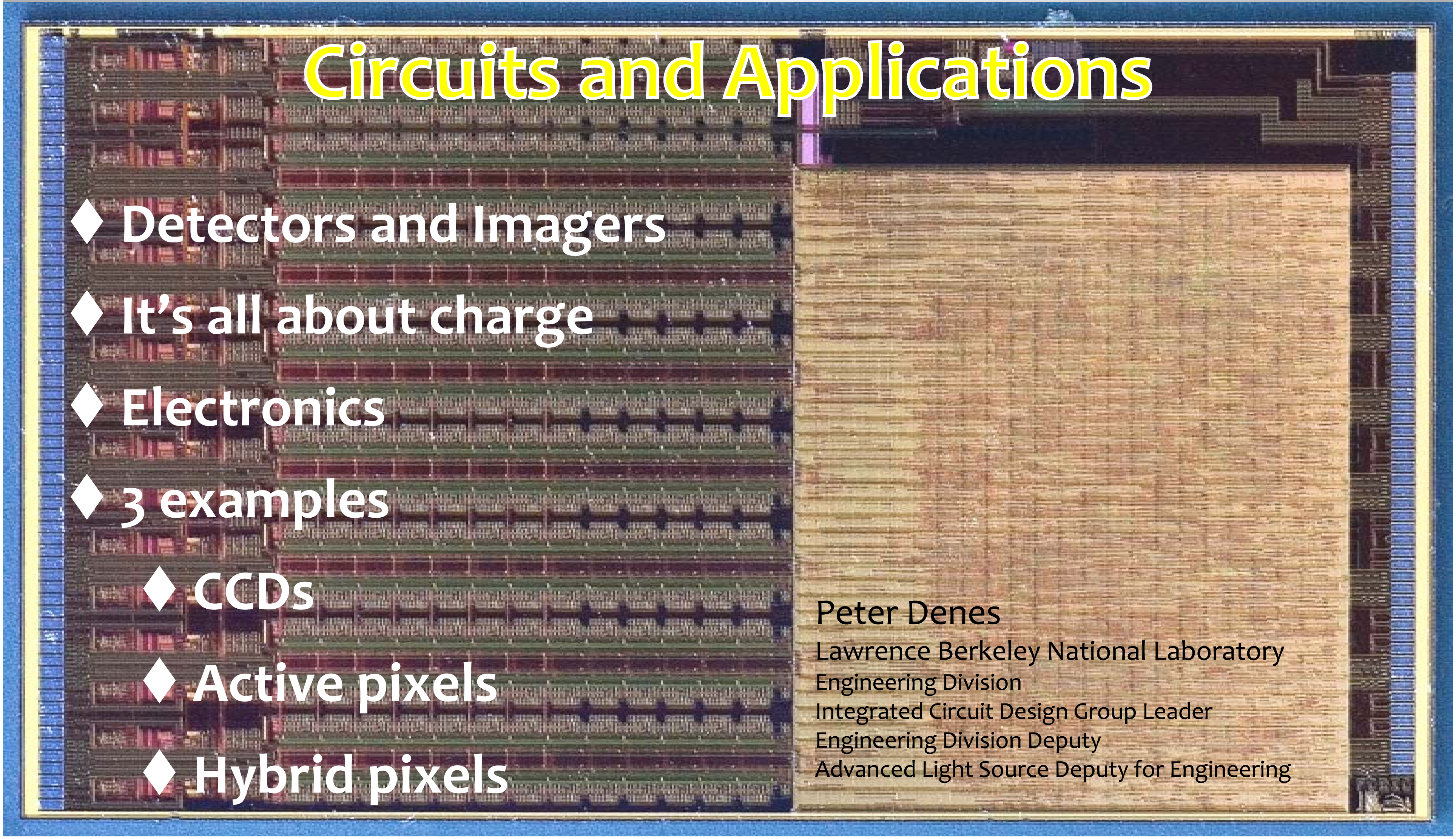
Front-End Electronics Systems for Particle Detection and Imaging

