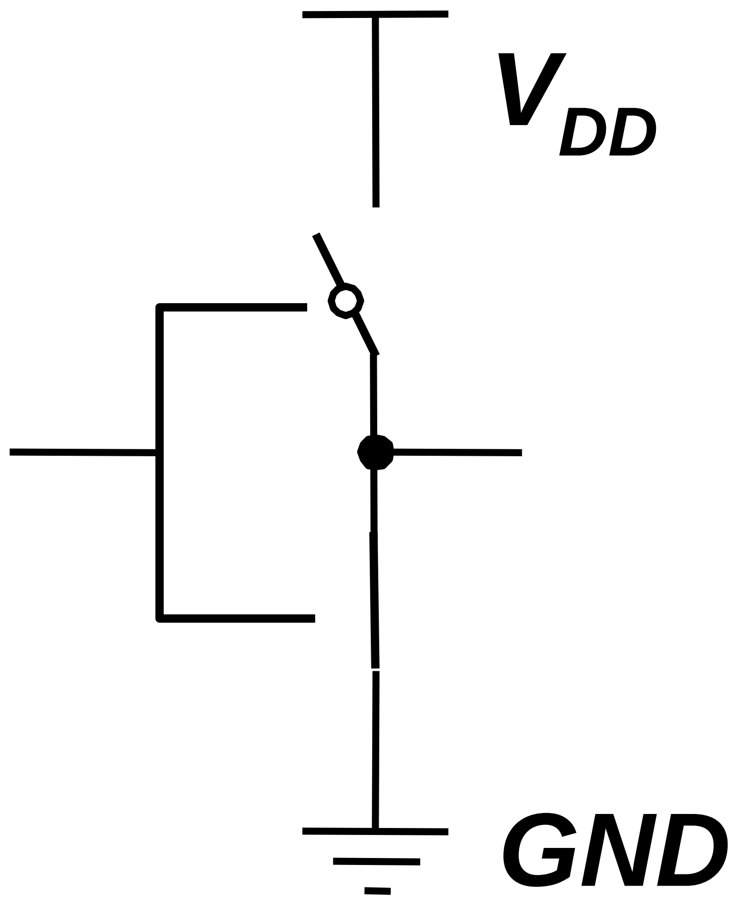


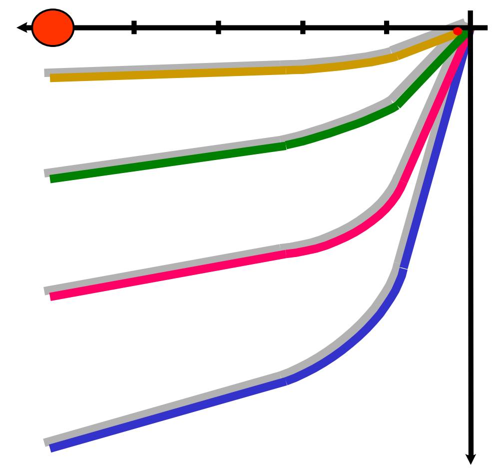
CMOS Inverteraren med transistorn som switch



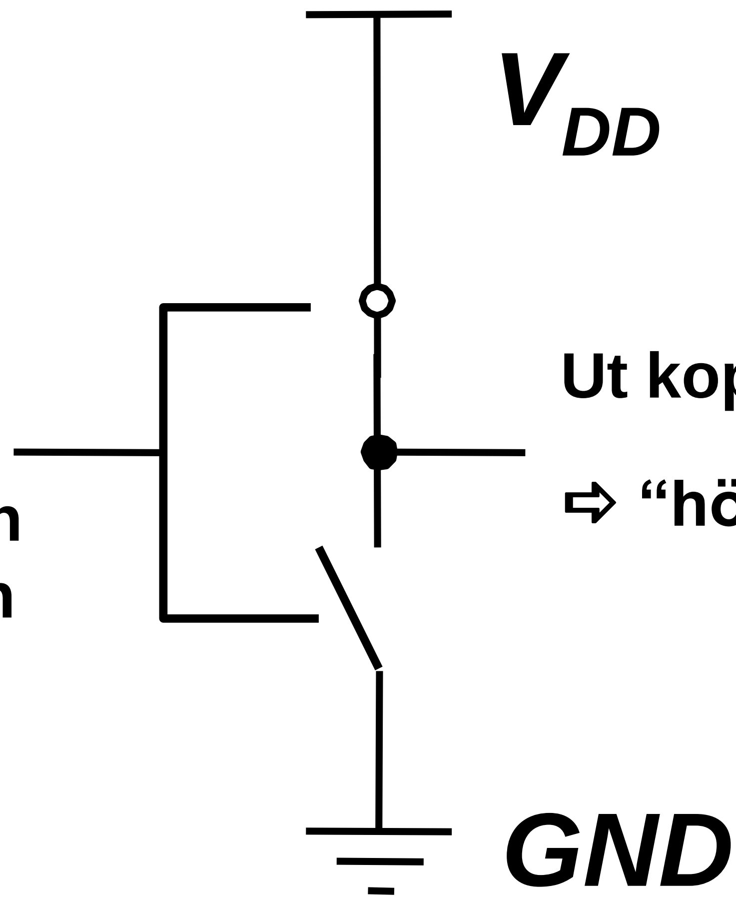
CMOS Inverteraren med transistorn som switch







CMOS Inverteraren med transistorn som switch



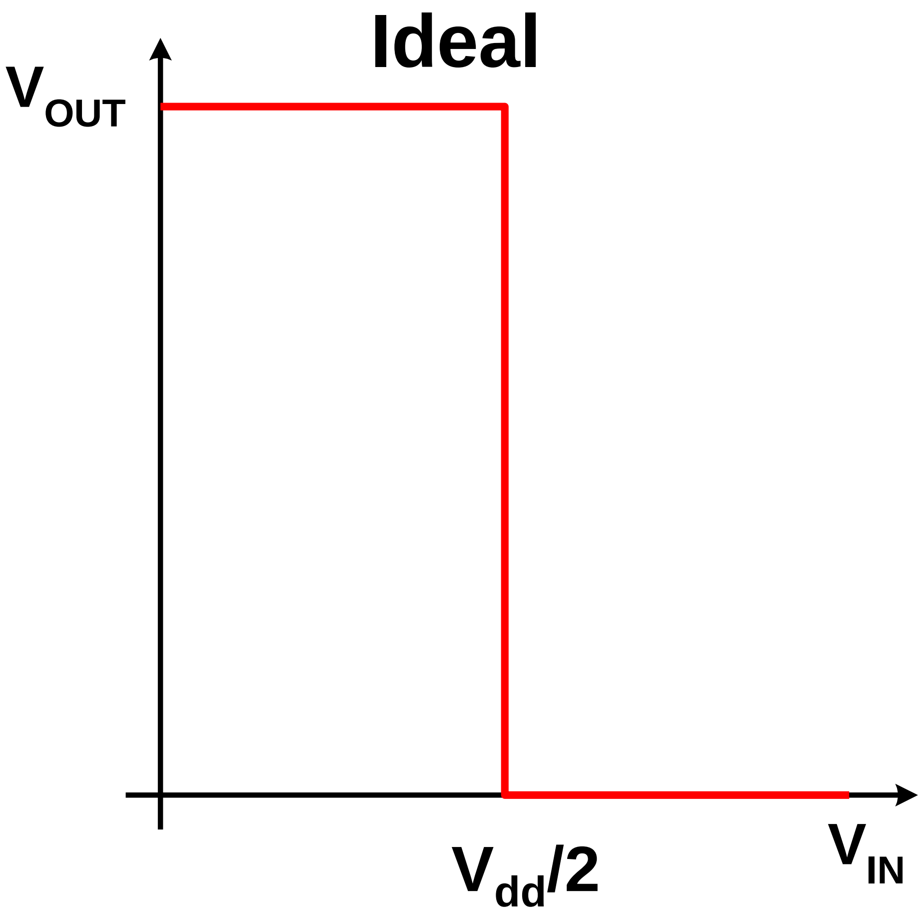
"låg" in ⇨

NMOS öppen
PMOS sluten

Ut kopplad till VDD

⇨ "hög"

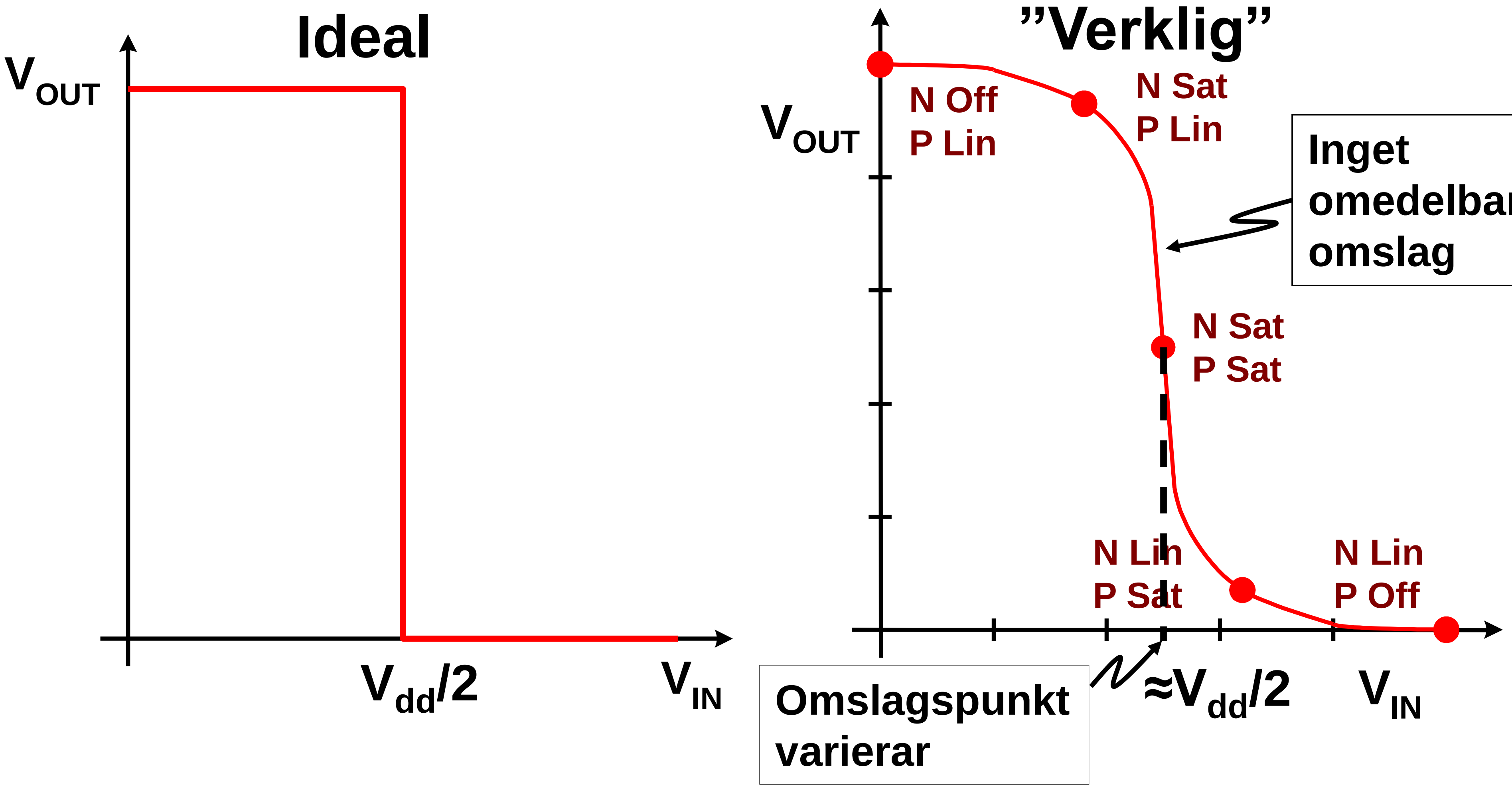
CMOS Inverteraren



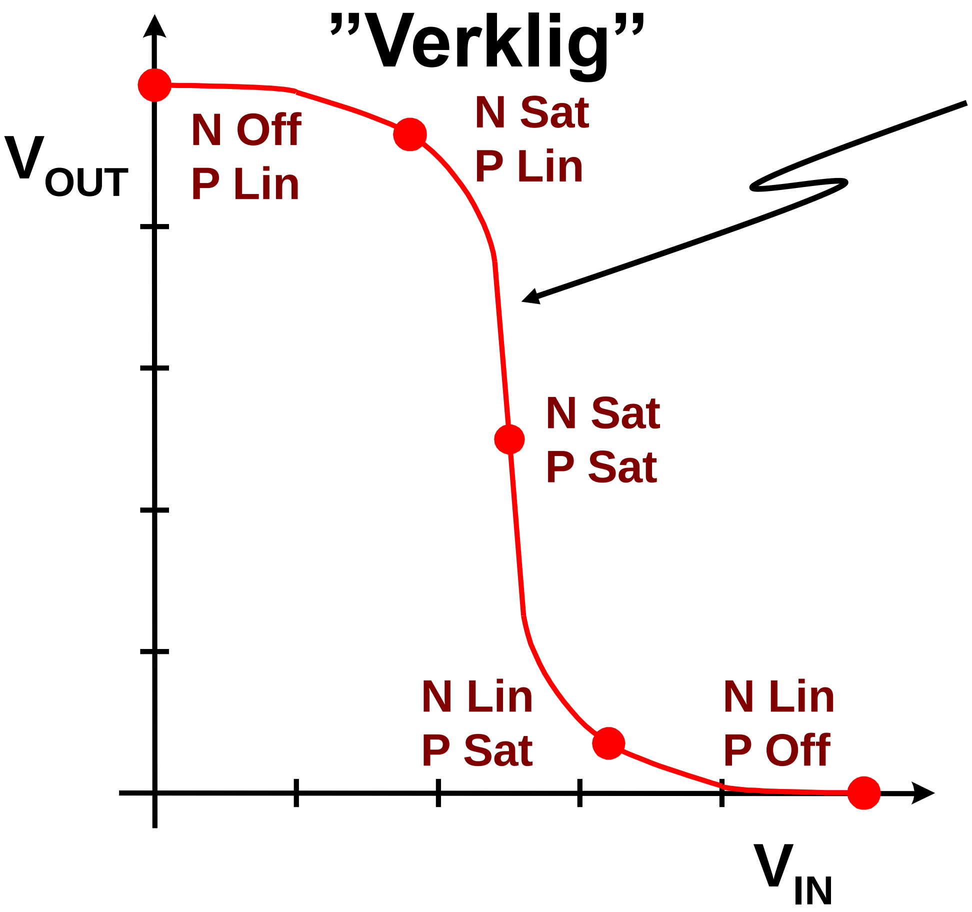
Idealt slår transistorerna om som strömbrytare vid $V_{DD}/2$.

Men hur är det egentligen?

CMOS Inverteraren

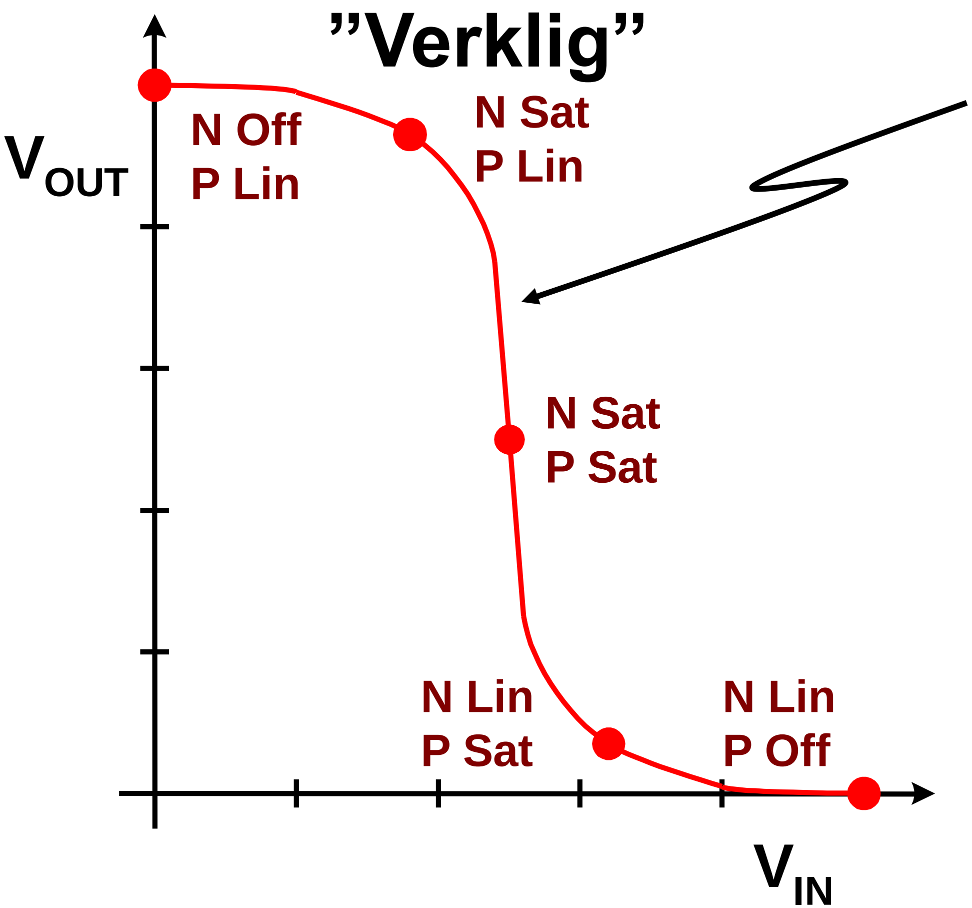


Omslagstid

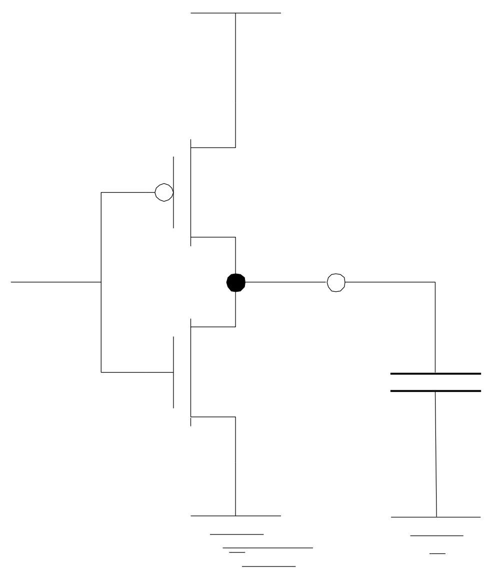


Vad beror omslagstiden på?

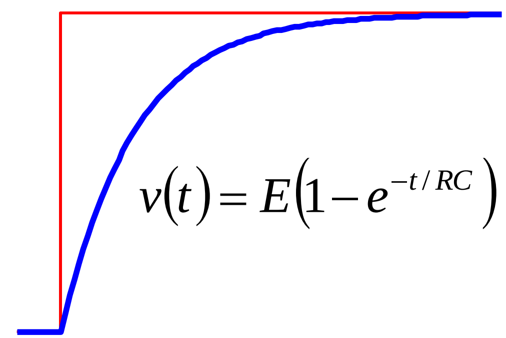
Omslagstid



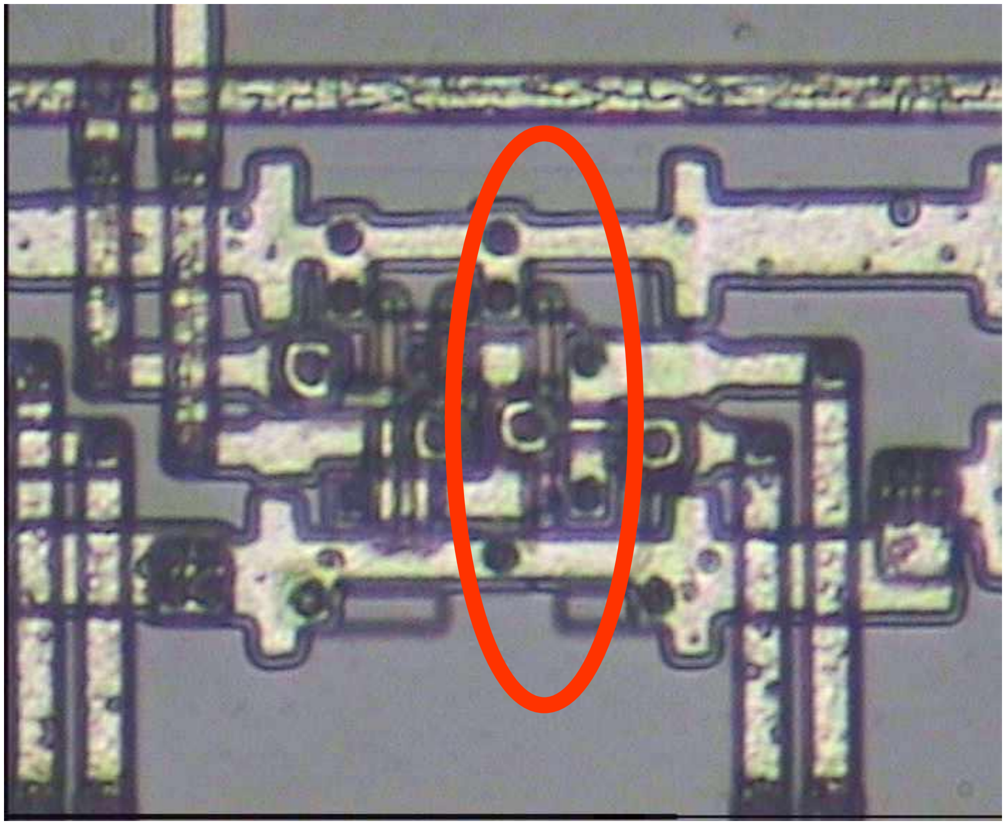
Vad beror omslagstiden på?



En kapacitans som inkluderar såväl interna som externa bidrag, t.ex. kapacitansen från ingången till nästa steg.
En kapacitans måste laddas upp och spänningen över den kan inte ändras momentant.

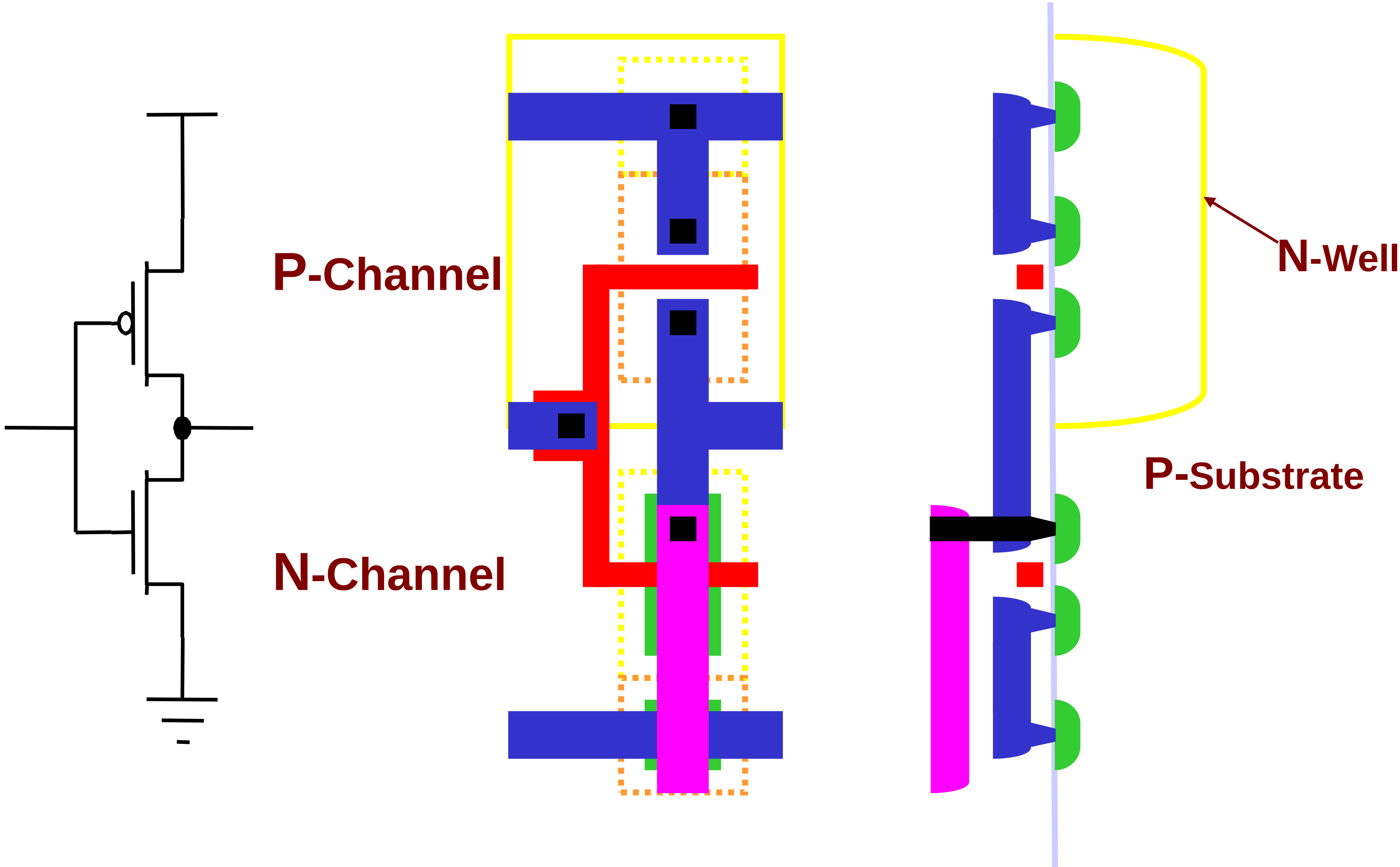


Hur konstruerar vi som ingenjörer tex en inverterare?