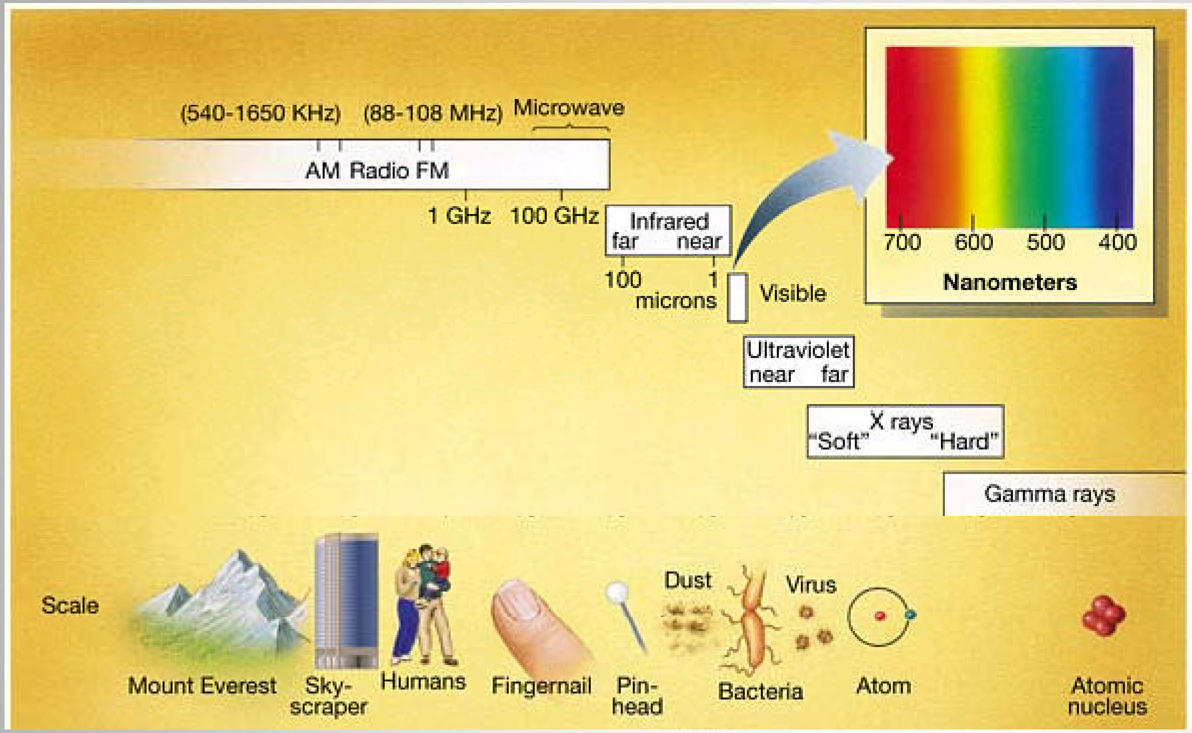


Circuits and Applications

- Detectors and Imagers
- It’s all about charge
- Electronics
- 3 examples
    - CCDs
    - Active pixels
    - Hybrid pixels

Peter Denes
Lawrence Berkeley National Laboratory
Engineering Division
Integrated Circuit Design Group Leader
Engineering Division Deputy
Advanced Light Source Deputy for Engineering

Scientific particle detection and imaging – wide spectrum

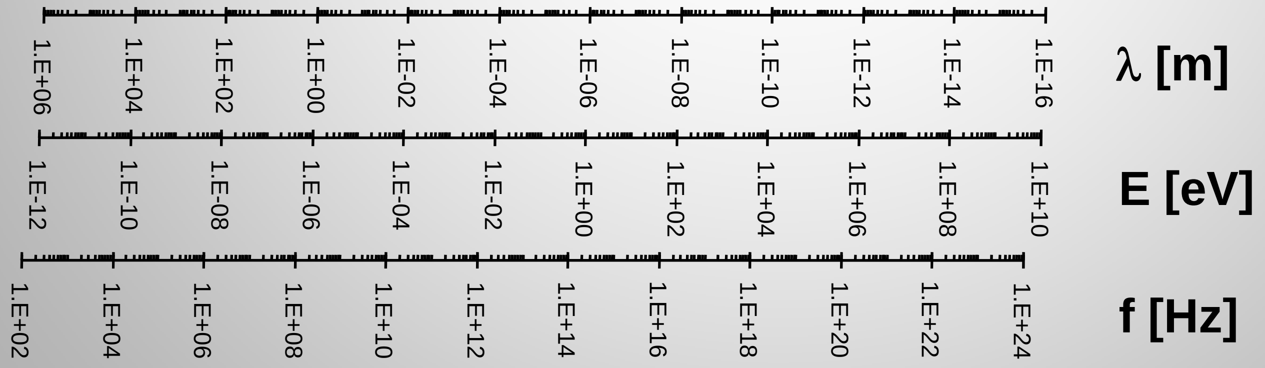


Many objects imaged with visible light

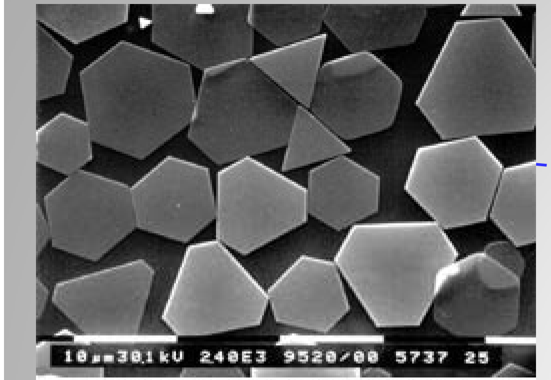
x-rays (synchrotrons, medical)

electrons (EM)

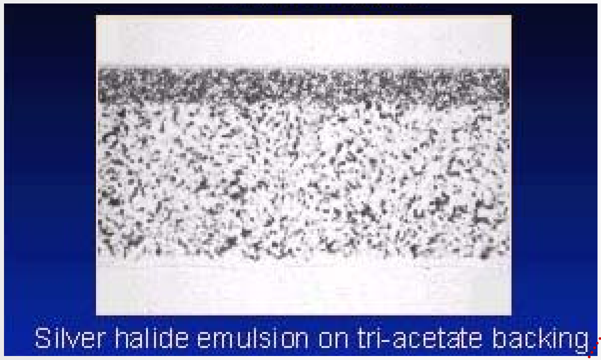
and other charged particles (particle physics, …)

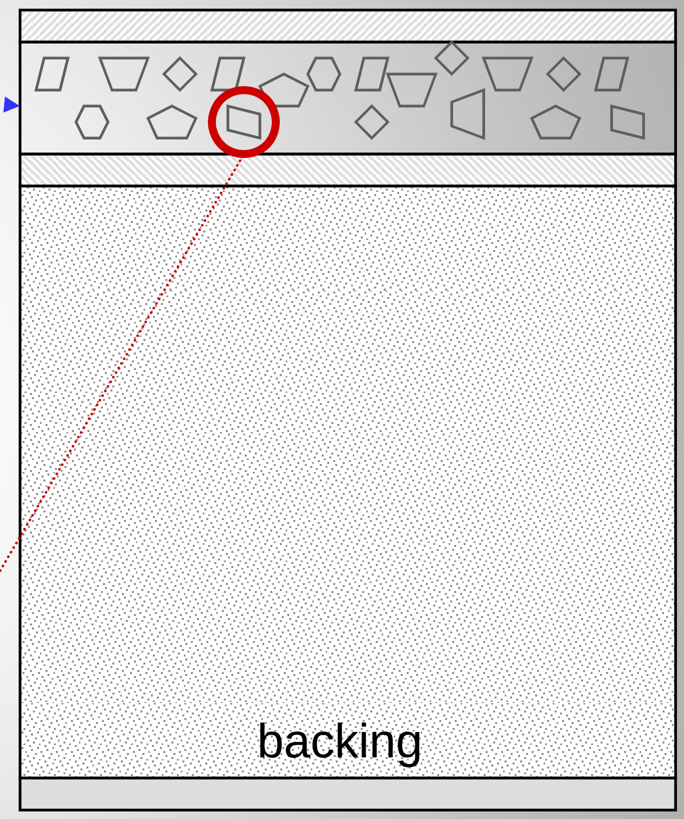


Focus on solid state detectors, but pay homage to film



Electron micrograph of tabular grain emulsion

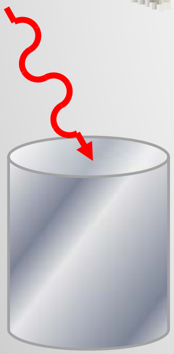

Silver halide emulsion on tri-acetate backing


AgX + gelatin
(emulsion)

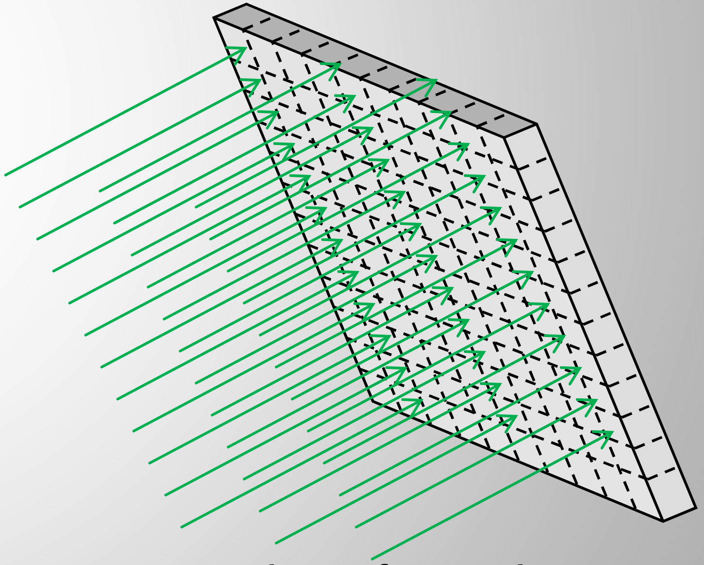
sub-micron to few micron grains
CMOS / CCD ~7 – 10 μm

"Detection" and "Imaging"

“Particle” is
of interest



“Particle” is
illumination



Number of particles
per detection element
per sampling interval
<< 1

Number of particles
per detection element
per sampling interval
> 1

What you want – what you get

Generally, we want to measure one or more of the following

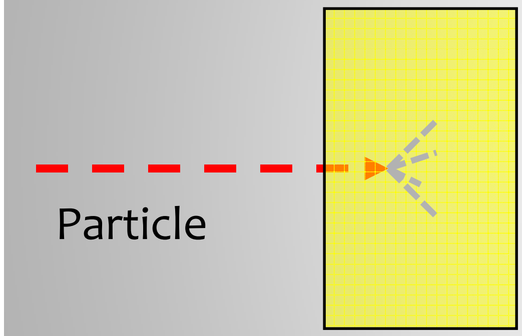
1. Energy of particle, or its dE/dx
2. Momentum of particle (⇒ position if in a magnetic field)
3. Time of particle's passage (⇒ position by TOF, or…)
4. Number of particles, or number of particles per unit area

What we end up measuring is

1. Charge [assume $q \propto E$]
2. Charge [$q(x,y)$ determines position]
3. Charge $\rightarrow V \rightarrow V(t) > V_T$ at time t
4. Charge [assume $q(x,y) \propto N(x,y)$]