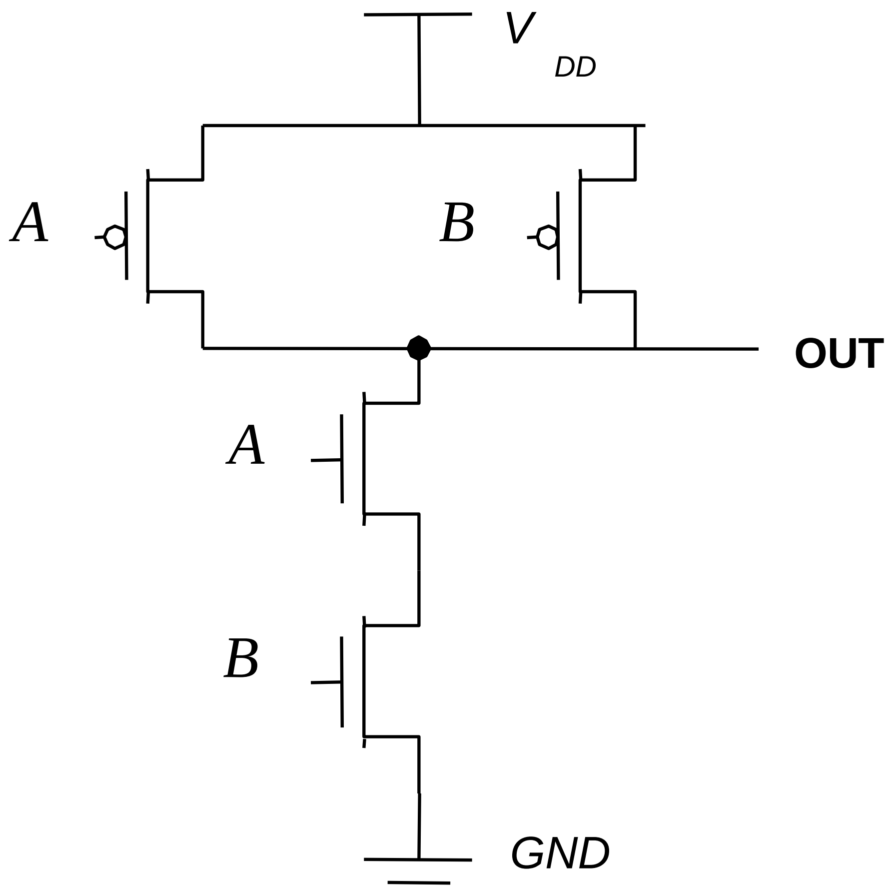
Om alls så i datorn.

Ofta kommer dessa grundkomponenter i ett cellbibliotek.



P-Channel
N-Channel
N-Well
P-Substrate

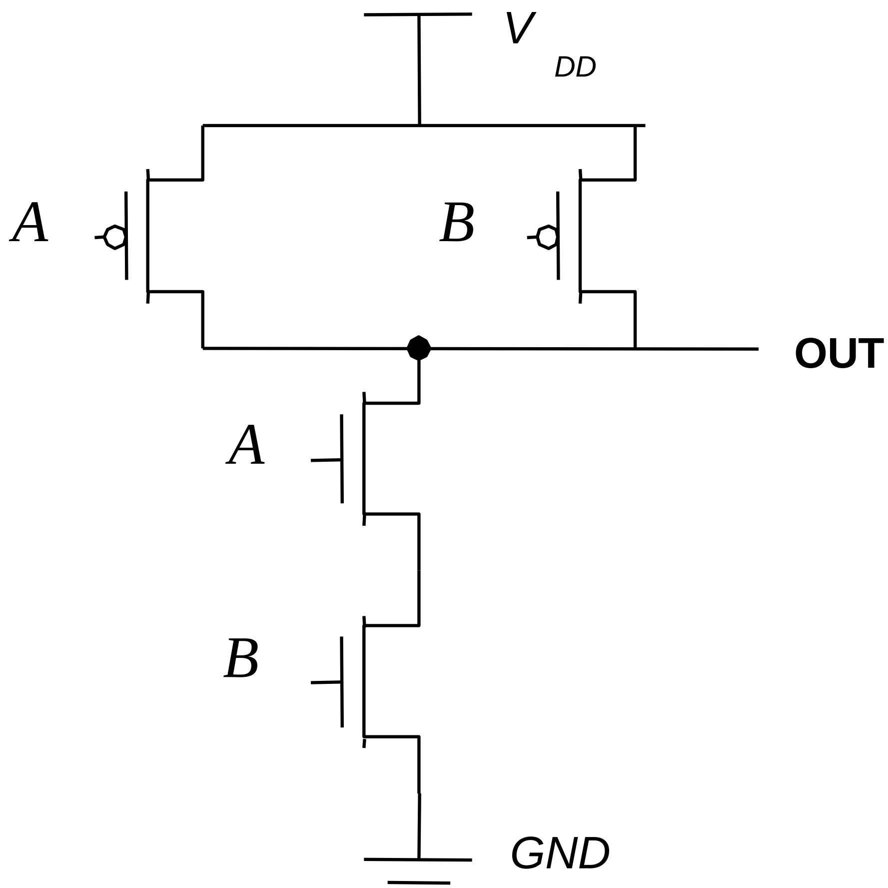
Logiska grindar



Truth Table

A	B	OUT
0	0	
0	1	
1	0	
1	1	

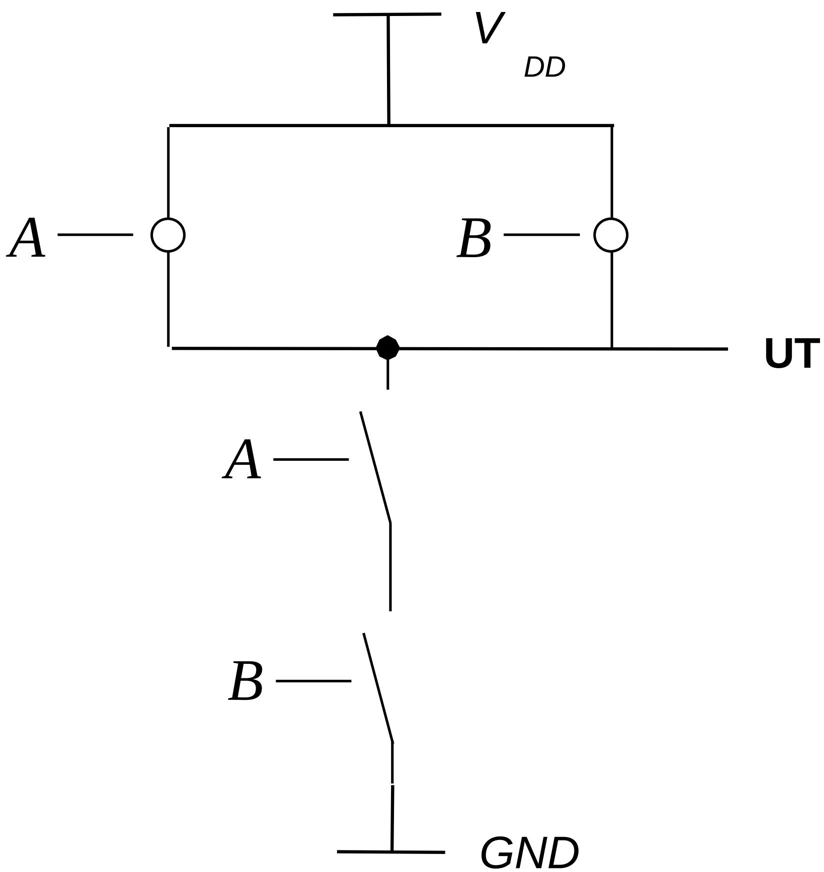
Logiska grindar, NAND



Sanningstabell

A	B	OUT
0	0	1
0	1	1
1	0	1
1	1	0

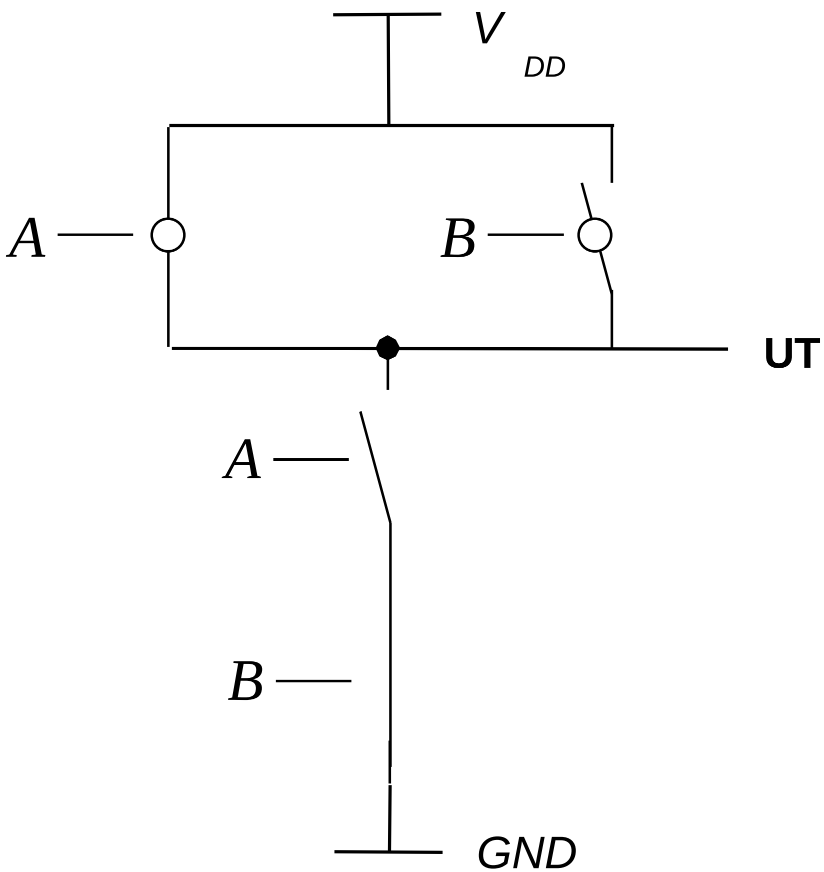
Logiska grindar, NAND



Sanningstabell

A	B	UT
0	0	1
0	1	1
1	0	1
1	1	0

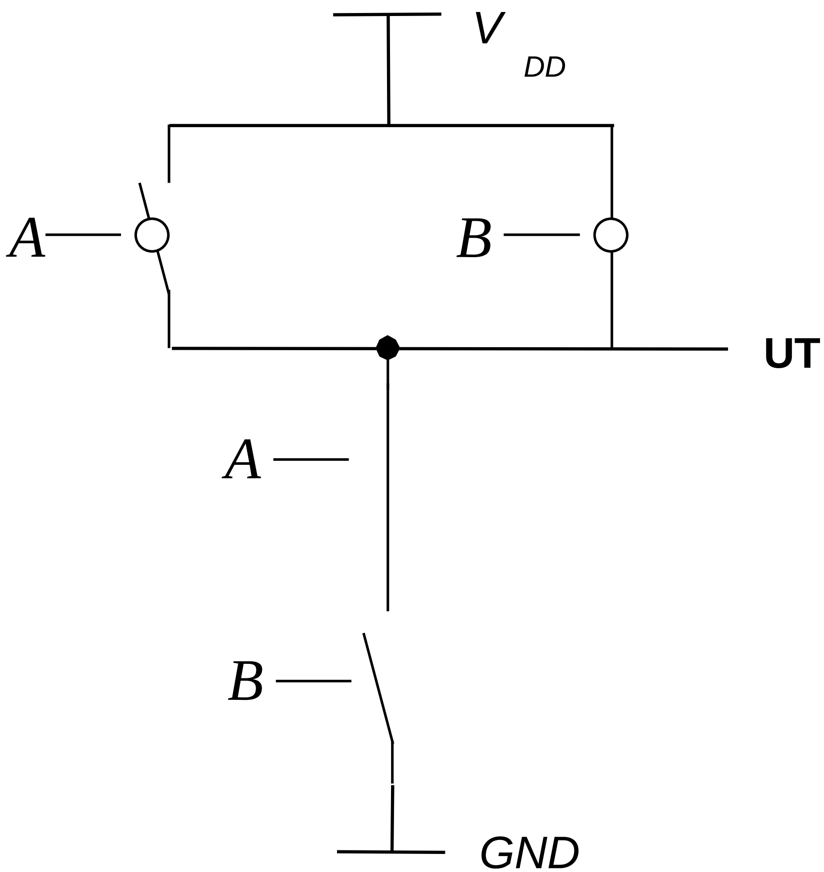
Logiska grindar, NAND



Sanningstabell

A	B	UT
0	0	1
0	**1**	**1**
1	0	1
1	1	0

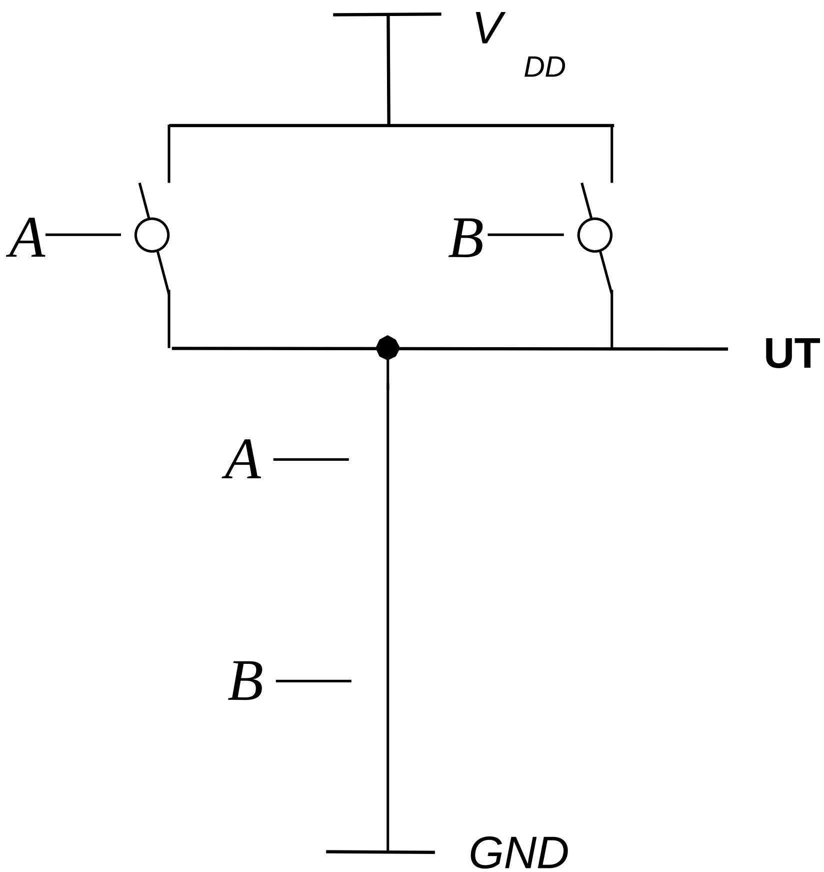
Logiska grindar, NAND



Sanningstabell

A	B	UT
0	0	1
0	1	1
1	0	1
1	1	0

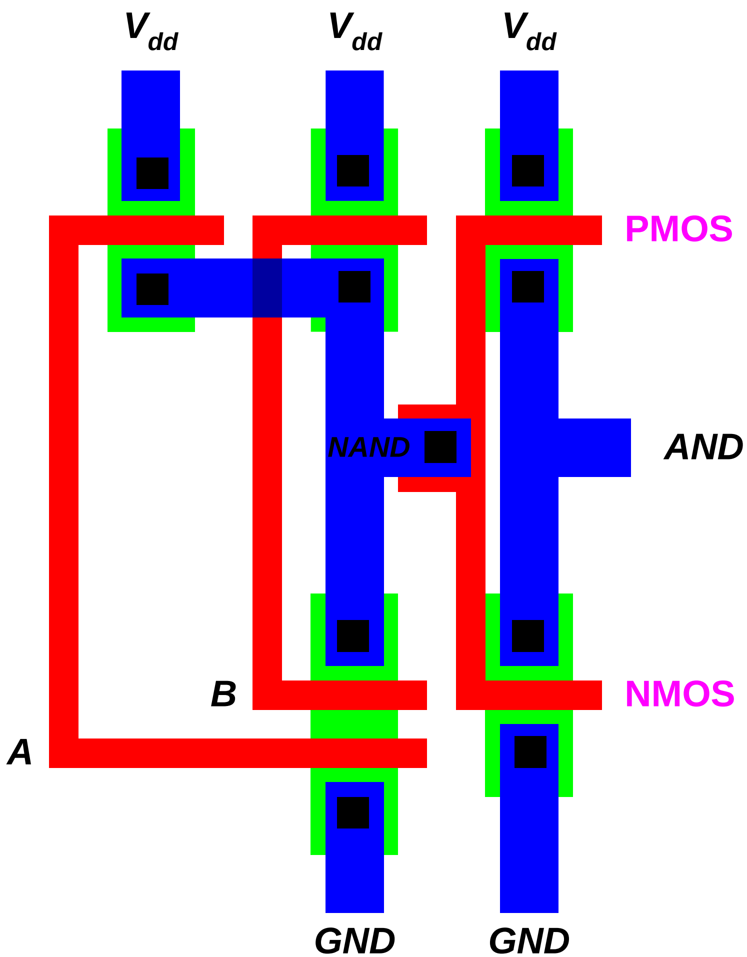
Logiska grindar, NAND

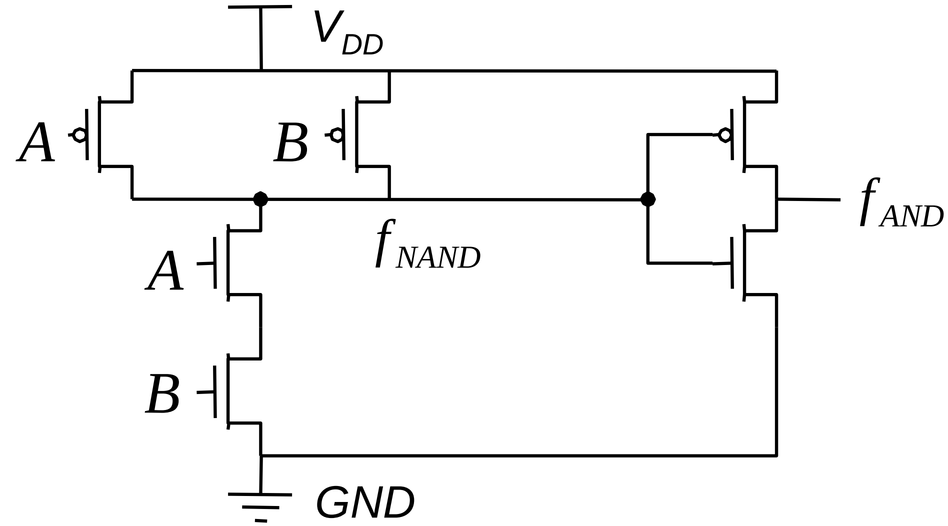


Sanningstabell

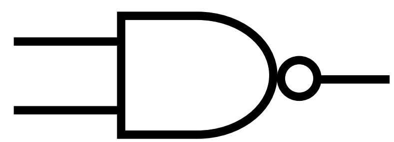
A	B	UT
0	0	1
0	1	1
1	0	1
1	1	0

Logiska grindar

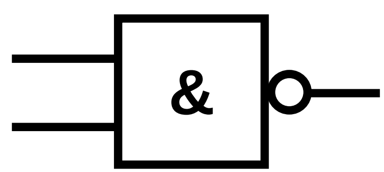




NAND + Inverter ⇨ AND

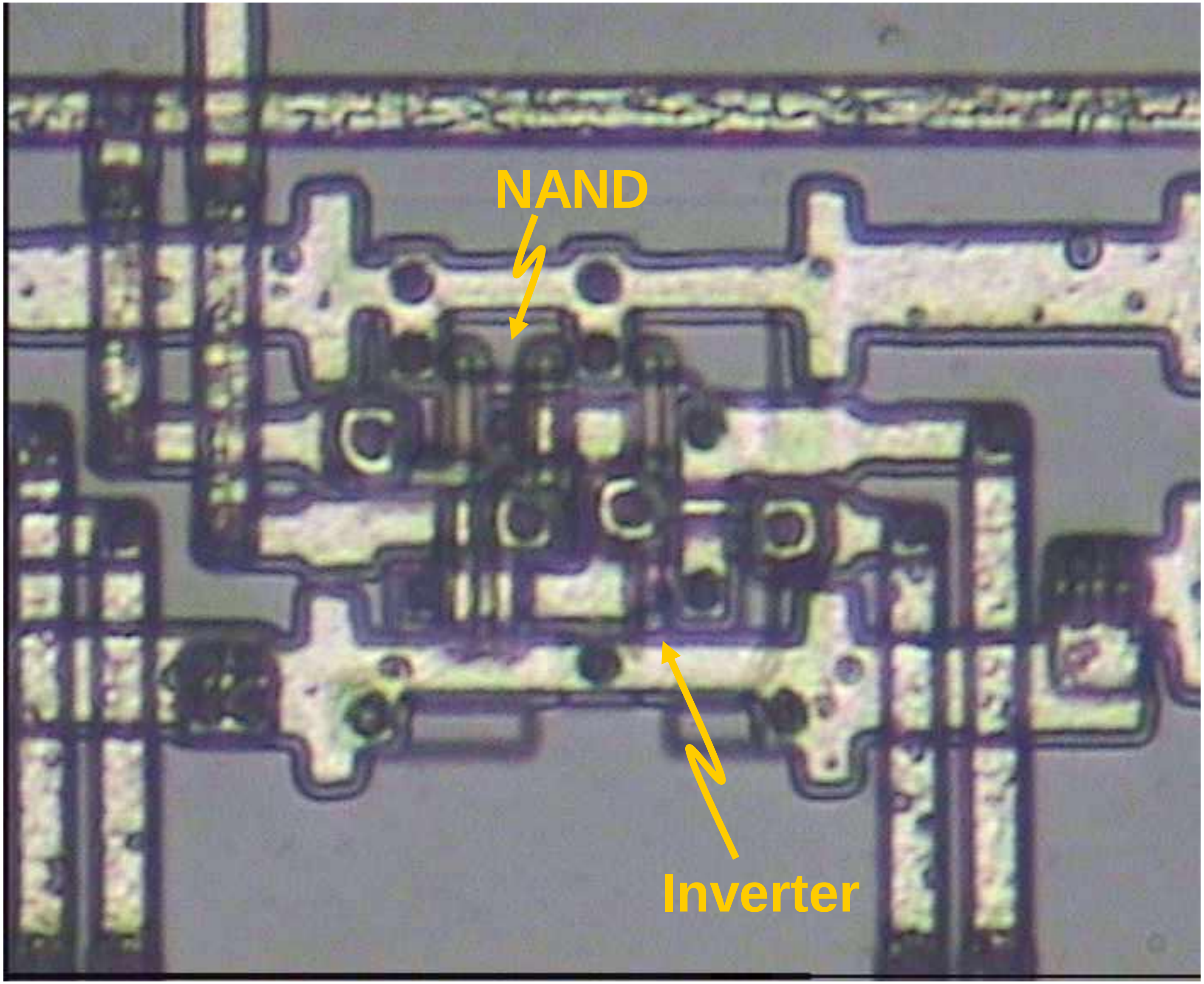


Amerikansk



Europeisk

A	B	NAND	AND
0	0	1	0
0	1	1	0
1	0	1	0
1	1	0	1

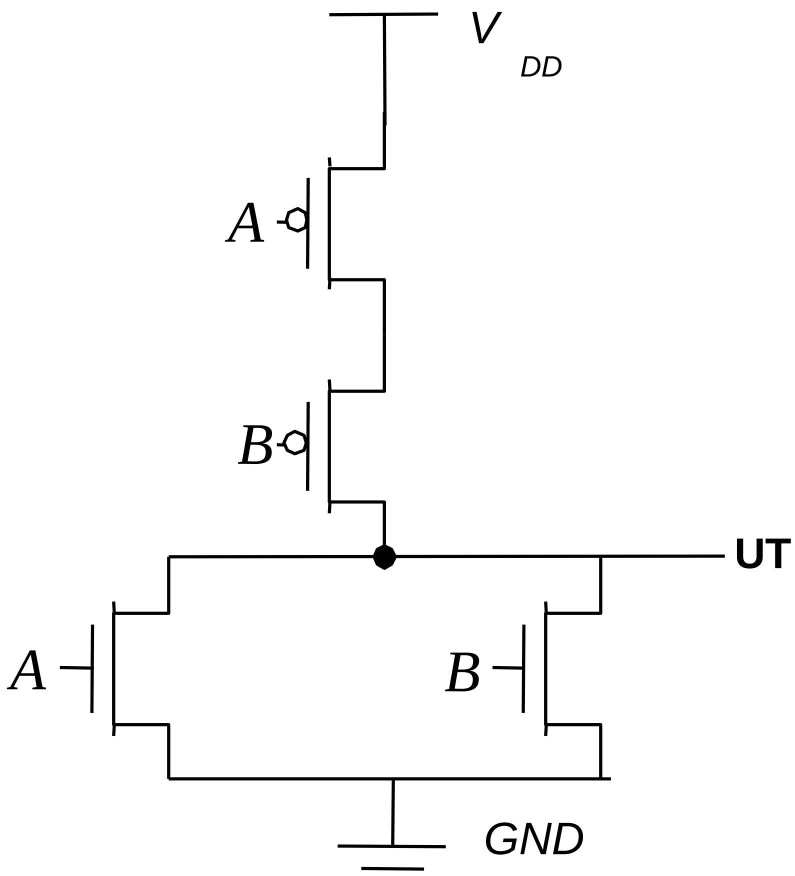


Two Input NAND/ AND

0.8 μm

CMOS

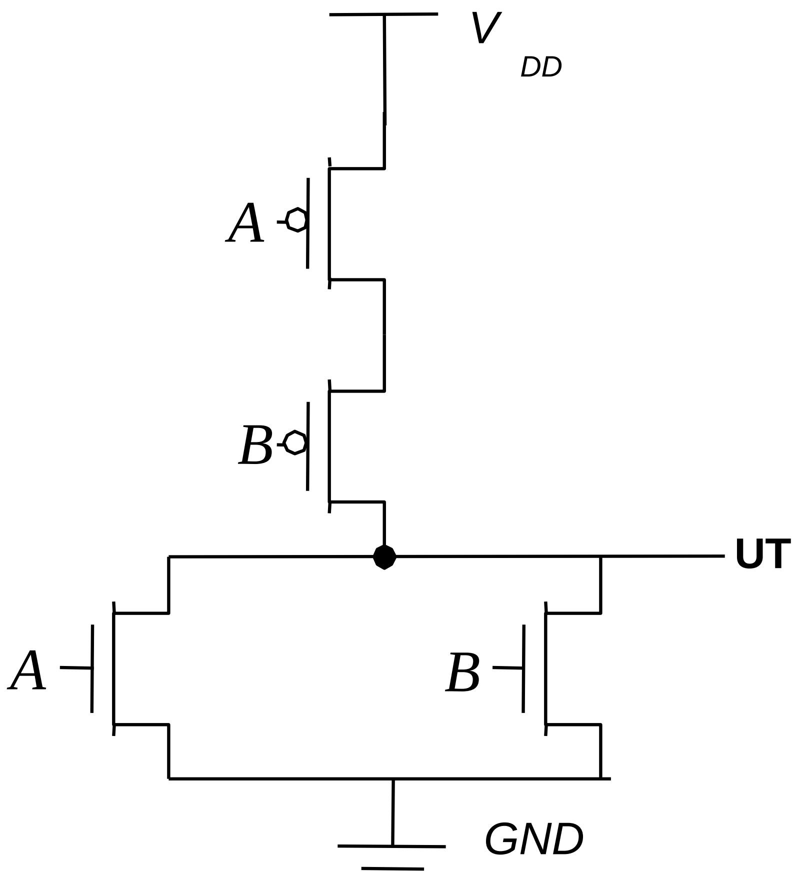
Logisk Funktion?