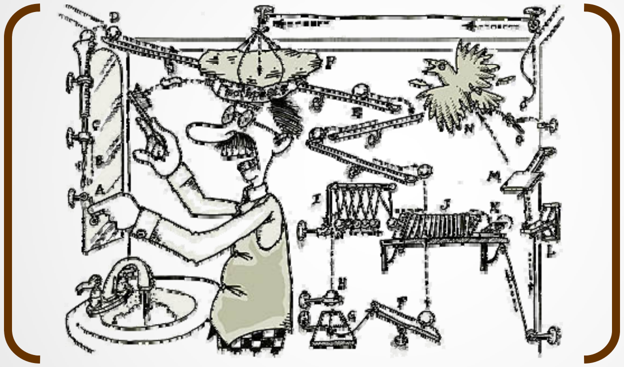
Detector / sensor

Particle interaction in sensing/detecting medium creates charge/light/heat …

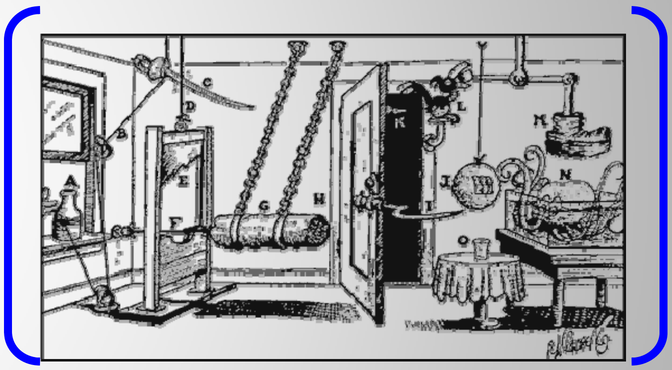


Particle

"Sensor"
"Detector"

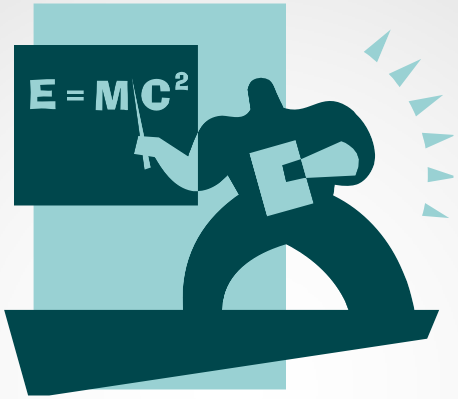


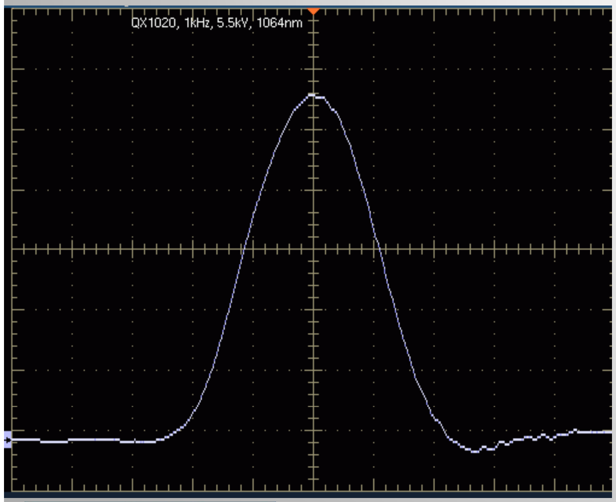
"Transducer"
(optional)
Convert light/heat … → charge

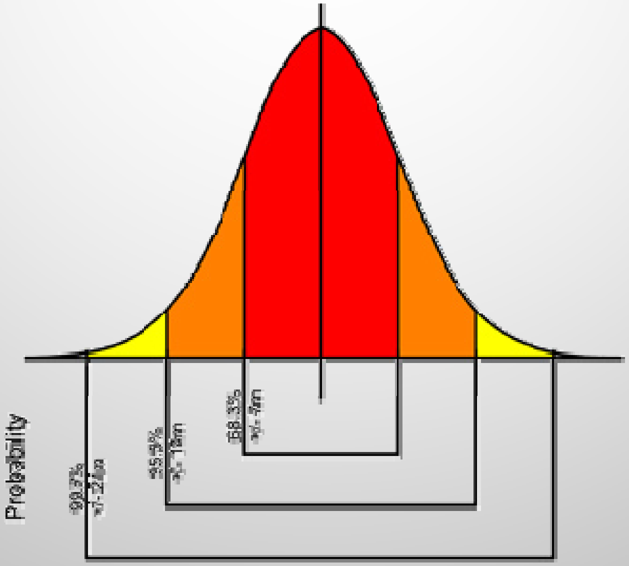


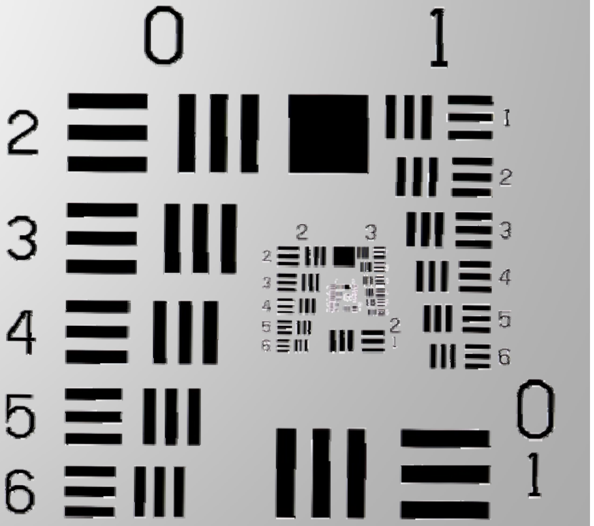
Charge → meaningful quantity
Front-end electronics

Different Languages



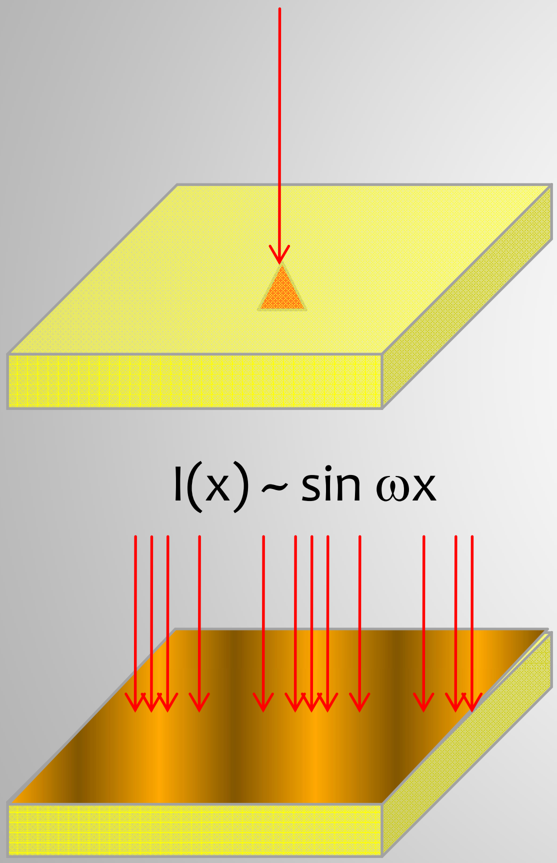






Electronics contribution to imager "performance"

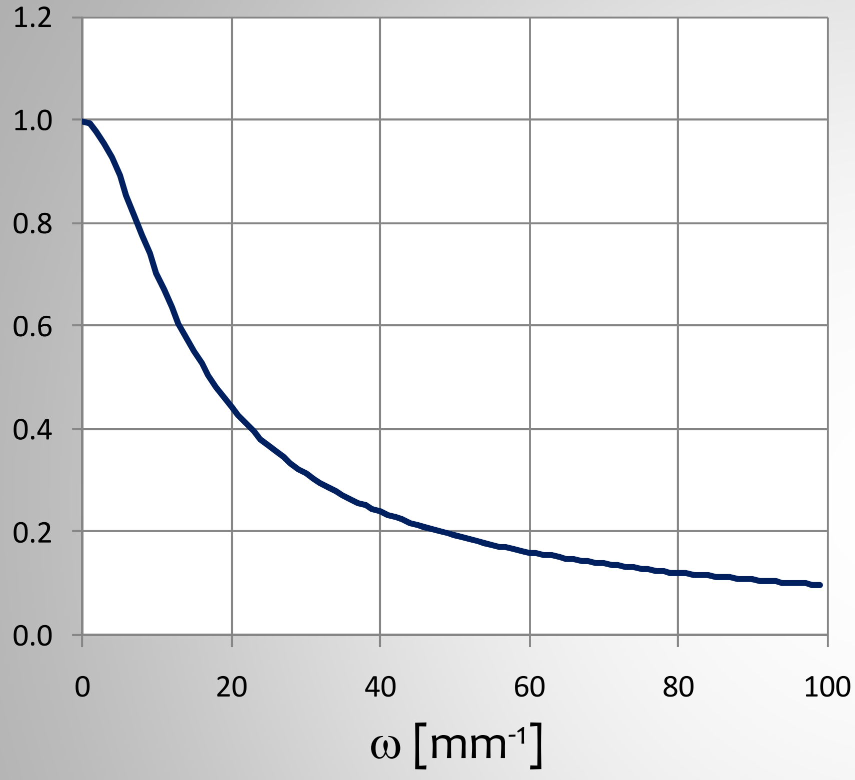
Picture "quality" defined by Detective Quantum Efficiency



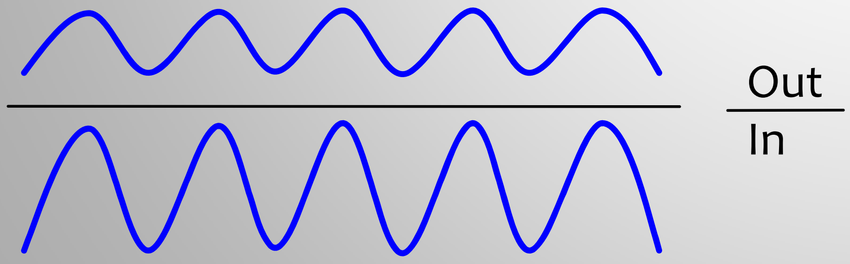
- **Point Spread Function**
  - Image is convolution of PSF and input