Sanningstabell

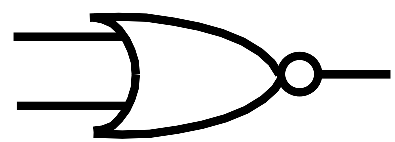
A	B	UT
0	0	
0	1	
1	0	
1	1	

Logisk Funktion: NOR

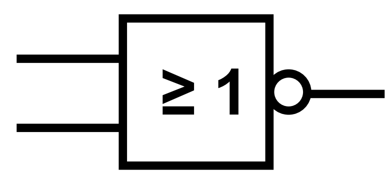


Sanningstabell

A	B	UT
0	0	1
0	1	0
1	0	0
1	1	0

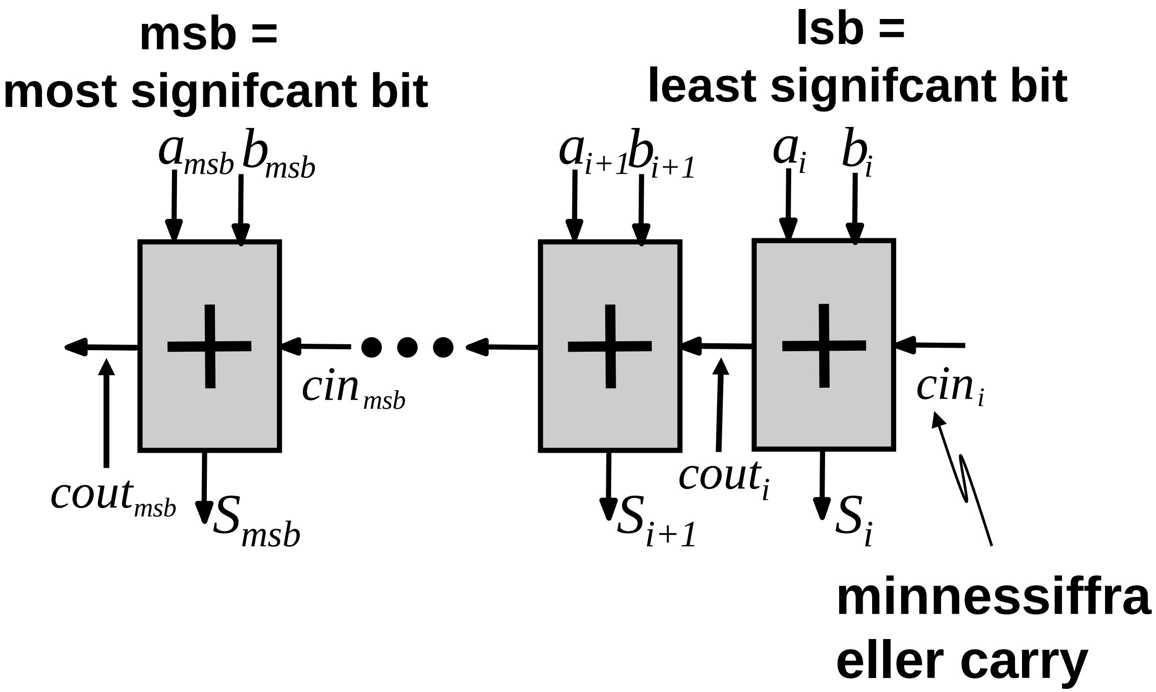


Amerikansk



Europeisk

...och nu en adderare

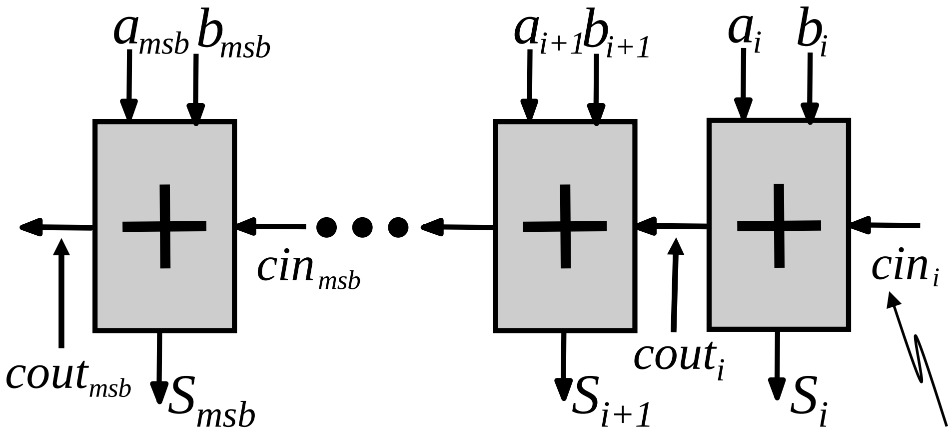


A	B	Cin	S	Cout
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

...och nu en adderare

msb =
most signifcant bit

lsb =
least signifcant bit



minnessiffra
eller carry

A	B	Cin	S	Cout
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

$$A = 244$$

$$B = 206$$

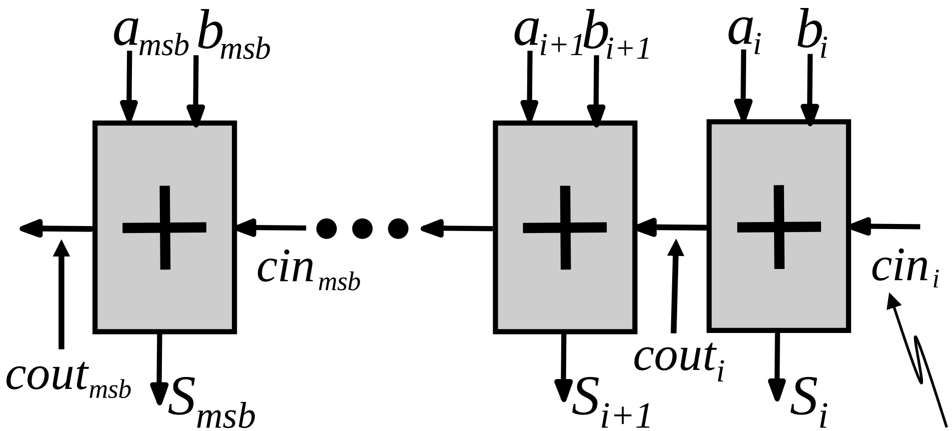
$$A + B = 450$$

$$\begin{array}{r} \underline{1}\ \underline{1}\underline{1}\underline{1}\underline{1}\underline{1} \\ 11110100 \\ +\quad 11001110 \\ \hline A + B = (1)11000010 \end{array}$$

...och nu en adderare

msb =
most signifcant bit

lsb =
least signifcant bit



minnessiffra eller carry

A	B	Cin	S	Cout
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

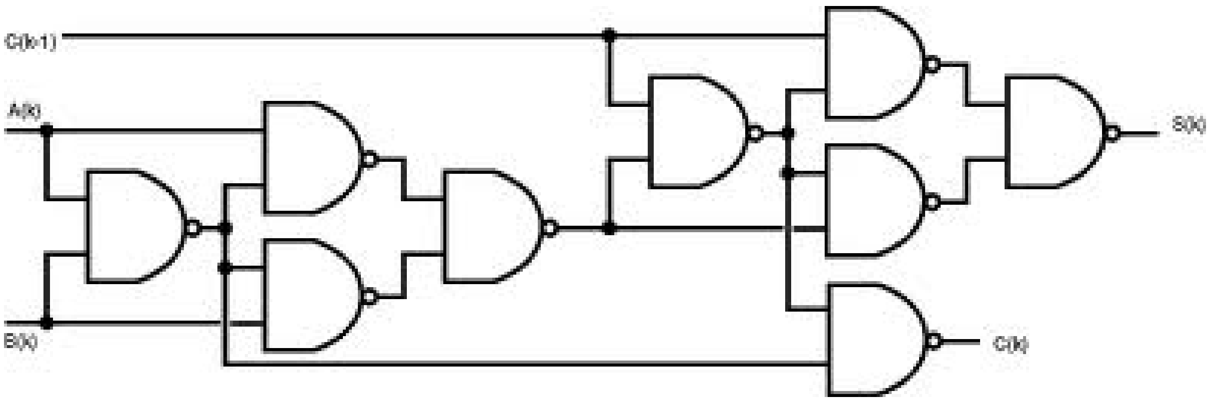
$$A = 244$$

$$B = 206$$

$$A + B = 450$$

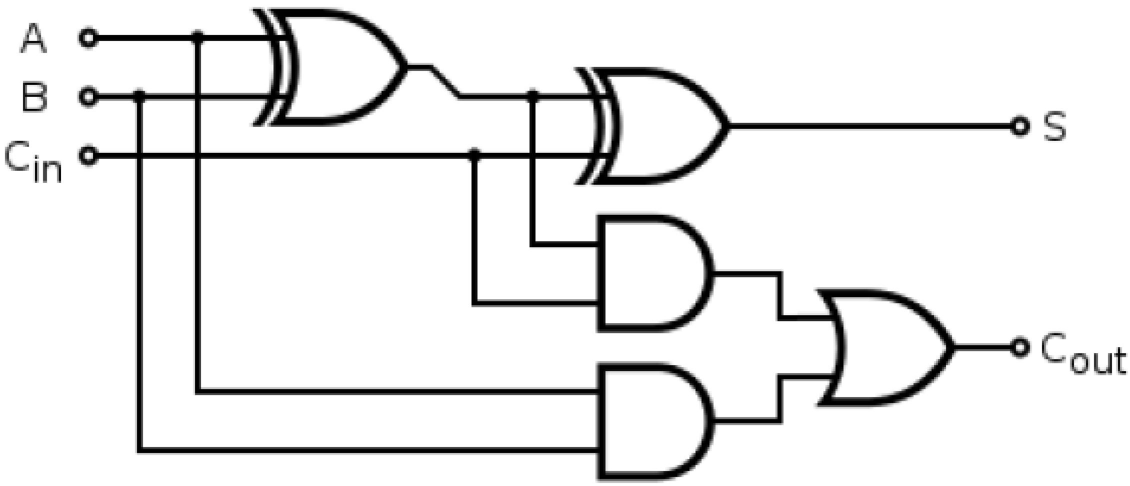
```
 1 1 1 1 1 1
   11110100
+  11001110
-----------
A + B = (1)11000010
```

Heladderare i CMOS, 1 bit



A	B	Cin	S	Cout
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Heladderare i CMOS, 1 bit

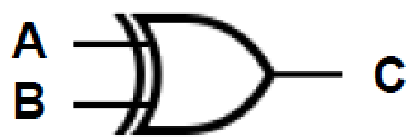


A	B	Cin	S	Cout
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

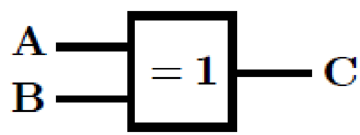
XOR

A	B	UT
0	0	0
0	1	1
1	0	1
1	1	0

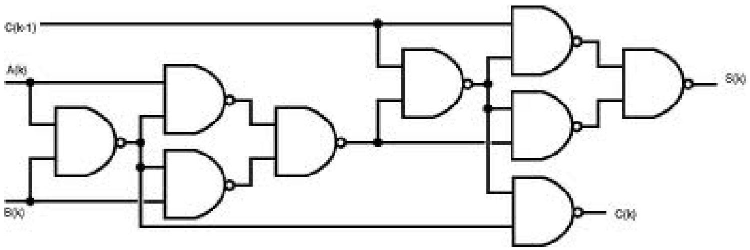
Amerikask symbol



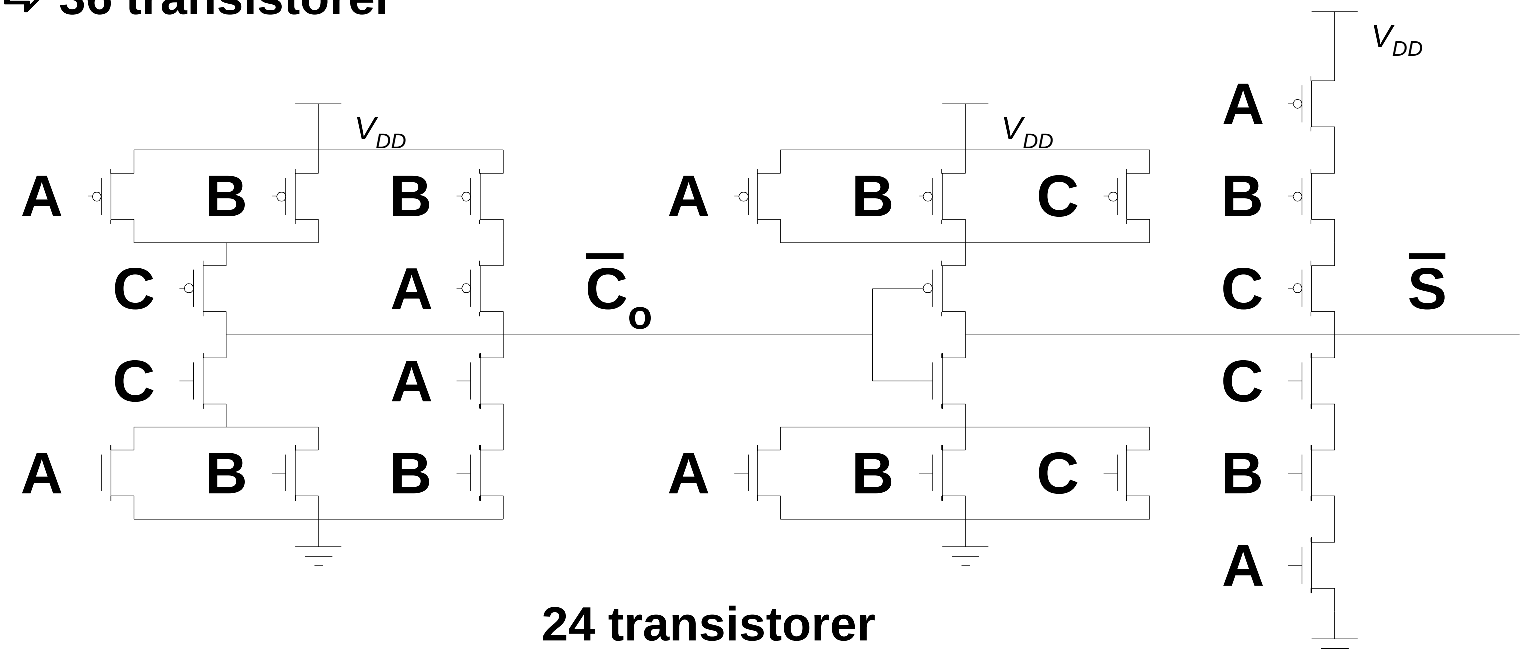
Europeisk symbol



Exempel på Heladderare i CMOS, 1 bit

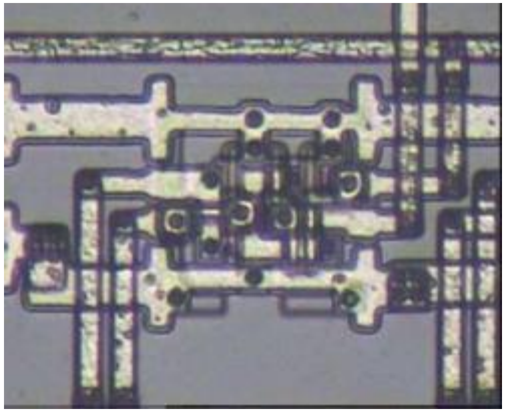


9 x NAND ⇨ 36 transistorer



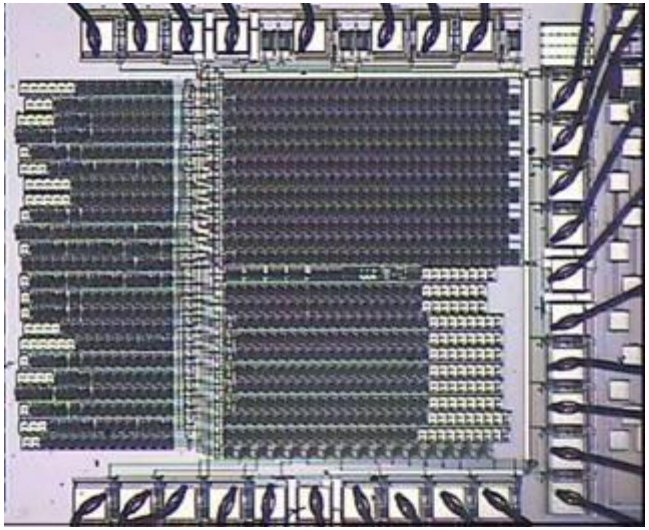
Mer i Digitaltekniken!

Integrerade kretsar av olika komplexitet



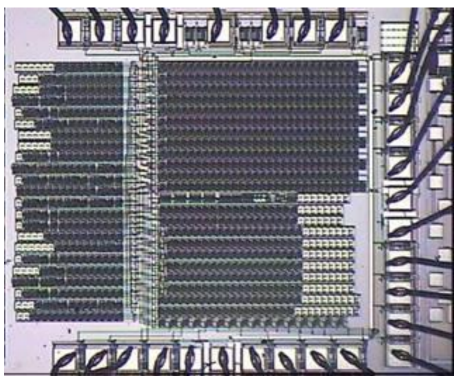
AND-Gate
6 Transistorer

Filter - 10000
Transistorer

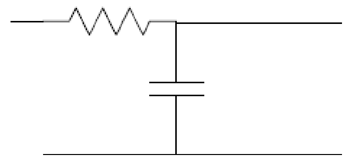


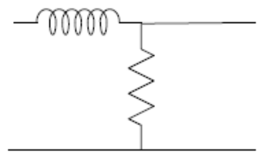
Digitala eller analoga filter?

Digitalt Filter
10000
Transistorer



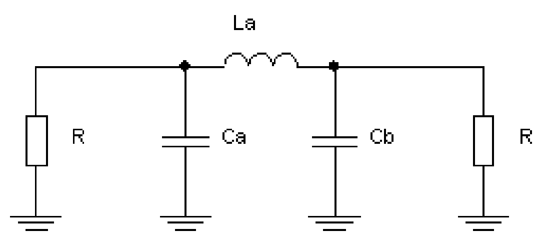
Analoga filter

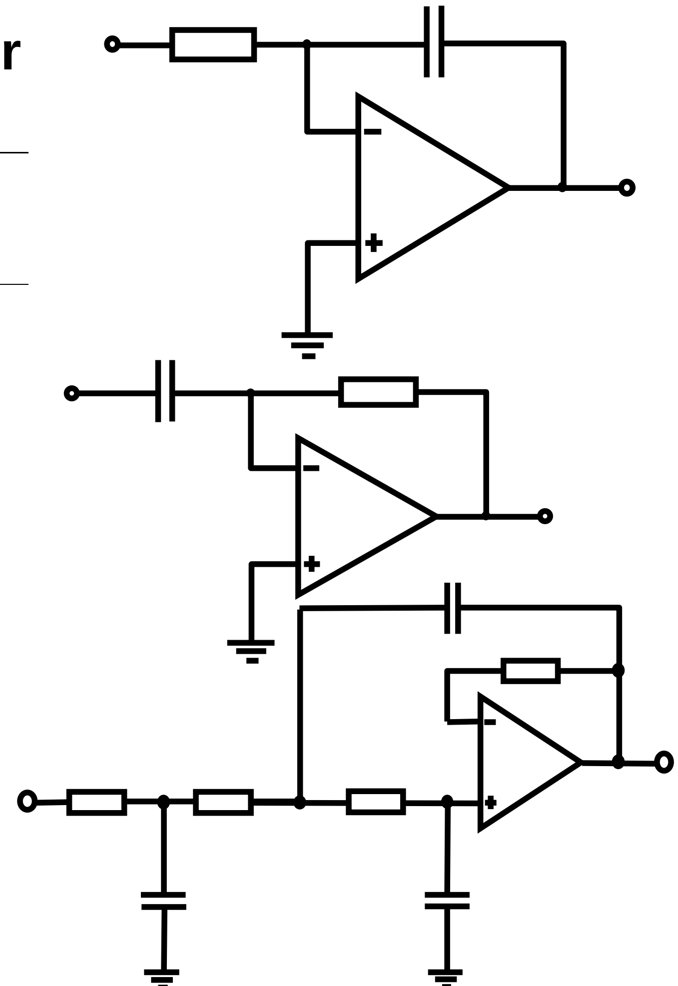




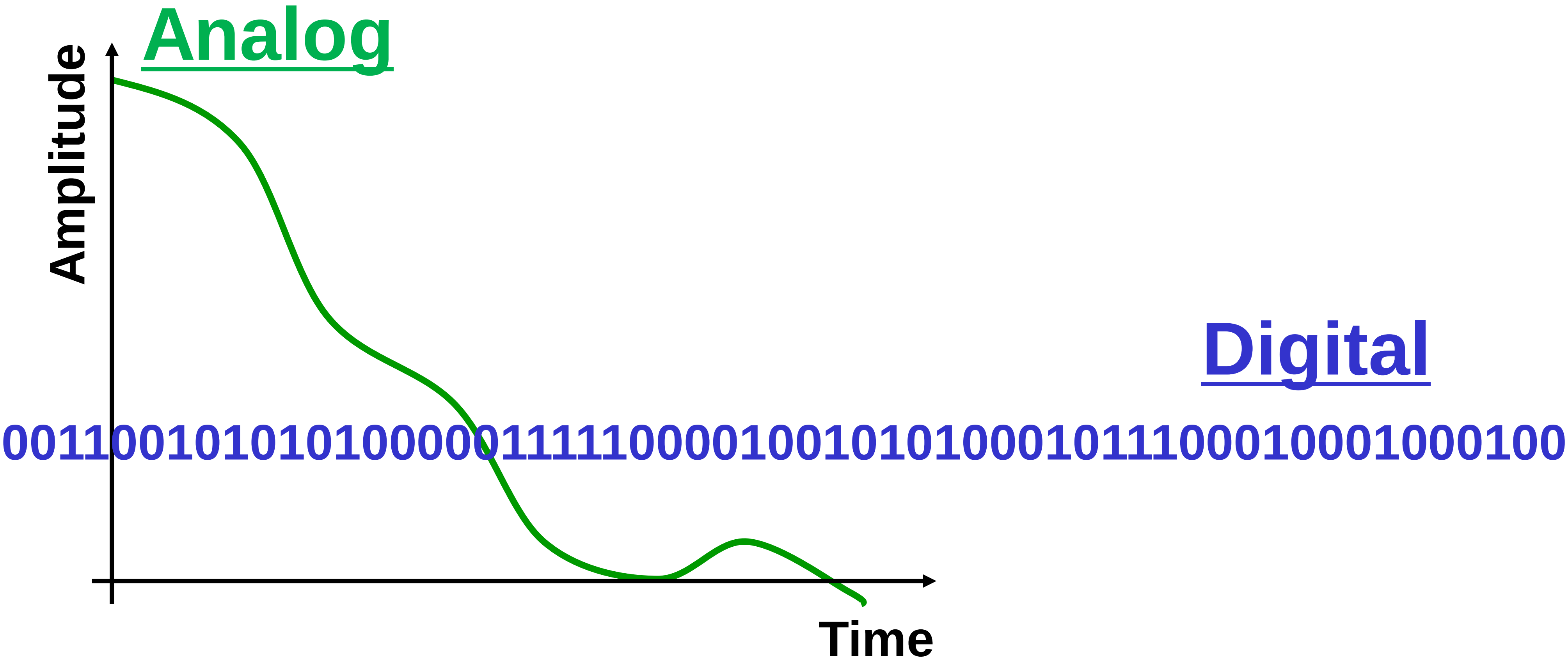
$$H = \frac{1}{1 + j\omega RC}$$

$$H = \frac{1}{1 + j\omega R/L}$$





Vad är ett digitalt filter?