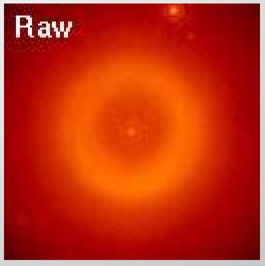
- **Modulation Transfer Function**
  - (magnitude of the) Fourier transform of PSF

MTF



- Spatial analog to (temporal) frequency response in electronics
  - “Signal processing” also possible
  - e.g. early days of Hubble Space Telescope





DQE

◆ Combine notion of Quantum Efficiency (probability of detecting a particle) with spatial response (probability of detecting/quantifying N(x,y) particles → DQE

- How faithfully does the detector transfer the (spatially varying) fluctuations of the input signal

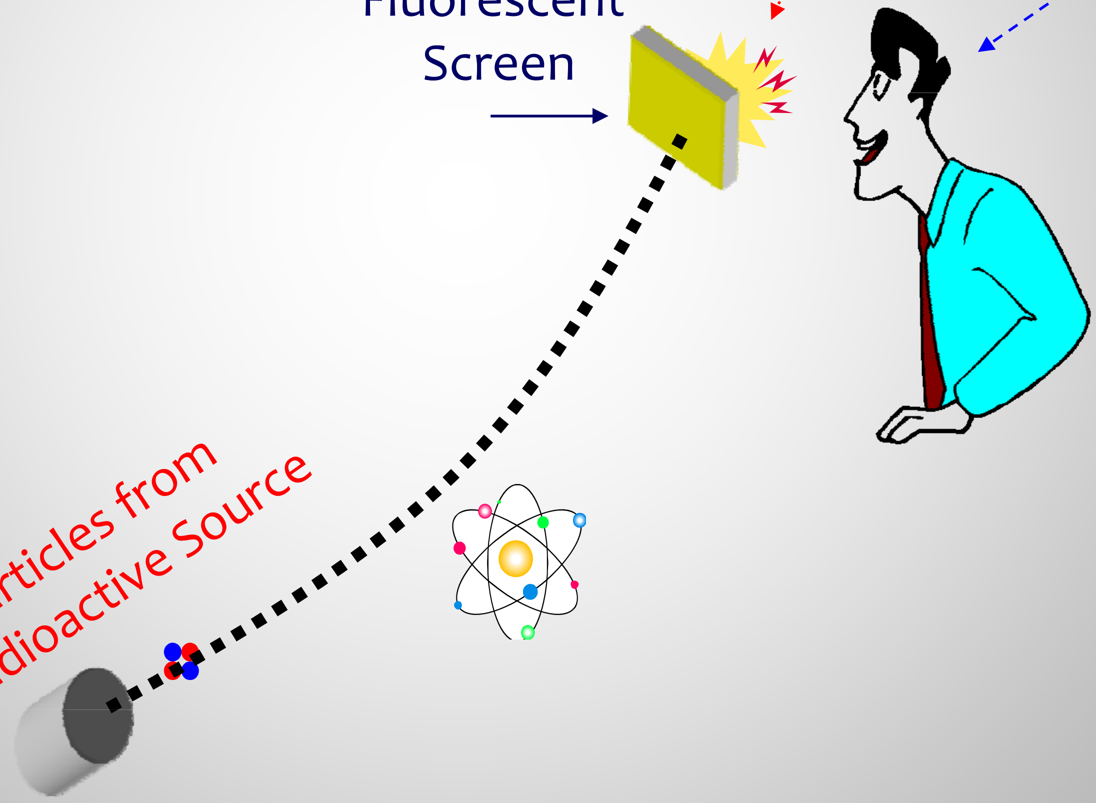
◆ Many definitions – most common is $DQE = \frac{(S/N)^2_{OUT}}{(S/N)^2_{IN}}$

◆ Example, flat field illumination (flux ϕ) of detector with certain QE

- $(S/N)_{IN} = \frac{\phi A \tau}{\sqrt{\phi A \tau}}$ (Poisson)
- $(S/N)_{OUT} = \frac{QE \times \phi A \tau}{\sqrt{QE \times \phi A \tau + \sigma_N^2}}$

for electronic noise σ_N

On to detectors!



Scintillation
Light

Particle
Detector

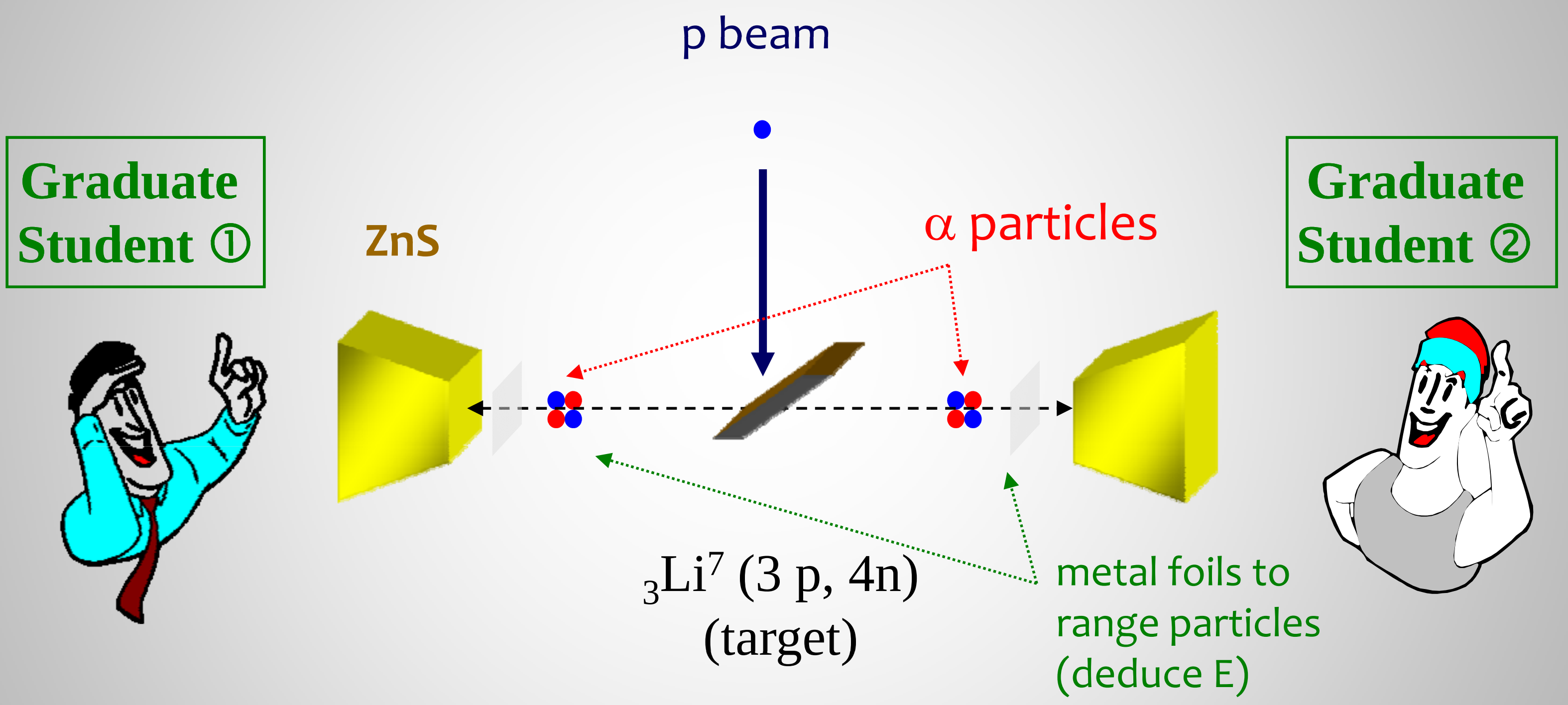
ZnS
Fluorescent
Screen

α particles from
Radioactive Source

Rutherford, 1911 – Discovery of the nucleus

Coincidence Experiment

Cockcroft+Walton, 1932



p beam

Graduate Student ①

ZnS

α particles

Graduate Student ②

$_3$Li^7 (3 p, 4n)
(target)

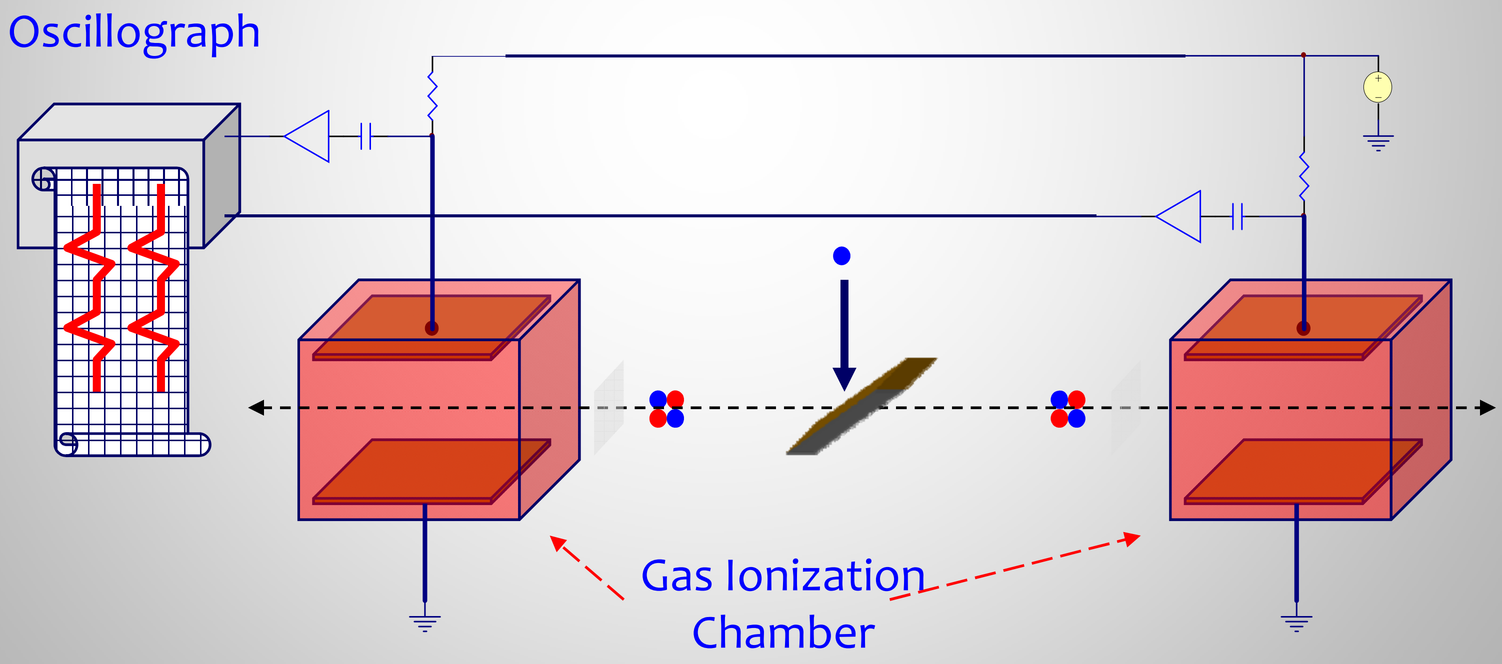
metal foils to
range particles
(deduce E)