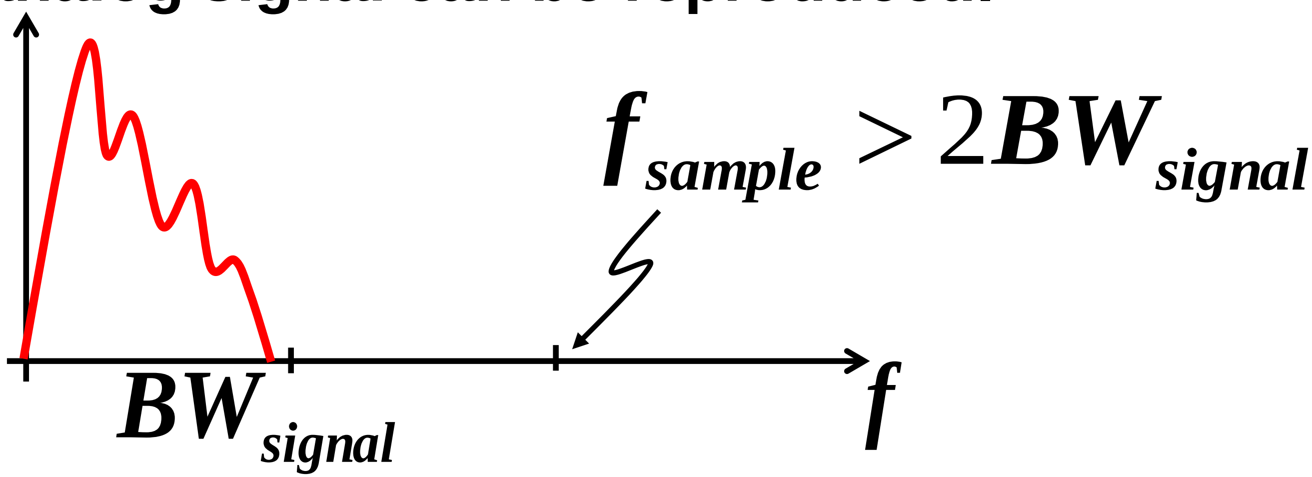


Samplings teoremet

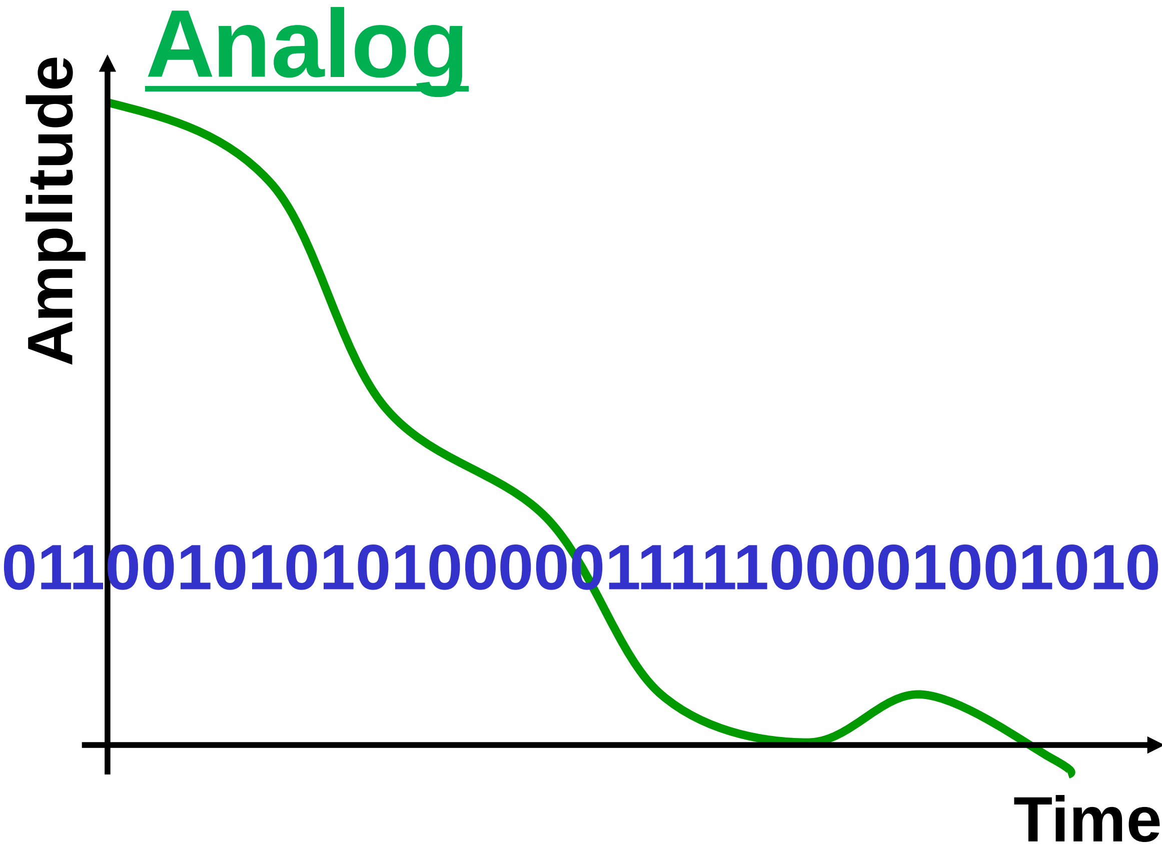
If an analog signal with a bandwitdth of BW_{signal},
is sampled with a sampling frequency of

$$f_{sample} > 2BW_{signal},$$

the analog signal can be reproduced.



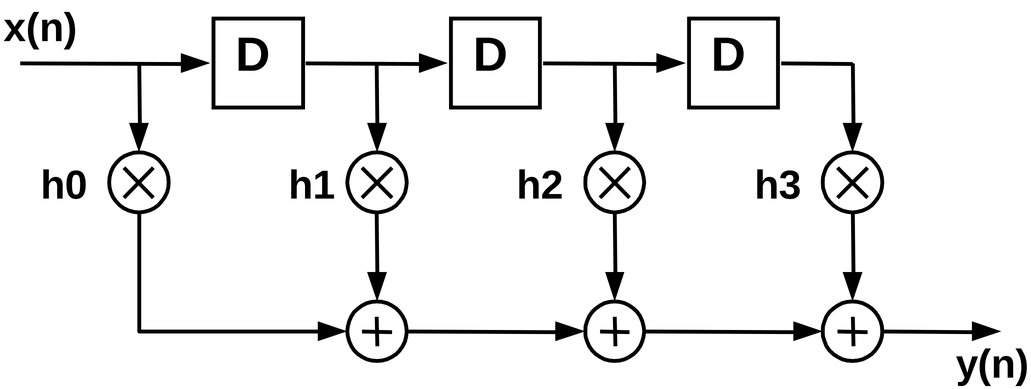
Vad är ett digitalt filter?



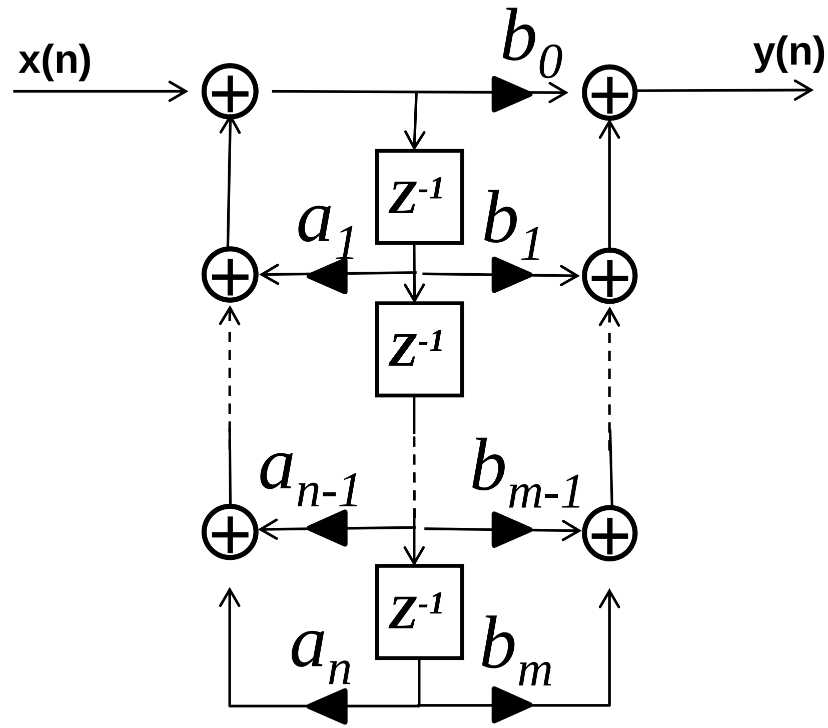
Digital

00110010101010000011111000010010101000101110001000100 0100

Vad är ett digitalt filter?

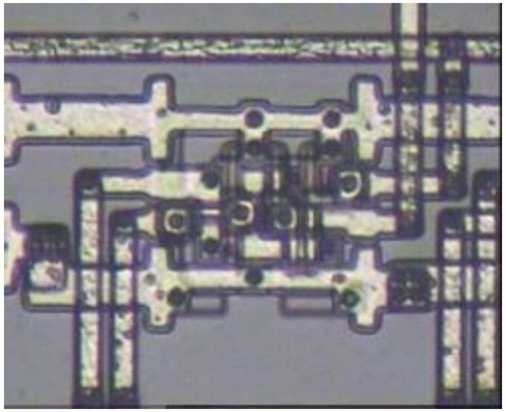


$$y(n) = \sum_{k=0}^{N-1} h(k)x(n-k)$$



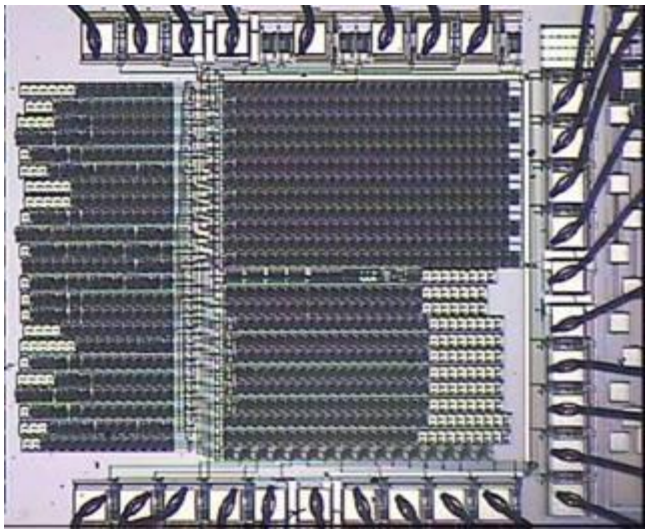
$$y(n) = \sum_{i=0}^{m} b_i x(n-i) + \sum_{j=1}^{n} a_j y(n-j)$$

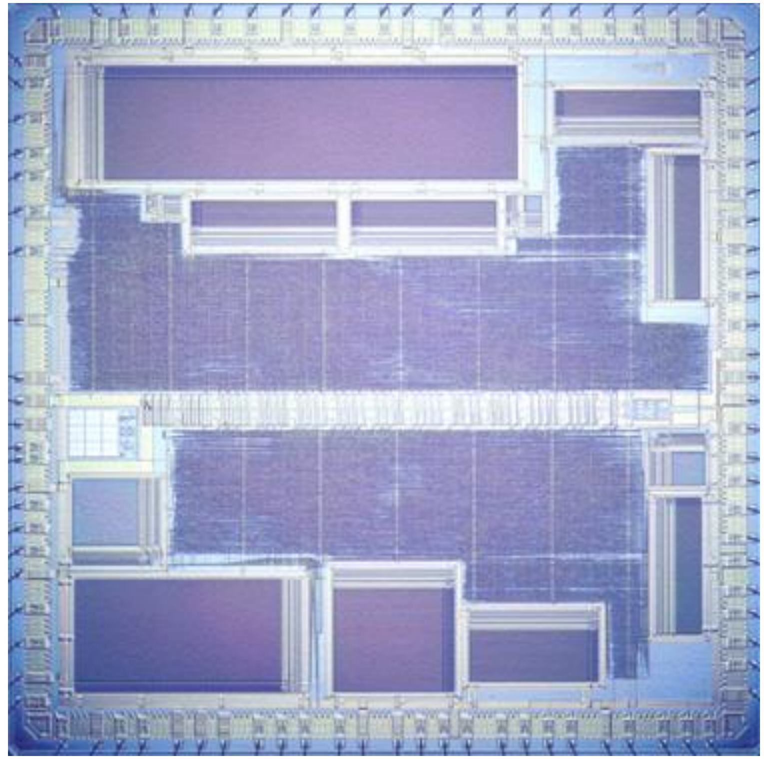
Integrerade kretsar av olika komplexitet



AND-Gate
6 Transistorer

Filter - 10000
Transistorer

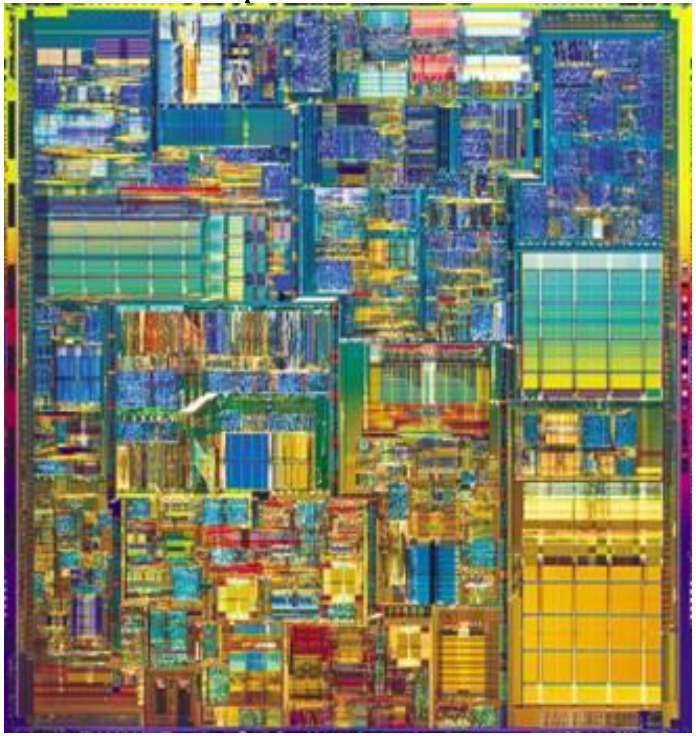




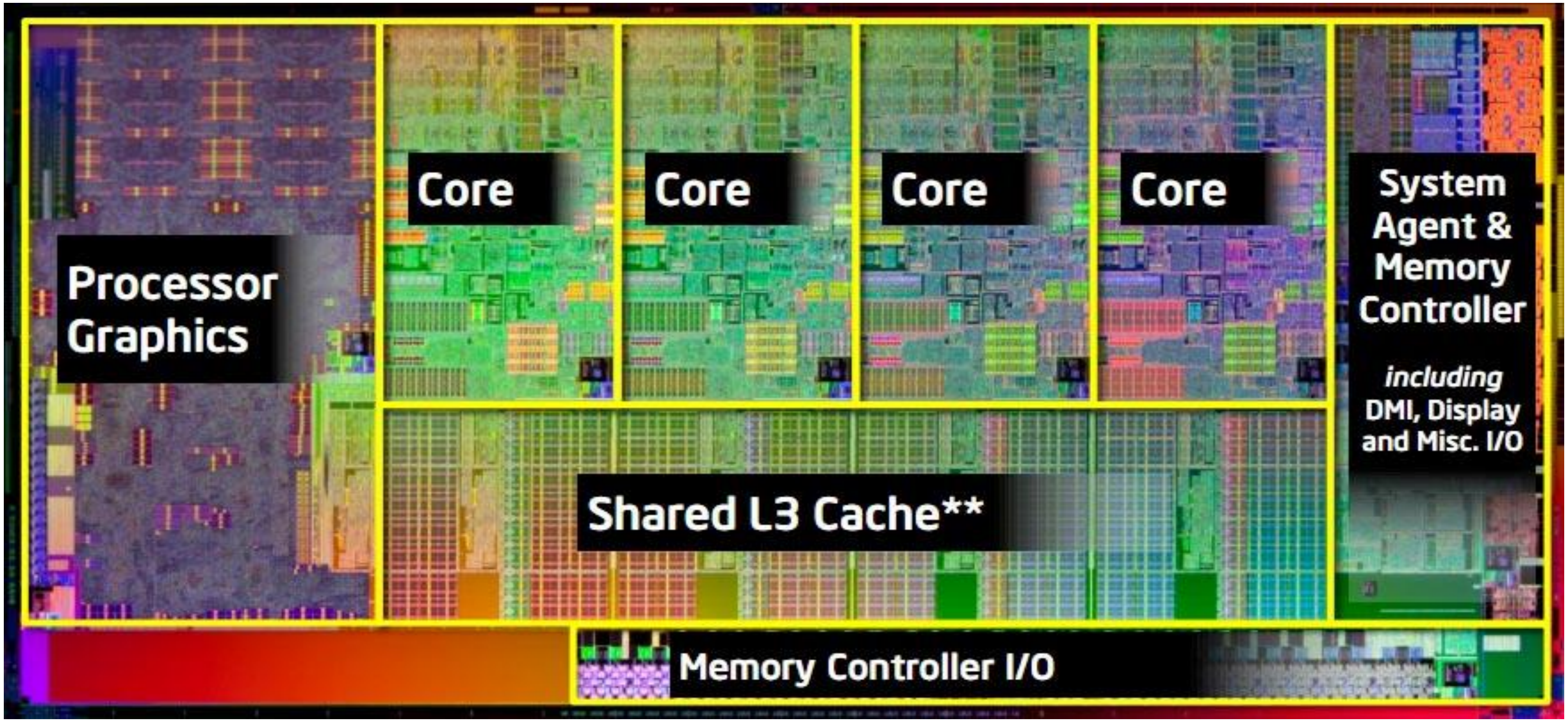
FFT - 1 Million
Transistorer

Och sen går vi bara vidare!

Intel Pentium 4 (2000)
42 million transistors
0.18μm / 1.5GHz



…och vidare, tex Intel SandyBridge!



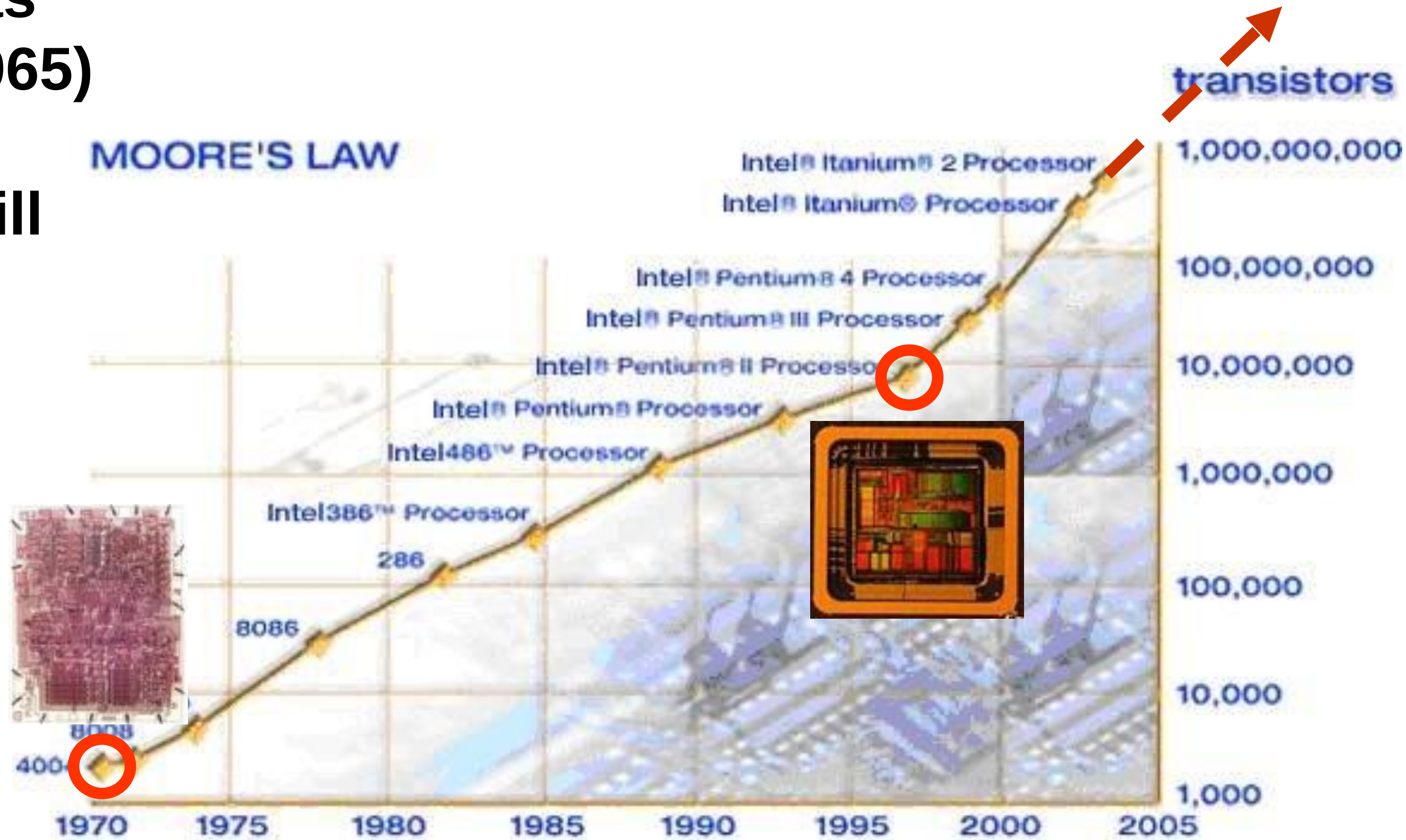
- **32 nm – 64 bit**
- **4 995 000 000 Transistors**
- **~3.5 GHz**
- **216 mm^2 (10x Pentium 4)**

Moores Lag

Antalet transistorer per chip dubbleras varje år. (1965)

Ändrar 1975 till vartannat år.

Gordon Moore
En av Intels grundare

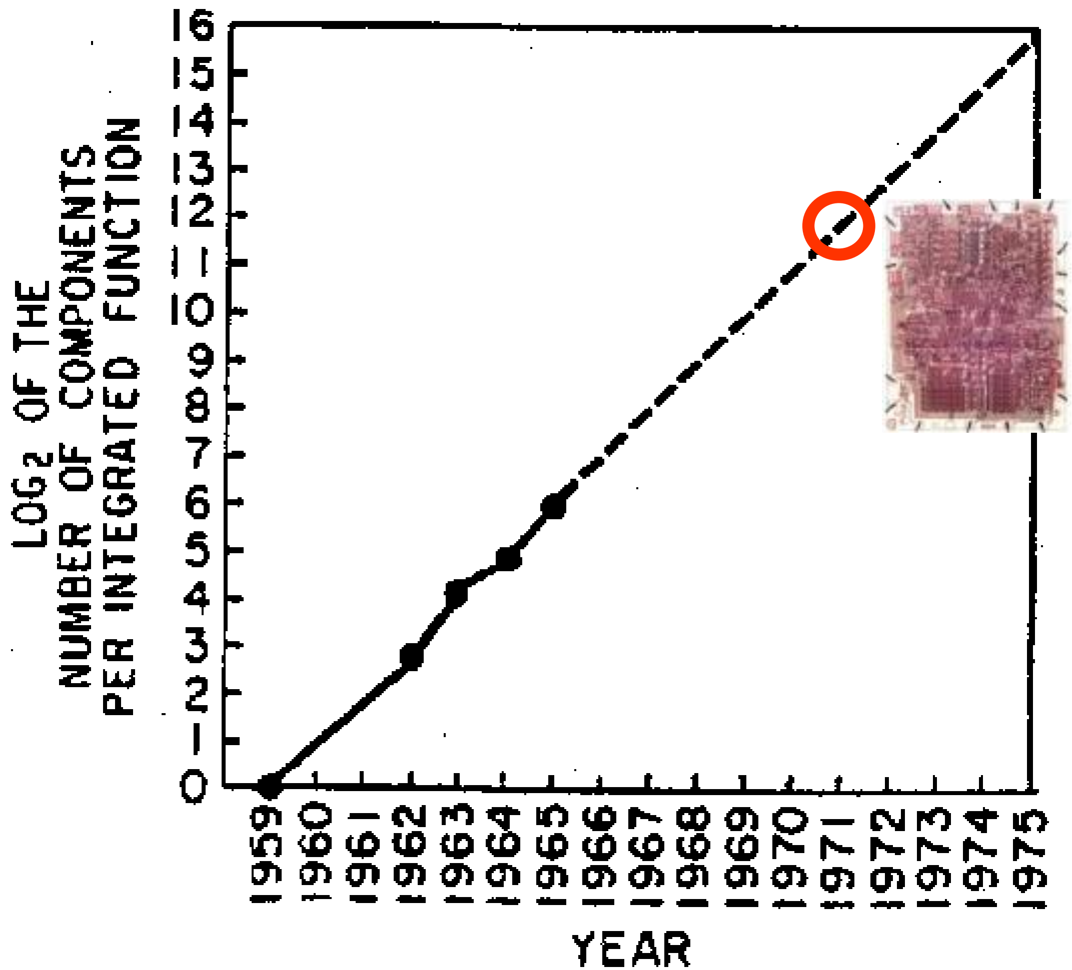


Moores Lag: Originalet

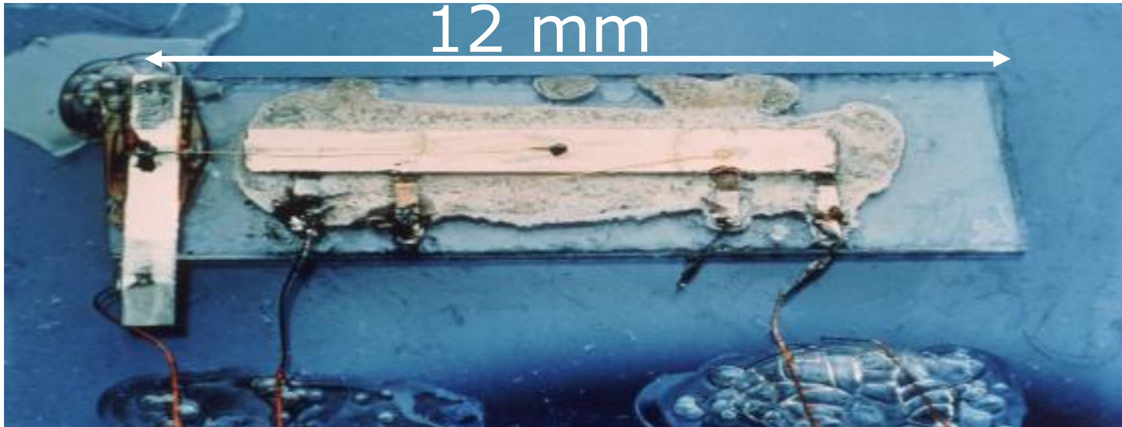
Antalet transistorer per chip dubbleras var år. (1965)

Ändrar 1975 till vartannat år.

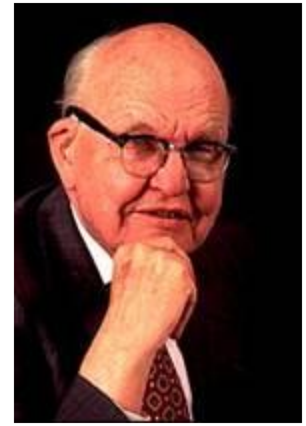
Gordon Moore
En av Intels grundare



Första integrerade kretsen (IC), 1958



Kilbys IC: Phase-shift oscillator, 1.3MHz
5 komponenter varav 1 Transistor



Jack Kilby
Nobelpriset 2000

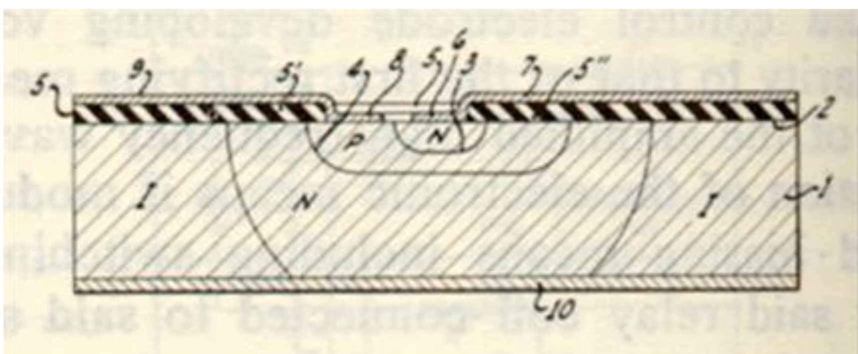


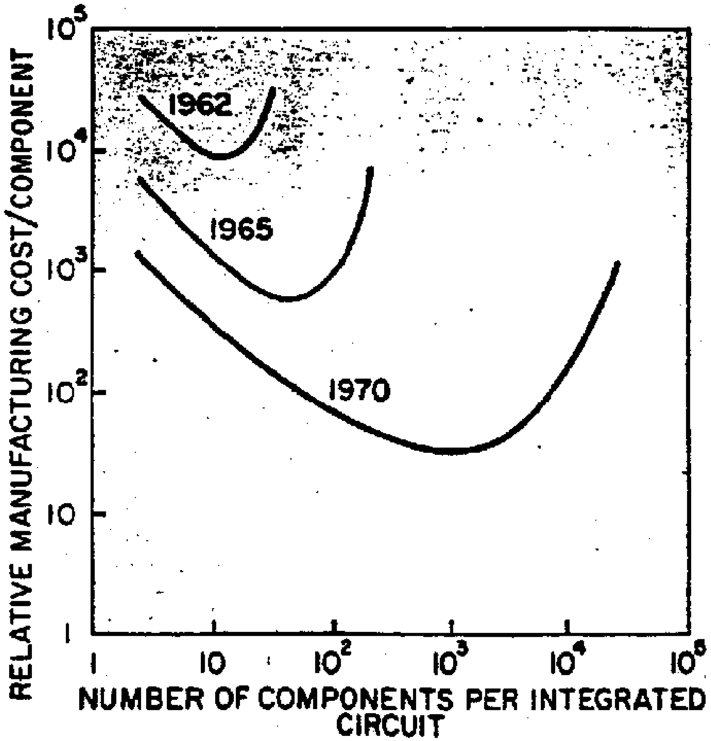
Bild i Noyce patentansökan

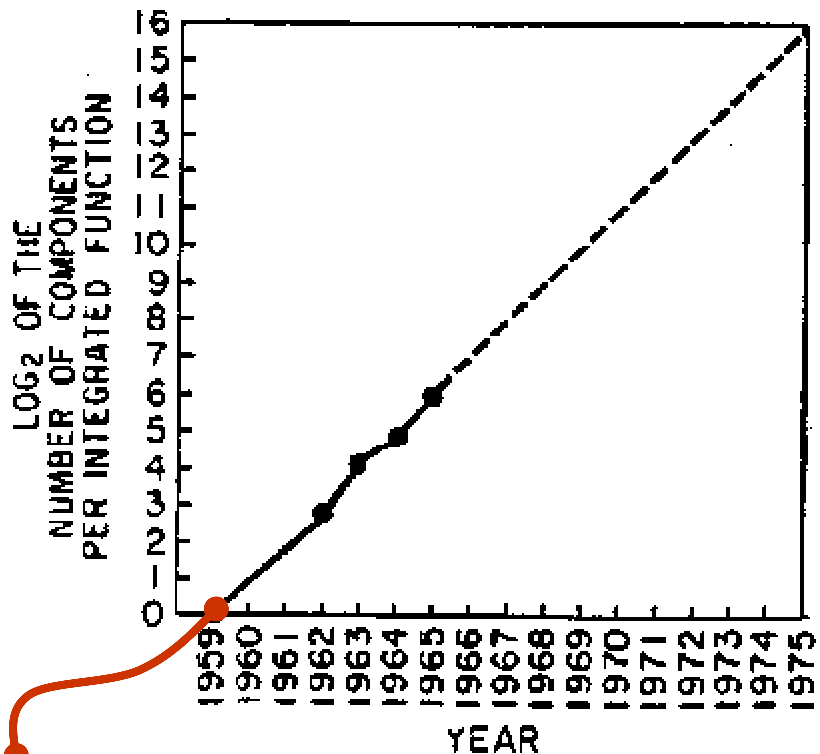
Robert Noyce
Co-founder of Intel

Original artikeln, 1965:

Cramming more components onto integrated circuits

Antalet transistorer per chip dubblas varje år.



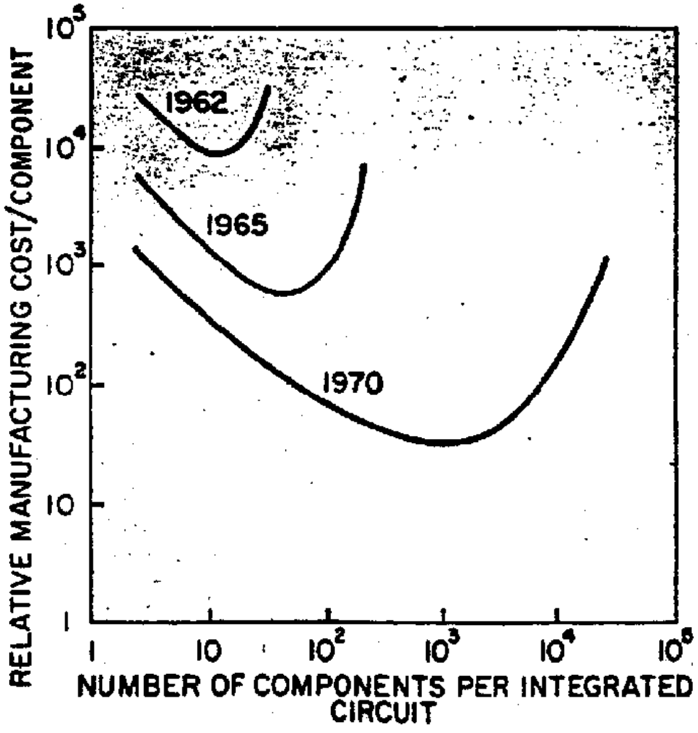


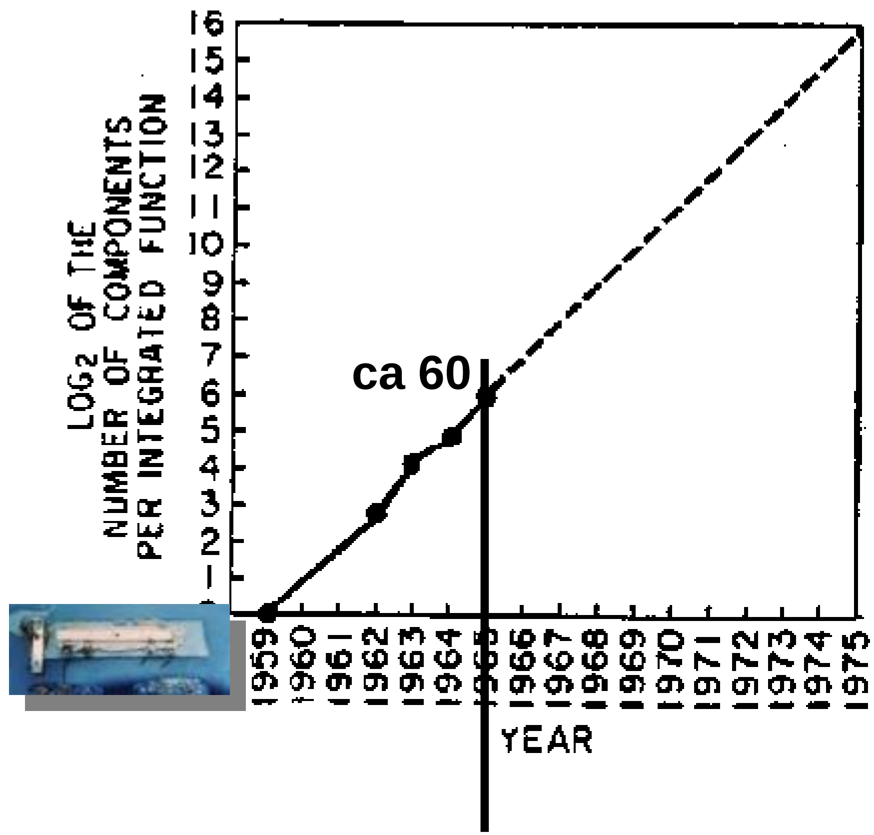
Första "chippet"

Original artikeln, 1965:

Cramming more components onto integrated circuits

Antalet transistorer per chip dubbleras varje år.



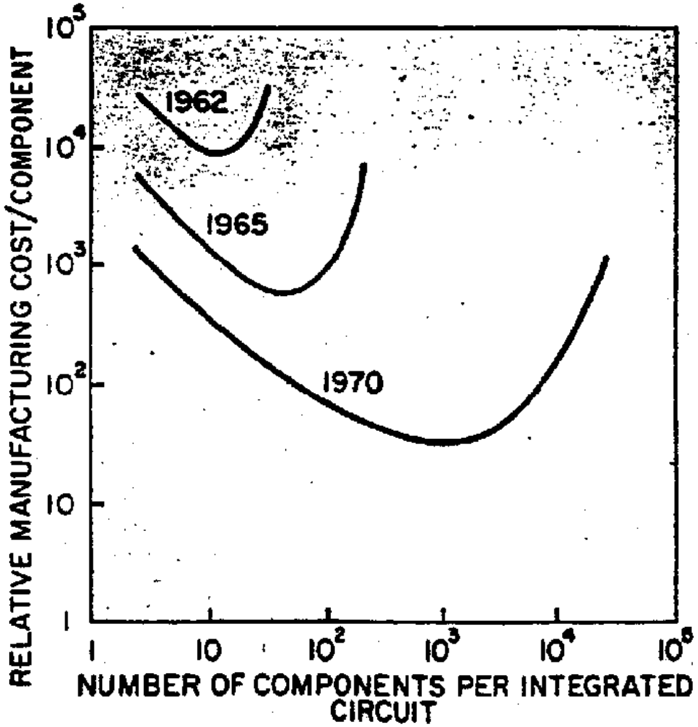


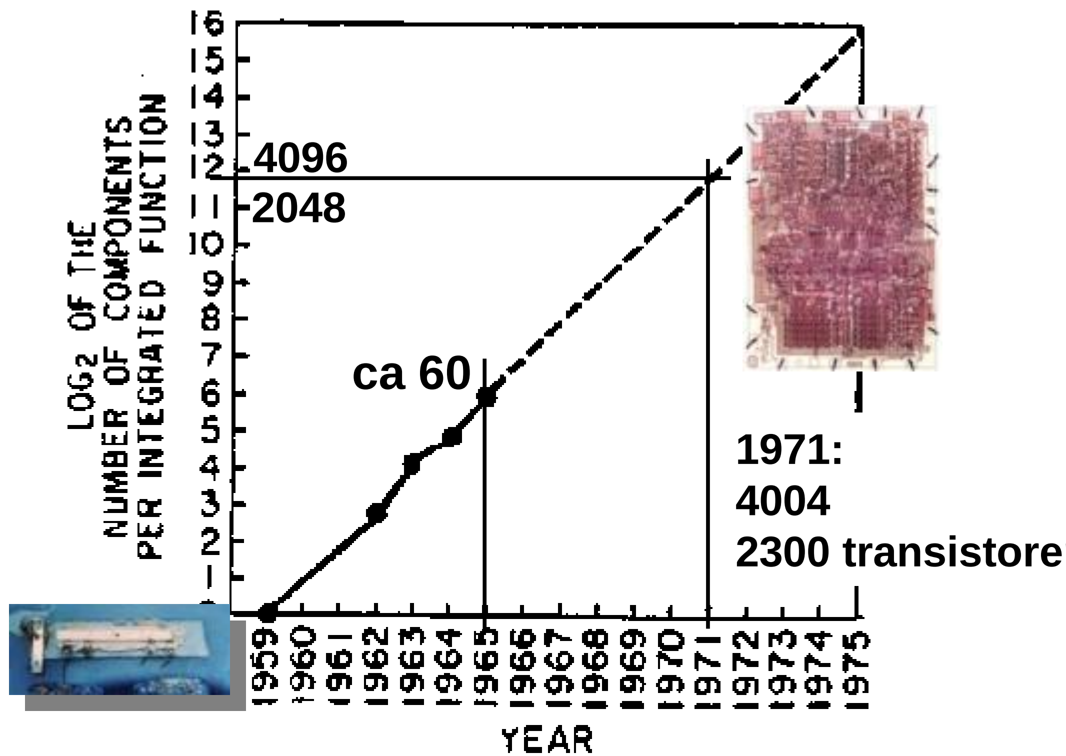
Original artikeln publiceras

Original artikeln, 1965:

Cramming more components onto integrated circuits

Antalet transistorer per chip dubbleras varje år.

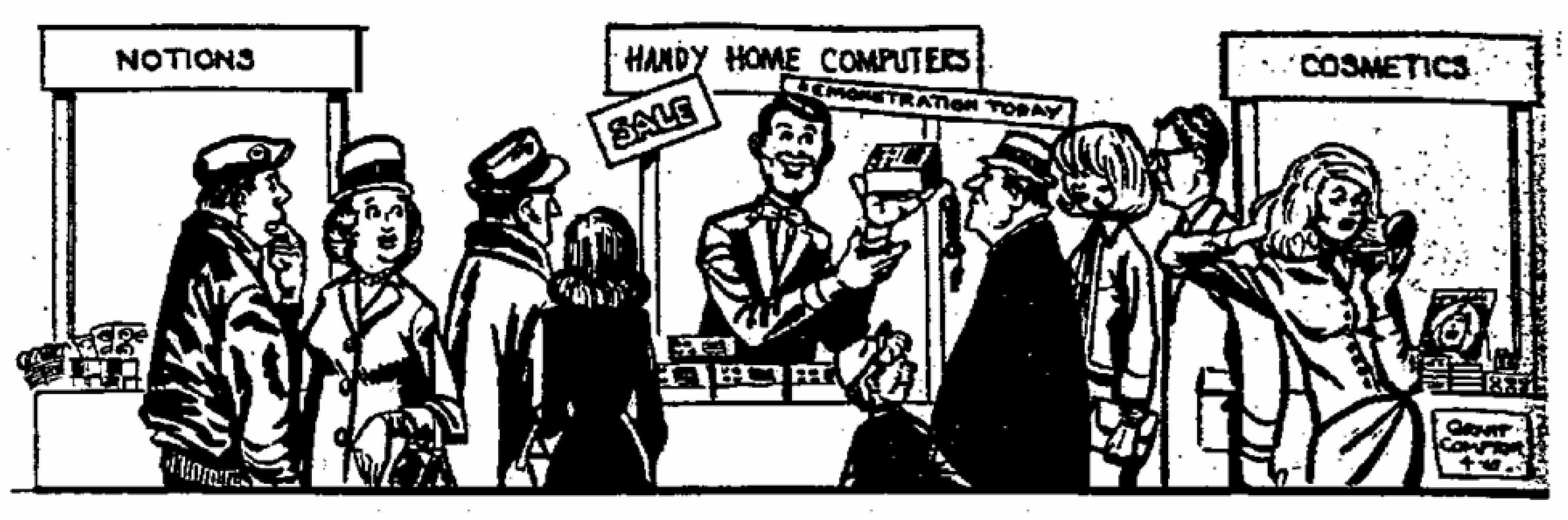




”I was just trying to get across the idea that chips were going to get more complex and because of that the cost per transistor was going to drop dramatically.”

Interview in 2000

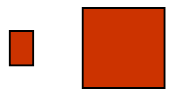
Moores Original artikel, 1965:
Cramming more components onto integrated circuits



”Integrated circuits will lead to such wonders as ***home computers*** . . . and ***personal portable communications equipment***”

4004 till Pentium

Intel 4004 (1971)
2300 transistorer
10μm/108kHz



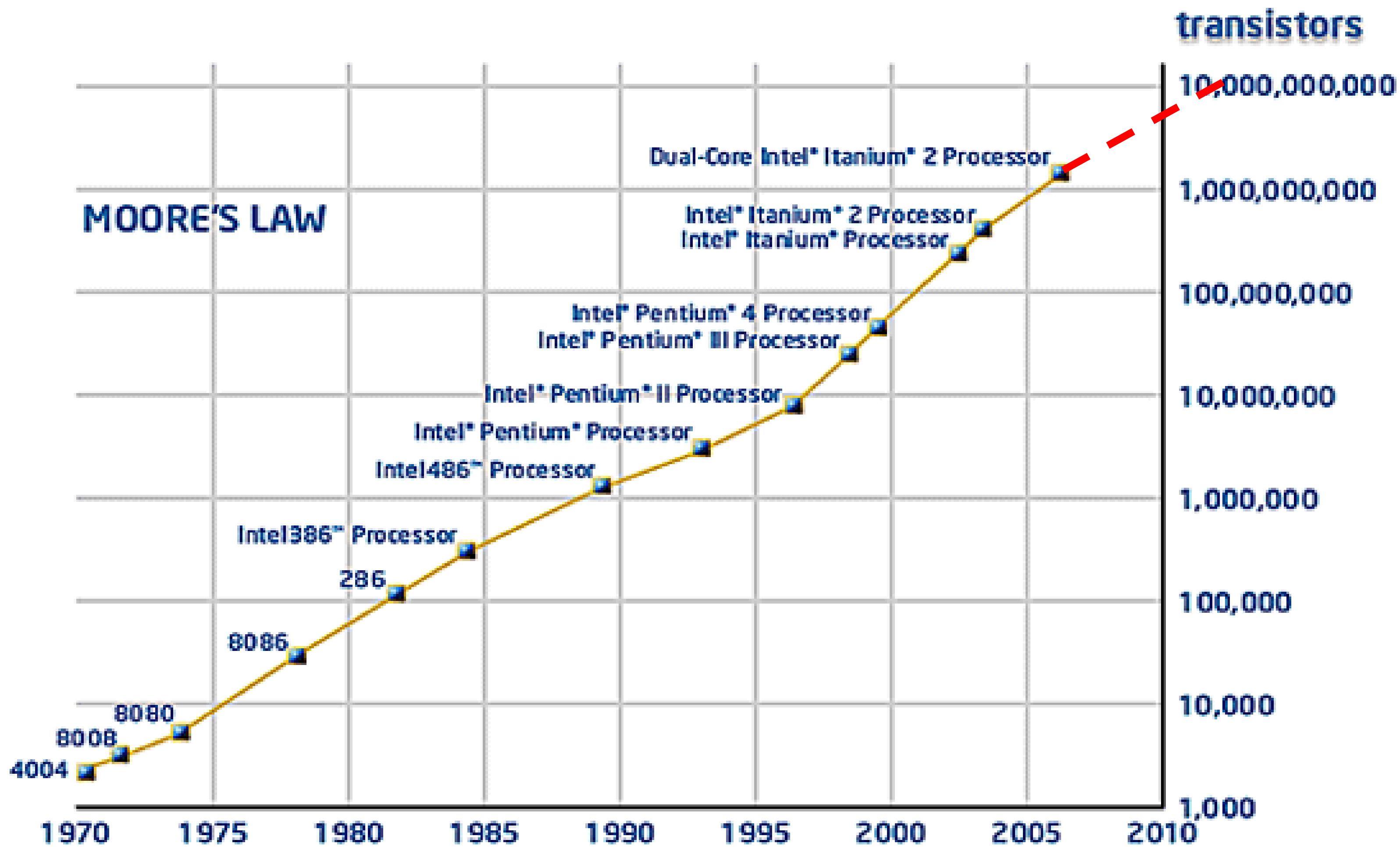
approx.

Intel Pentium 4 (2000)
42 millioner transistorer
0.18μm / 1.5GHz

Om hastigheten för en bil hade ökat lika mycket som klockfrekvensen hade man kunnat köra från New York till San Fransisco på 13 sekunder!

18 000 gångern fler transistorer på 29 år!

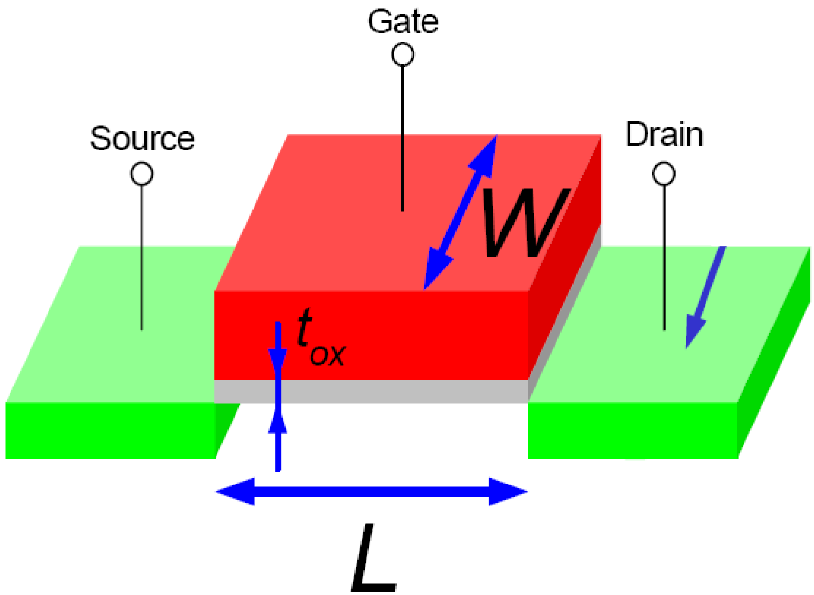
Moores lag 2007



ca 5 milliarder transistor idag

Så vad är problemet?

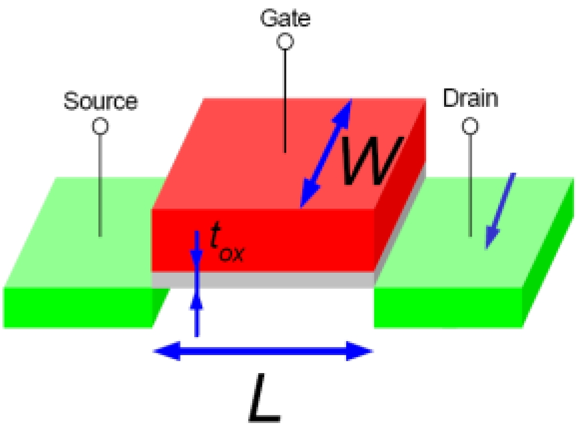
- Fysiken
- Hastigheten
- Effektförbrukningen



Det är *L* som anger processen, t.ex. 45nm

Hastigheten

$$T_{pd} = \frac{C_{\mathrm{L}} \cdot V_{DD}}{k(V_{DD} - V_T)^2}$$

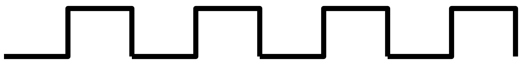


Minskad kapacitans ger snabbare krets vilket kommer med ny process.

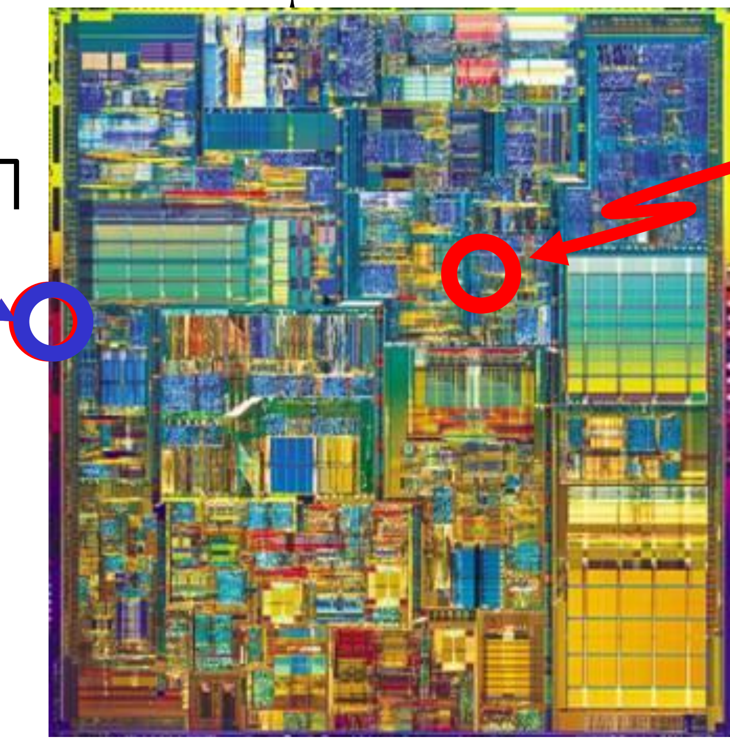
Högre matningsspänning ger snabbare kretsar men transistorerna brinner upp och...

Klockning av processorer!

Intel Pentium 4 (2000)
42 million transistors
0.18μm / 1.5GHz



Om jag skickar in
en klocka här.

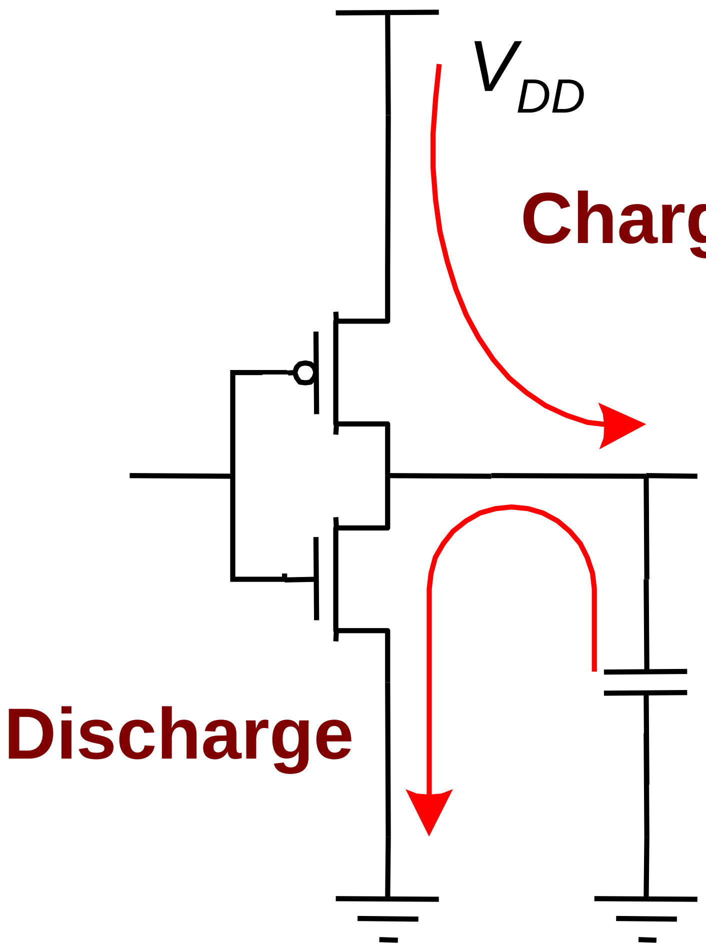


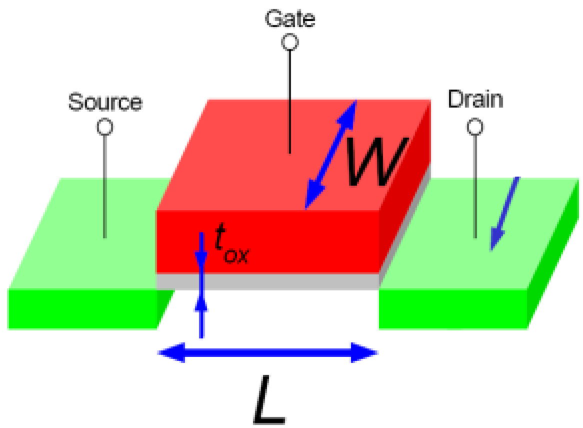
Hur ser den ut här?

Kanske så här.
Och hur bra funkar
datorn då?

Ofta mer än 50% av effekten i att ”fixa till” klockan.

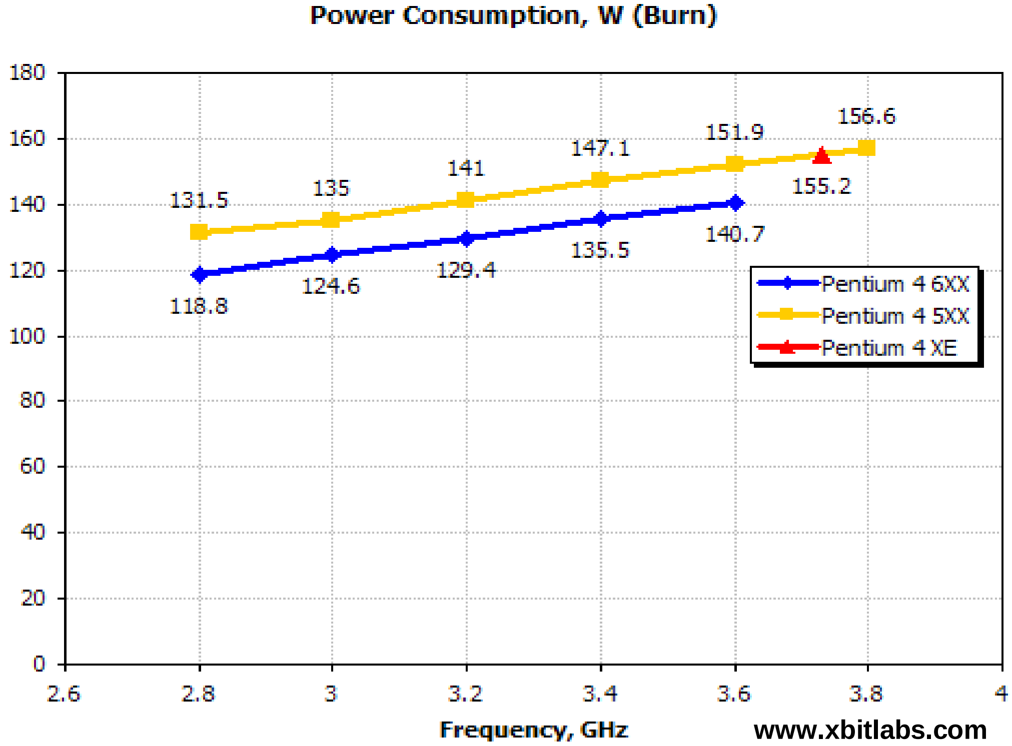
Effektförbrukningen (*dynamisk*)





$$P_{dynamic} = f\, C_L V_{DD}^2$$

CPU power consumption



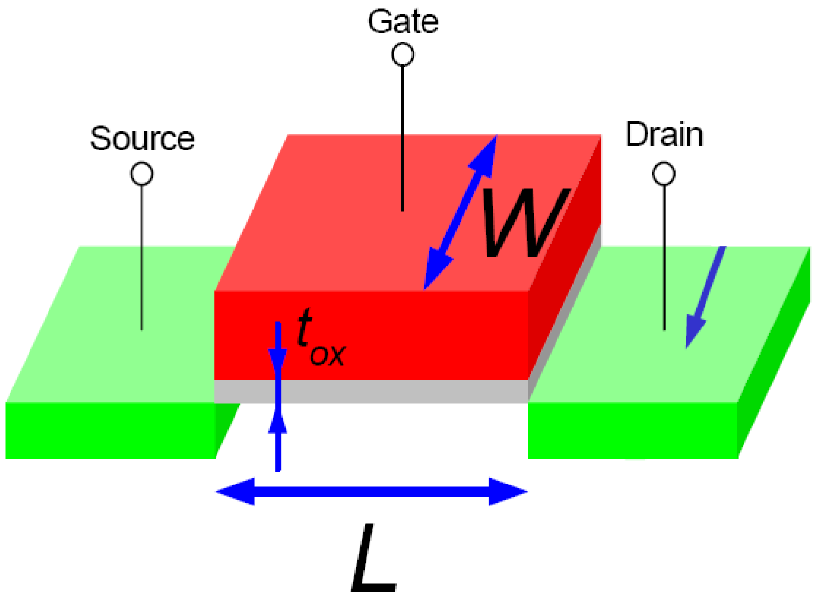
Pentium IV chip area 1.3 cm^2
(i 130 nm technology)

Detta ger ca. 100 W/cm^2 som måste transporteras bort, dvs säga kylning.

Jämförelse: Den här ger ca 10 W/cm^2.

Så vad är problemet?

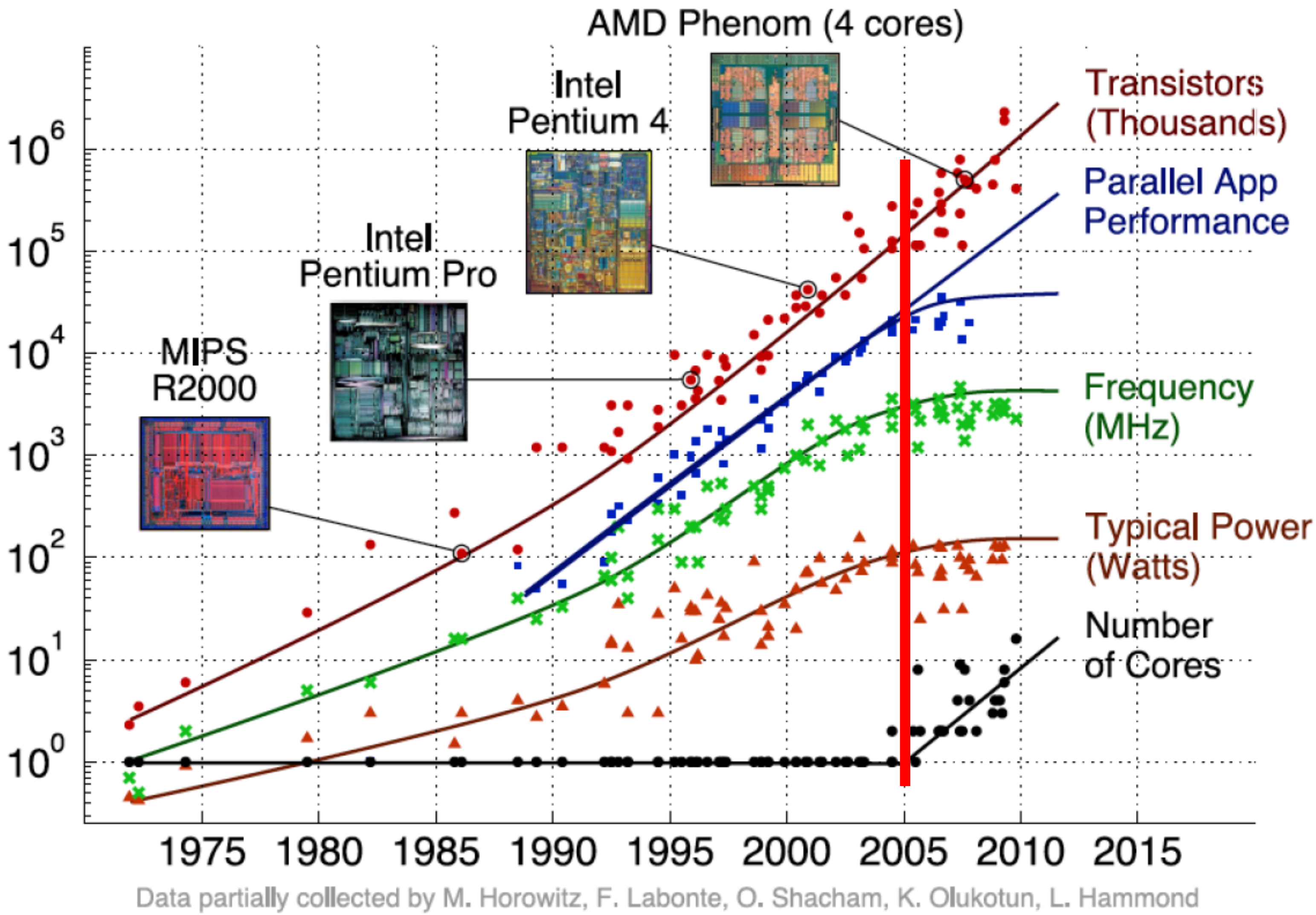
- Fysiken
- Hastigheten
- Effektförbrukningen



Det är *L* som anger processen, t.ex. 45nm

Mer i Digitaltekniken!

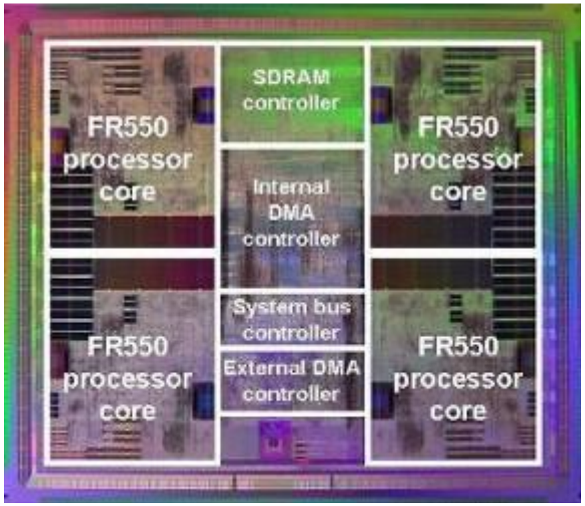
The end of "some" scaling!

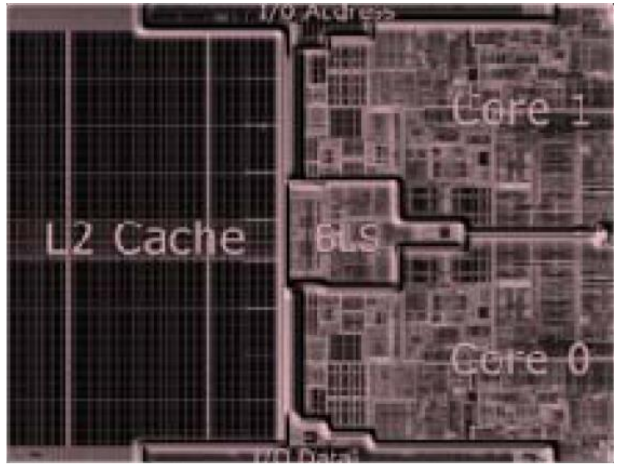


Multi-core processorer

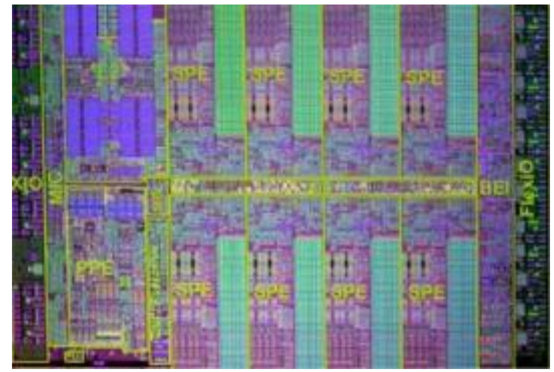
Intel KEROM dual core, 2007, 290millioner trans.

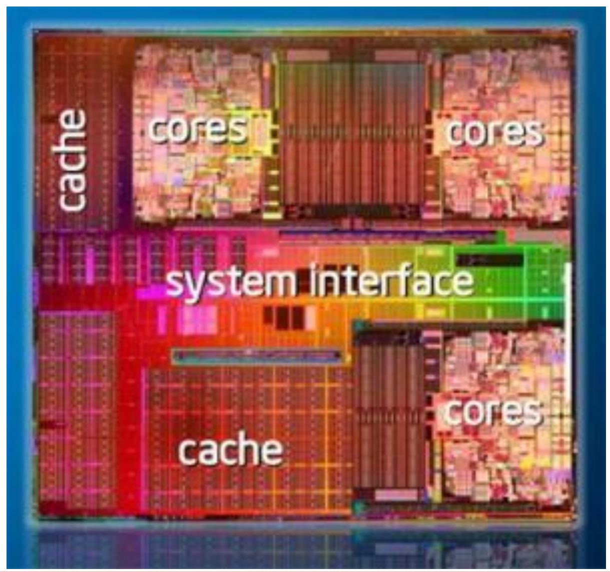
Fujitsu FR-V, 2005,
83 millioner trans.





IBM/Sony/Toshiba Cell
2005, 234 millioner trans.





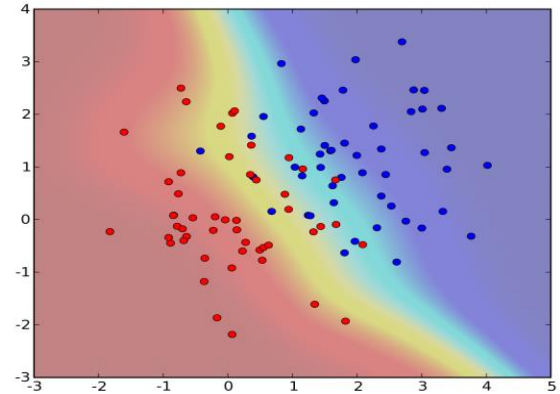
Intel Nehalem.
2.3 milliarder
transistorer

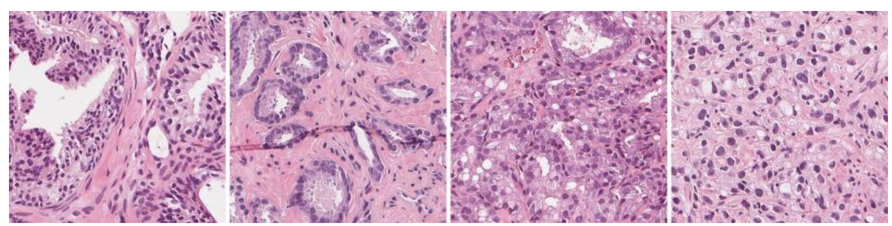
Multi-core processorer: ökad prestanda vid samma klockfrekvens

Vad är ”hett” idag?

Vad är ”hett” idag? AI/ML

- **ML – takes data and produce an algorithm**
- **Classify species of plant based on petal length and width.**
- **Classify – airbag on/off based on accelerometer data**
- **Classify cancer or not based on histopathological images**

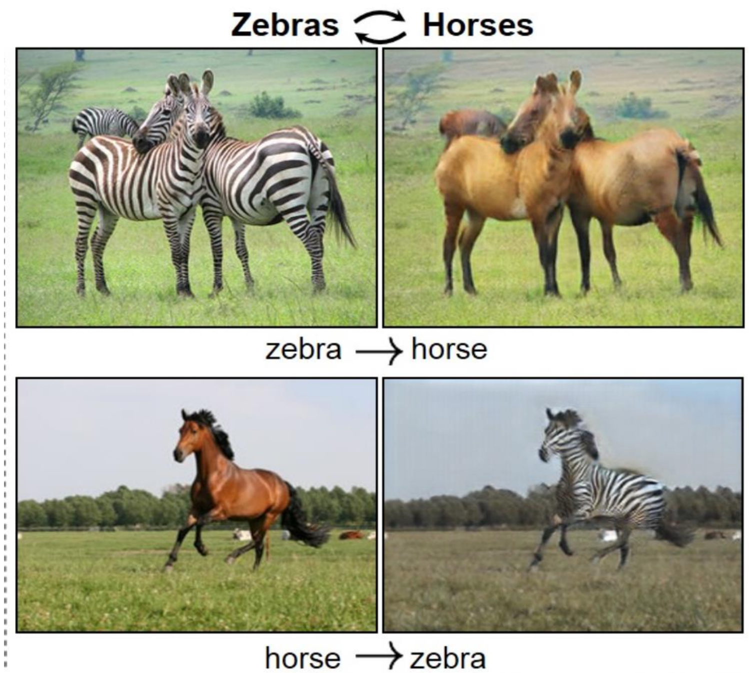




Benign *Gleason grade 3* *Gleason grade 4* *Gleason grade 5*

Varför nu?

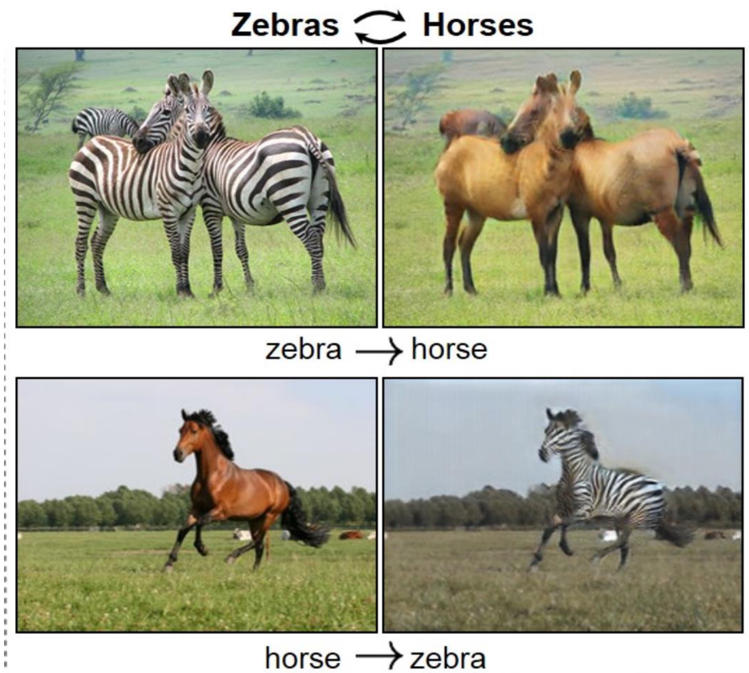
- AI/ML - good tools
- Better hardware
- Better software
- More data.
- Many ‘hard’ problems ‘solved’



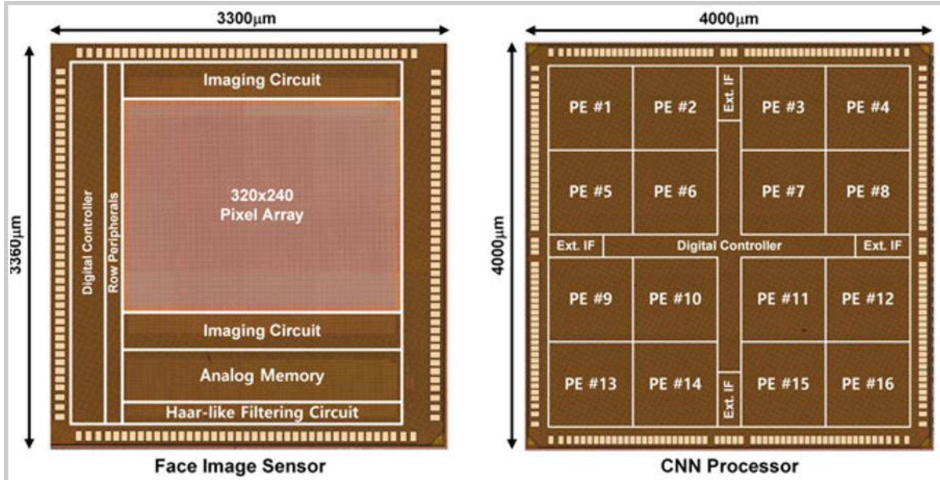

●●●○○ Verizon
4:20 PM
76%
Albums
chihuahua or muffin
Select
@teenybiscuit

Varför nu?

- AI/ML - good tools
- Better hardware
- Better software
- More data.
- Many ‘hard’ problems ‘solved’



Dedikerad hårdvara: tex för autonoma system.



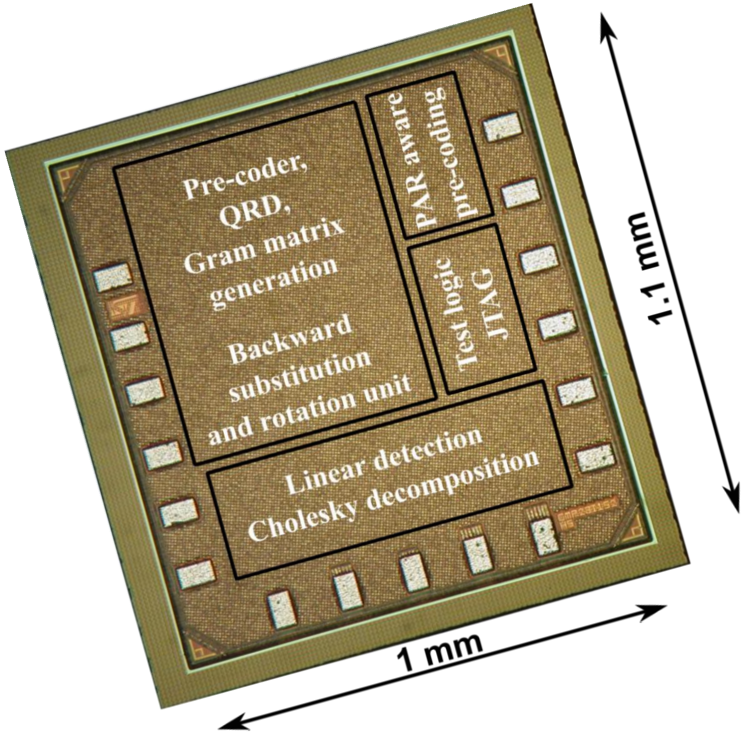
Technology	65nm 1P8M Logic CMOS
Die Area	3300x3360μm²
Pixel Array	320x240
Pixel Size	7x7μm²
Supply Voltage	Analog: 2.5V, Digital: 0.5V ~ 0.8V
Clock Frequency	Analog: 50MHz, Digital: 5MHz ~ 100MHz
Power Consumption	23.8μW @ 1fps

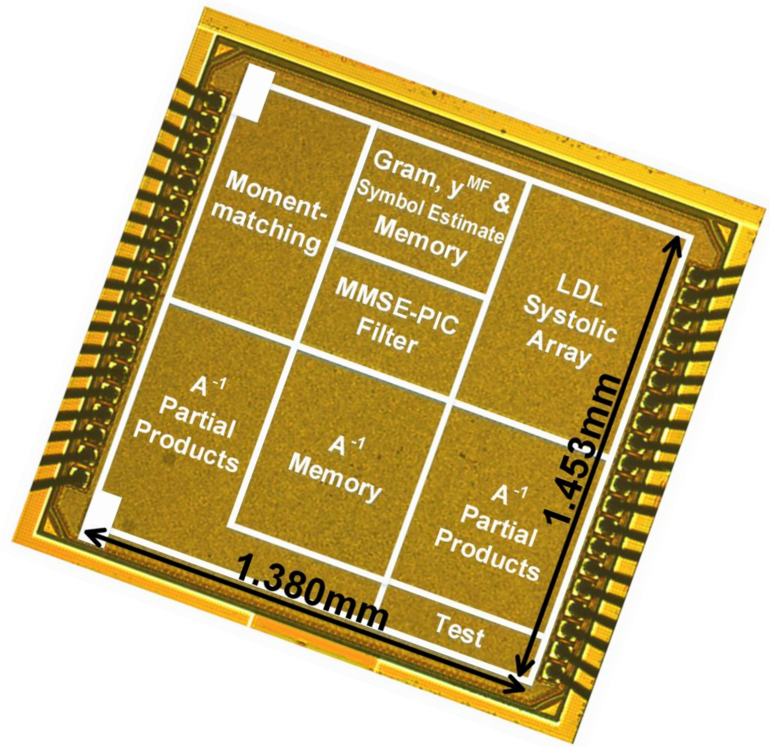
Technology	65nm 1P8M Logic CMOS
Die Area	4000x4000μm²
Supply Voltage	0.46V ~ 0.8V
Clock Frequency	5MHz ~ 100MHz
Peak Power Consumption	211mW (0.8V, 100MHz)
	5.3mW (0.46V, 5MHz)
Energy Efficiency	2.11nJ/cycle (0.8V, 100MHz)
	1.06nJ/cycle (0.46V, 5MHz)

Figure 14.6.7: Chip photograph and performance summary.

ISSCC (International Solid State Circuits Conference) 2017

Dedikerad hårdvara för Massive MIMO för 5G!

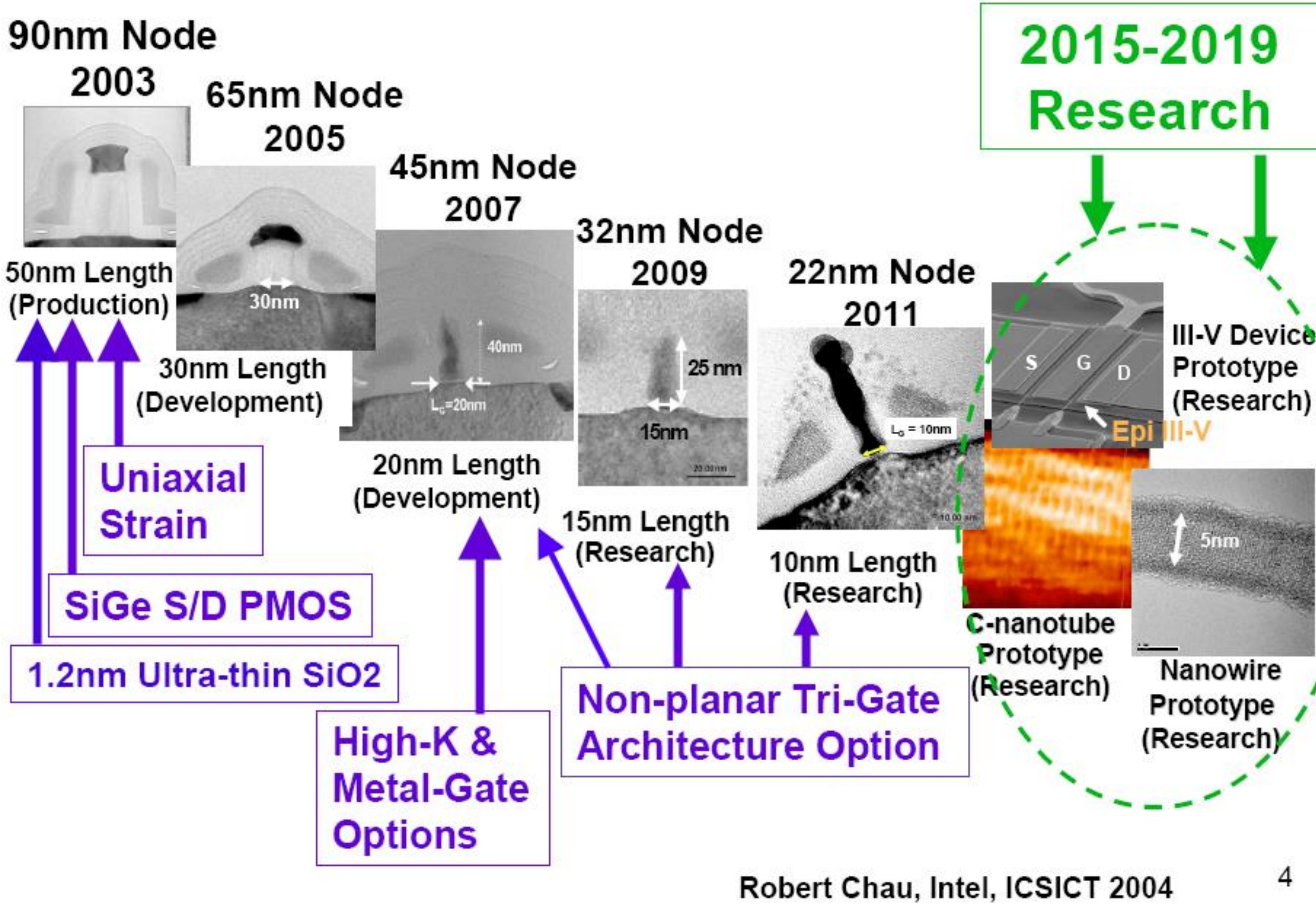




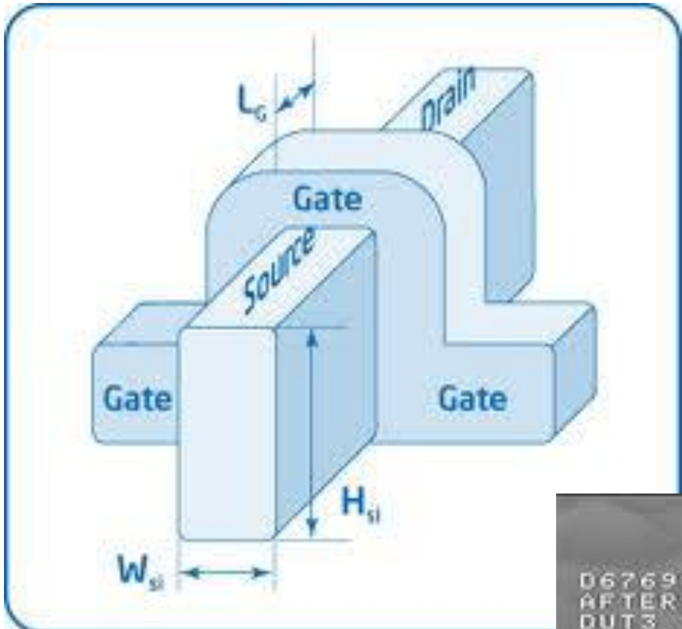
3.6 A 60pJ/b 300Mb/s 128×8 Massive MIMO precoder-detector in 28nm FD-SOI
H. Prabhu, J. Neves Rodrigues, L. Liu & O. Edfors, ISSCC 2017

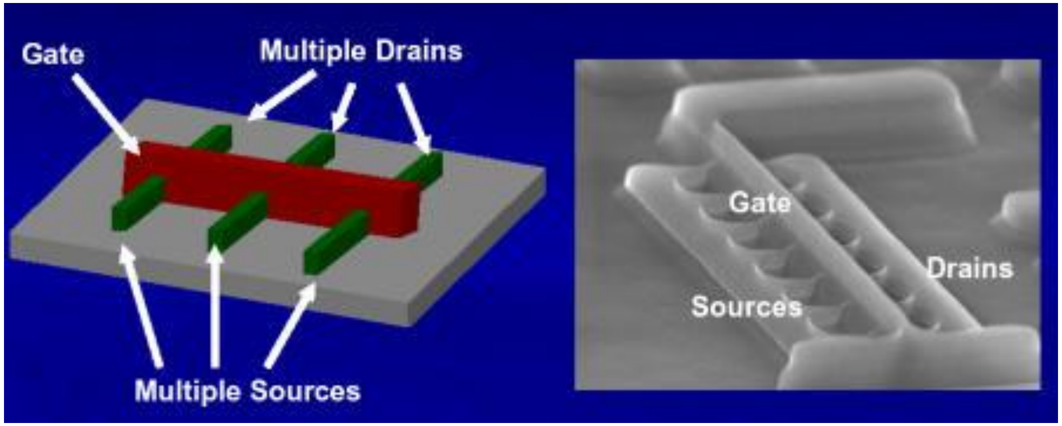
A 1.8Gb/s 70.6pJ/b 128×16 link-adaptive near-optimal massive MIMO detector in 28nm UTBB-FDSOI,
W. Tang, H. Prabhu, L. Liu, V. Öwall & Z. Zhang, ISSCC 2018.

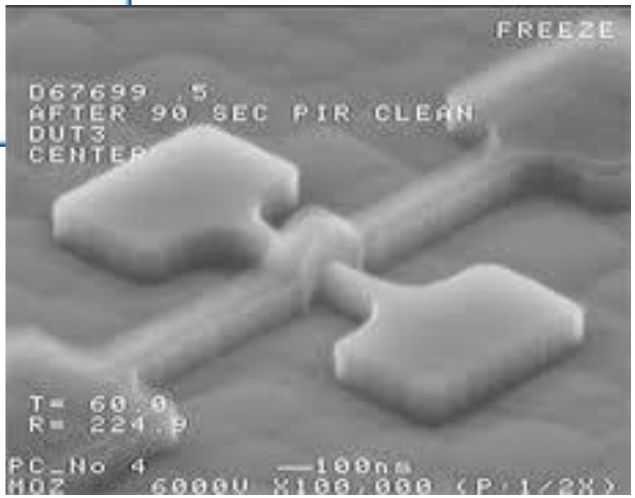
Så vart är vi på väg?



FINFETs/Trigates

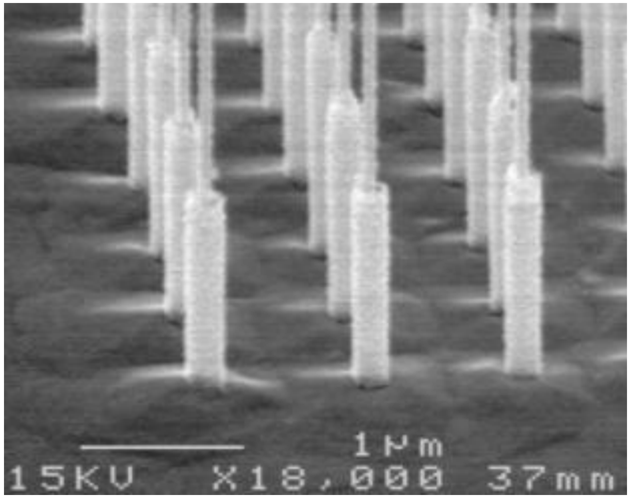




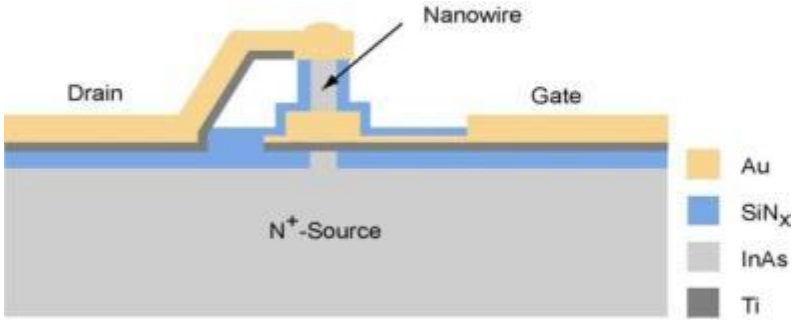


Wrap-Gate FETs

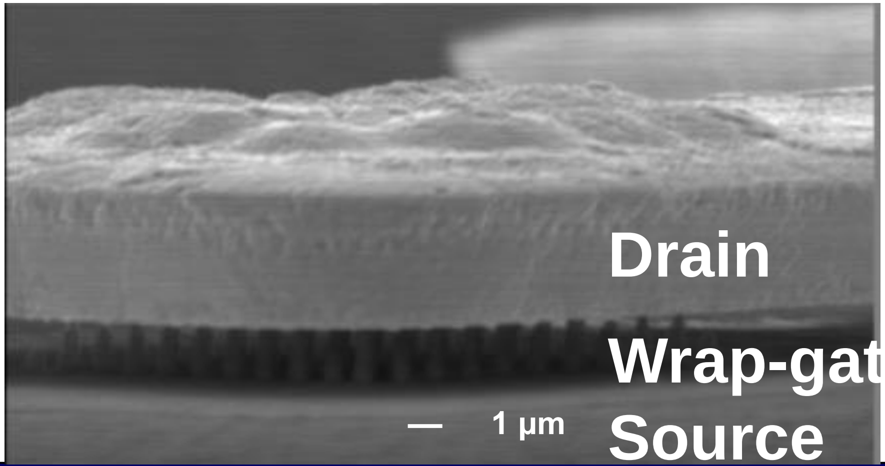
Wrap-gates

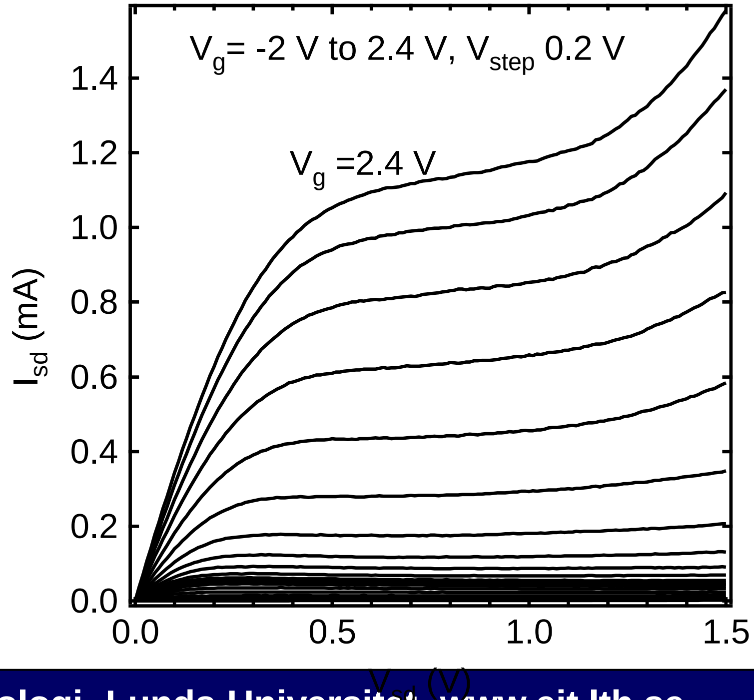


Device layout



Nanowire Transistor





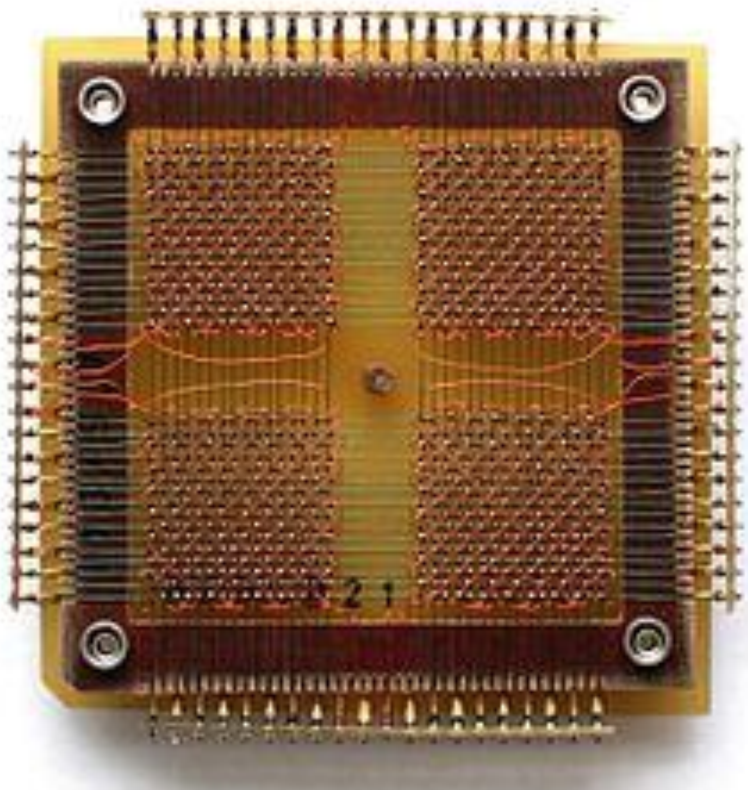
Mer om allt detta i

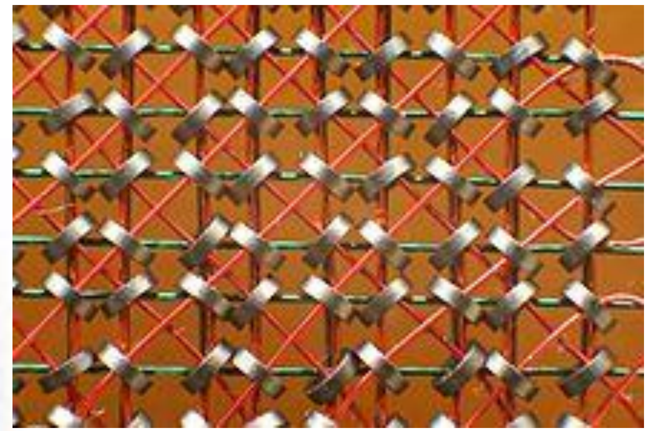
EITF65 Digitalteknik

och senare i

ETIN20 Digital IC konstruktion

Vad är detta?



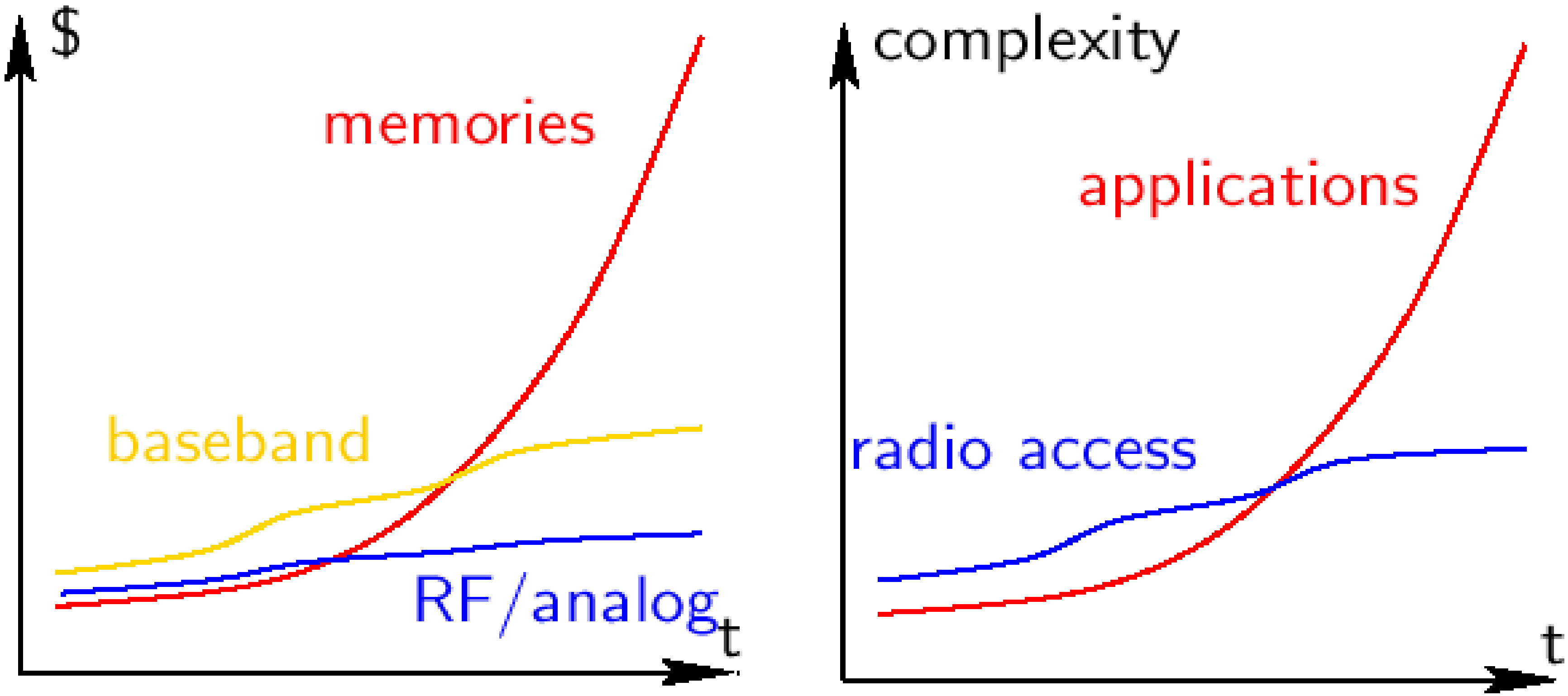


A 32 x 32 magnetic-core memory plane storing 1024 bits of data. Magnetic-core memory was the predominant form of random-access computer memory for 20 years (circa 1955–75).

Minnen är en av de viktigaste beståndsdelarna i modern elektronik.

Men hur lagrar vi ett värde?

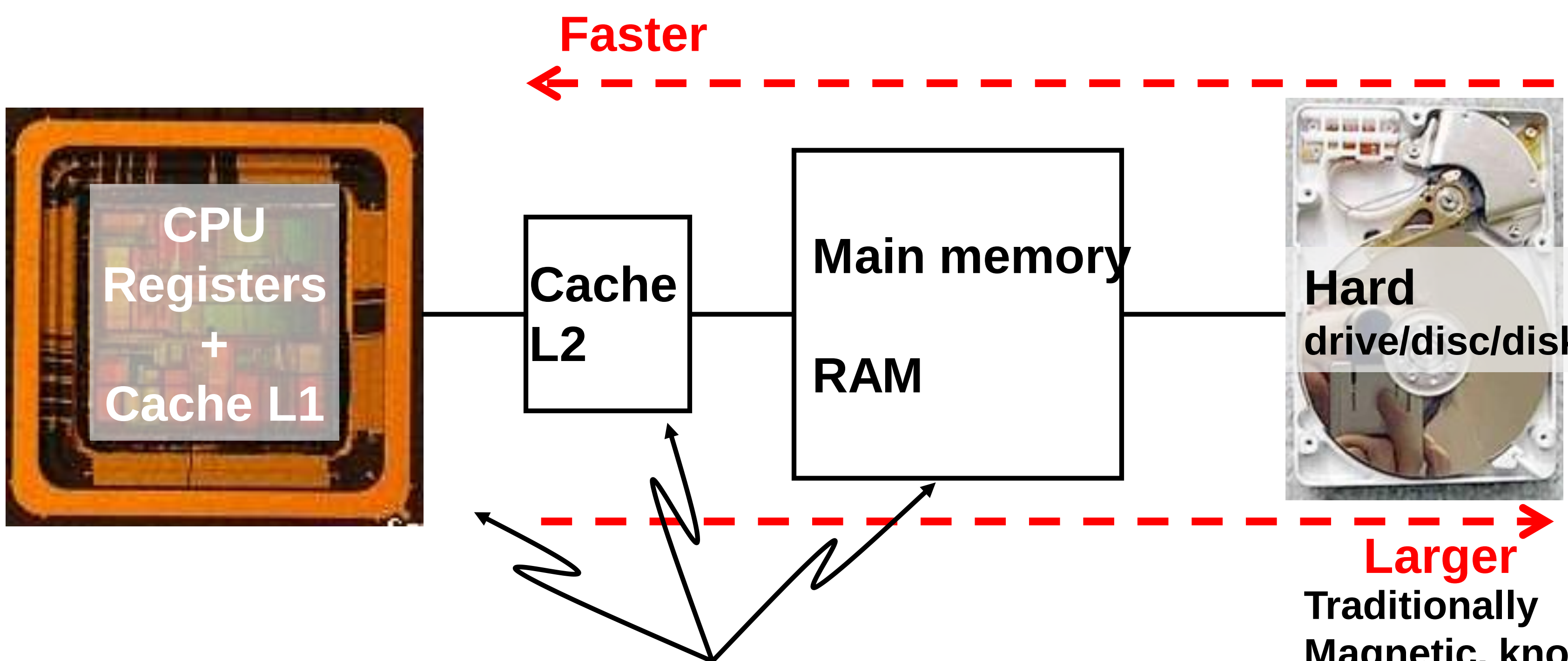
Cell-phone circuit complexity and cost



Courtesy: Sven Mattisson, Ericsson

Minnen i datorer

Larger memories become slower ⇨
Often several layers of memory hierarchy is used to have both large storage capabilities and fast memory acces



Semiconductor memories

Traditionally Magnetic, know moving more and more towards SSD.

Så vad är en
SSD eller Flashminne?

Vad är ett Flashminne?

Halvledarminnen:

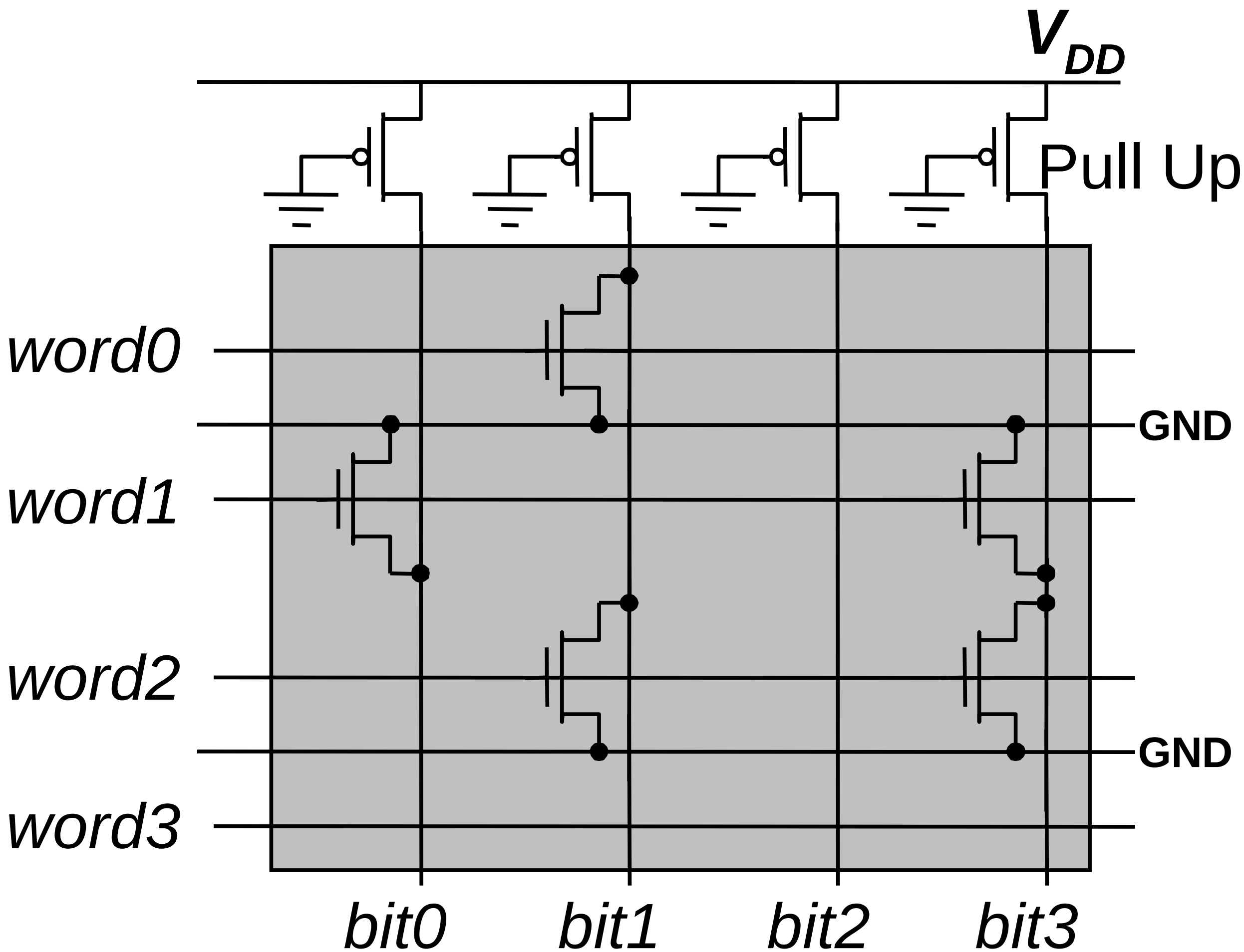
- **ROM – Read Only Memory**
- **RAM – Random Access Memory**
- **FLASH**

Vad är ett Flashminne?

Halvledarminnen:

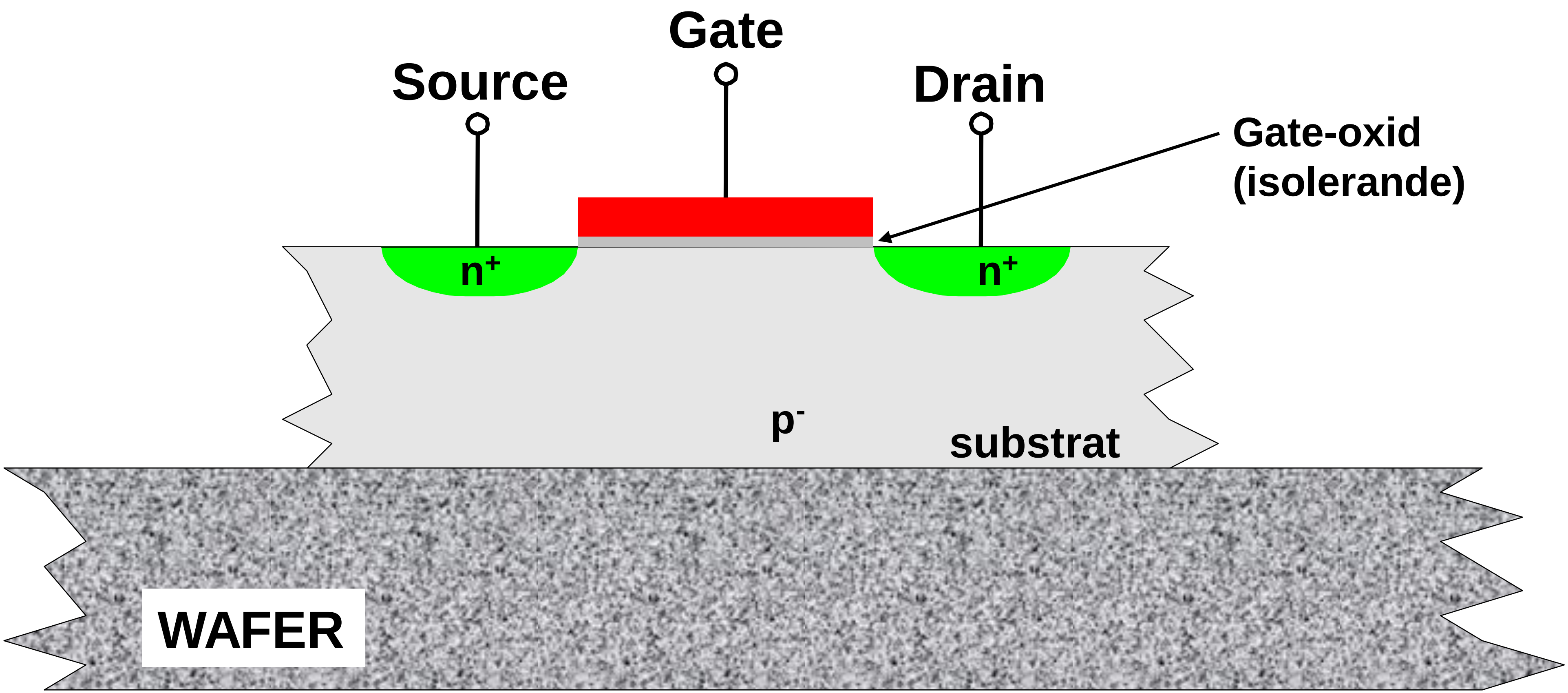
- ROM – Read Only Memory
  - Innehållet definierat av transistorplacering
  - finns kvar när strömmen slås ifrån
- RAM – Random Access Memory
  - data lagras som laddning
  - försvinner när strömmen slås ifrån
- FLASH
  - data kan både läsas och skrivas
  - finns kvar när strömmen slås ifrån

ROM

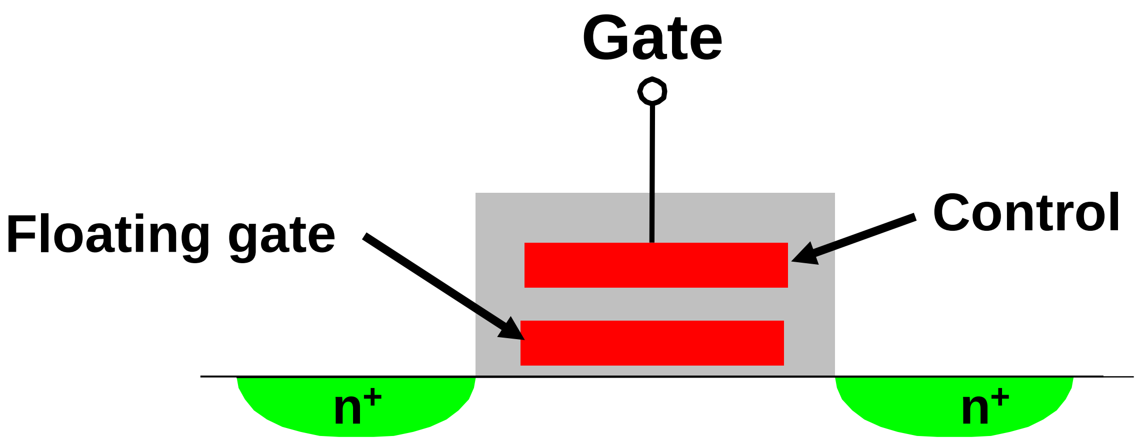


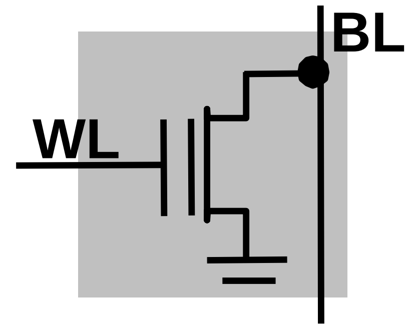
Placeringen av transistorer bestämmer minnesinnehållet!

MOS transistorn



Flash minnen–
floating gate transistors

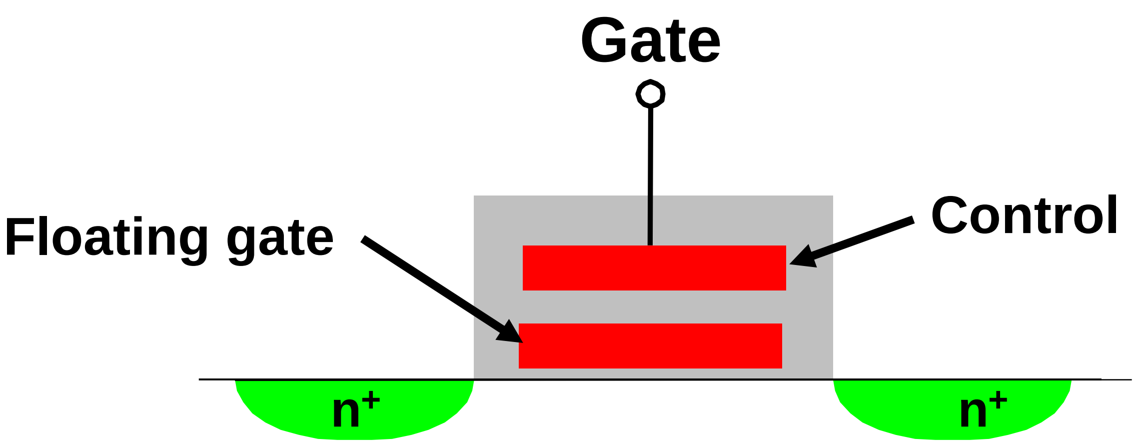


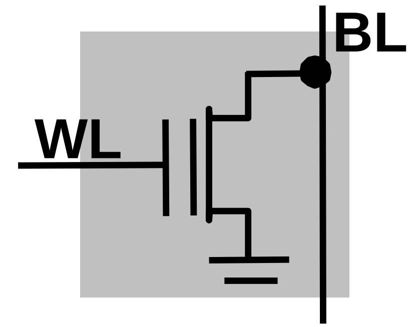


I ett Flash-minne har vi en speciell transistor. Alla platser i minnet har en transistor men vi kan elektriskt kontrollera funktionaliteten av minnescellen.

- EPROM, EEPROM och Flash har olika sätt att styra transistorn.

Flash minnen – Floating gate transistors



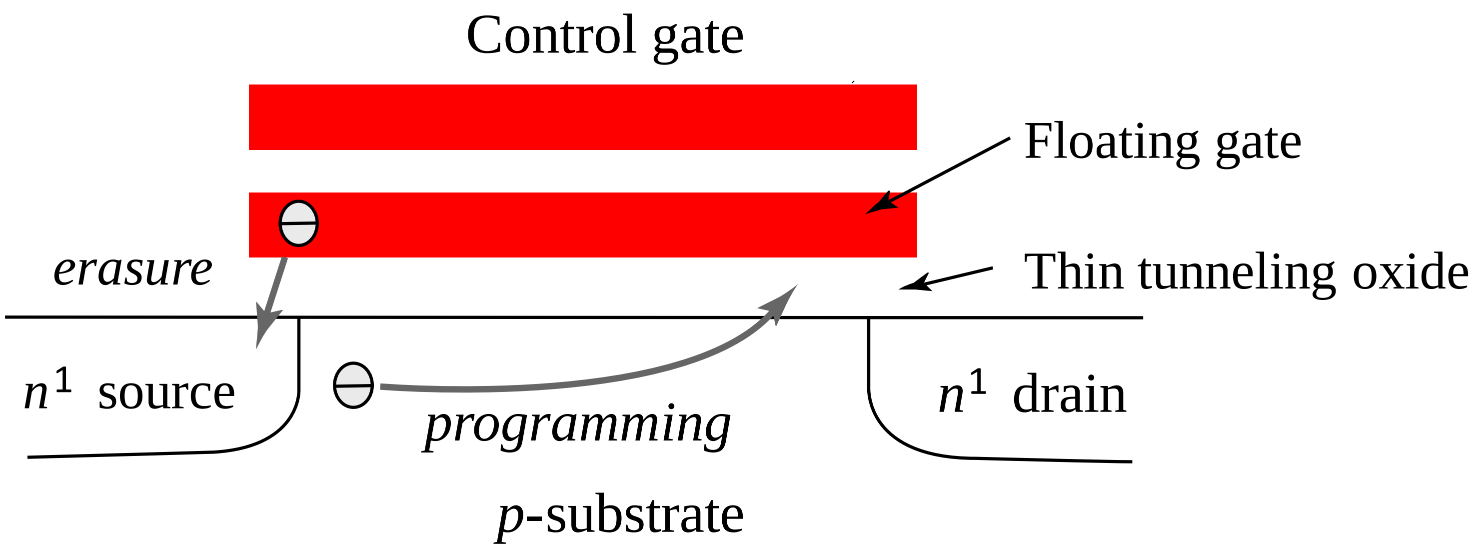


Floating gate är inte kontakterda

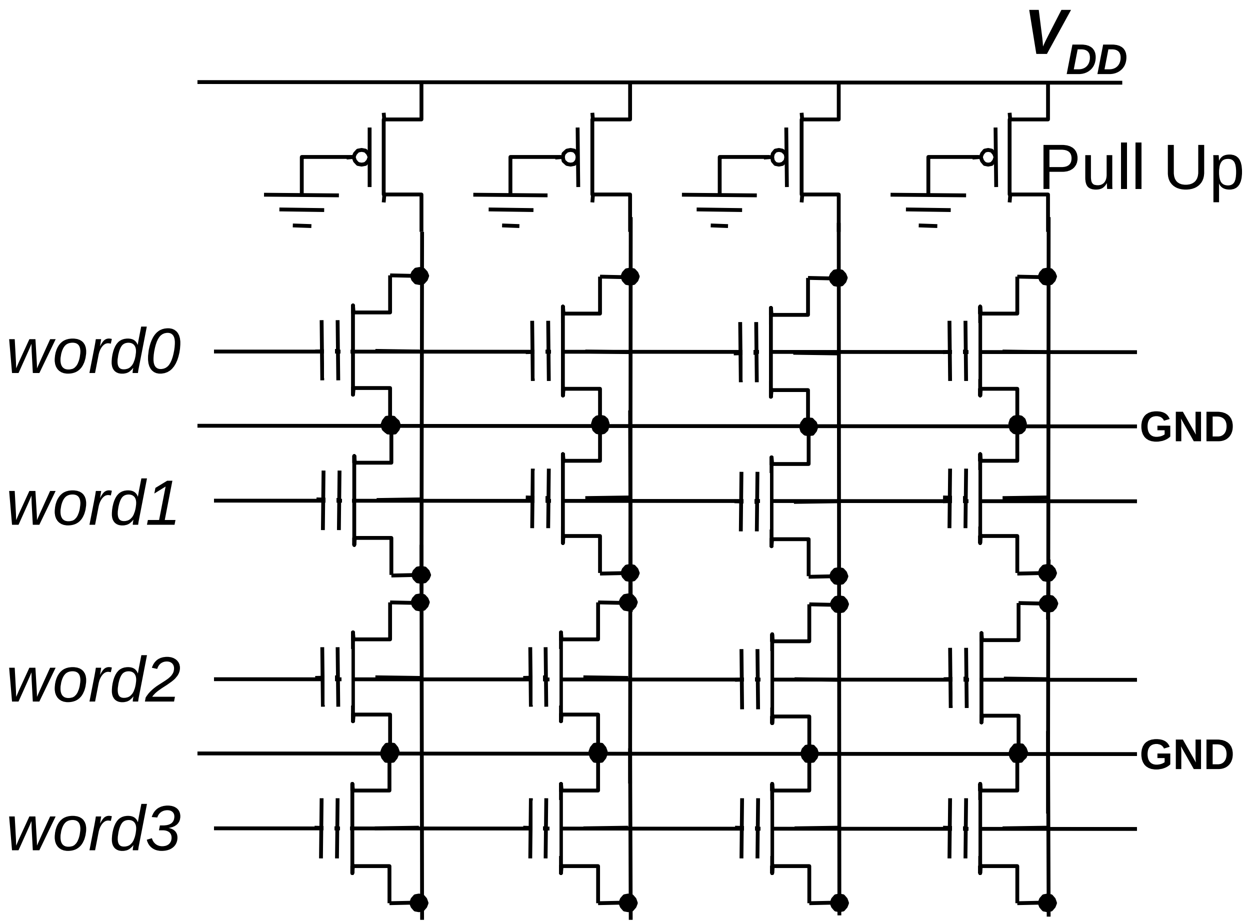
- Om vi laddar floating gate mycket negativt
  - ⇨ Ingen kanal ⇨ Ingen transistor

- Om ingen laddning
  - ⇨ Kanal ⇨ Transistor

Flash EEPROM

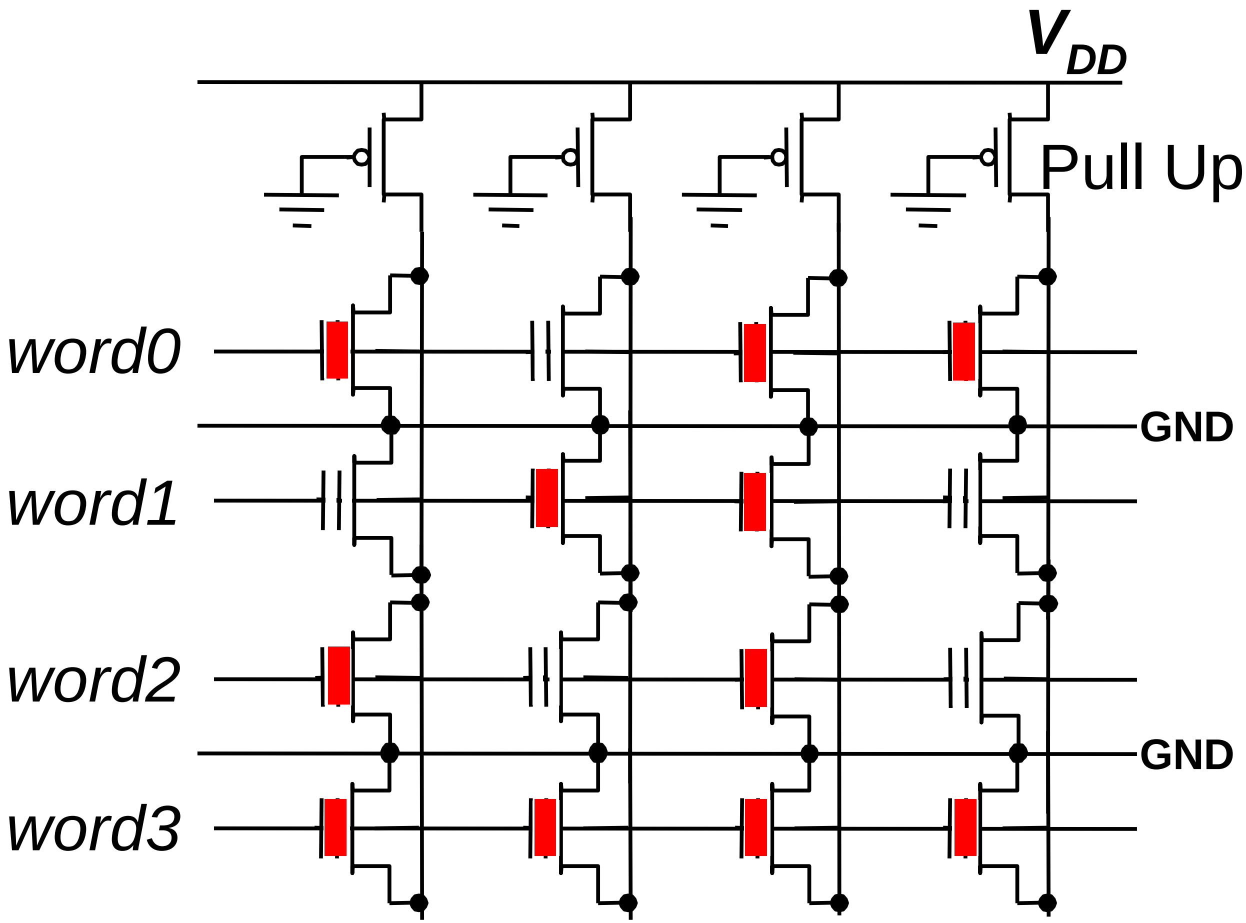


FLASH stucture



Floating gate transistors everywhere!

FLASH write: trapped charge



 = trapped charge. Transitor is always off ⇨ Same content as ROM.

Tack!