First demonstration that E (from p + $_3\mathrm{Li}^7 \rightarrow \alpha + \alpha$) = Δmc^2
(Δm is difference between initial and final nuclei masses)

Coincidence Experiment

Cockcroft+Walton - Electronic Verification

One of the last visual counting experiments
(and one of the first electronic counting experiments)

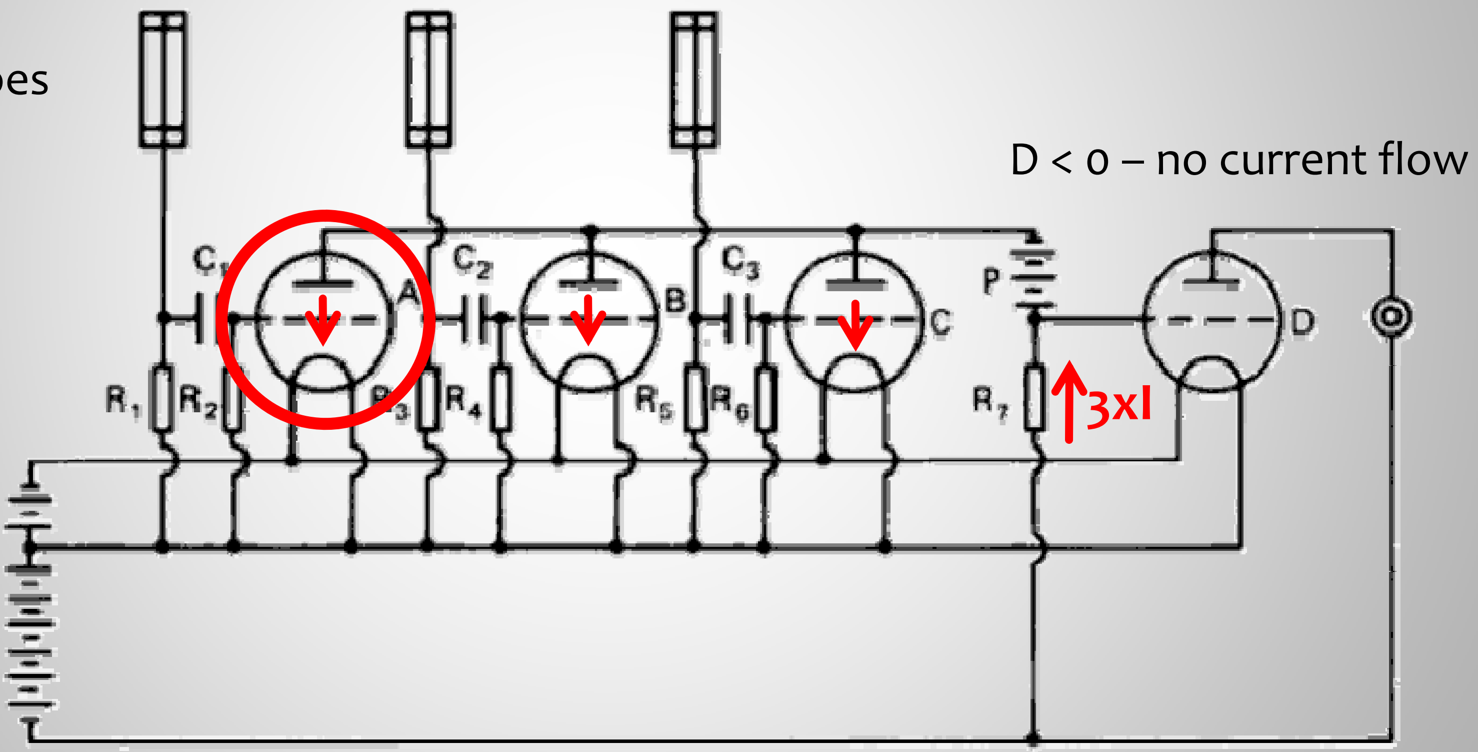


Oscillograph

Gas Ionization Chamber

Electronic coincidence circuit

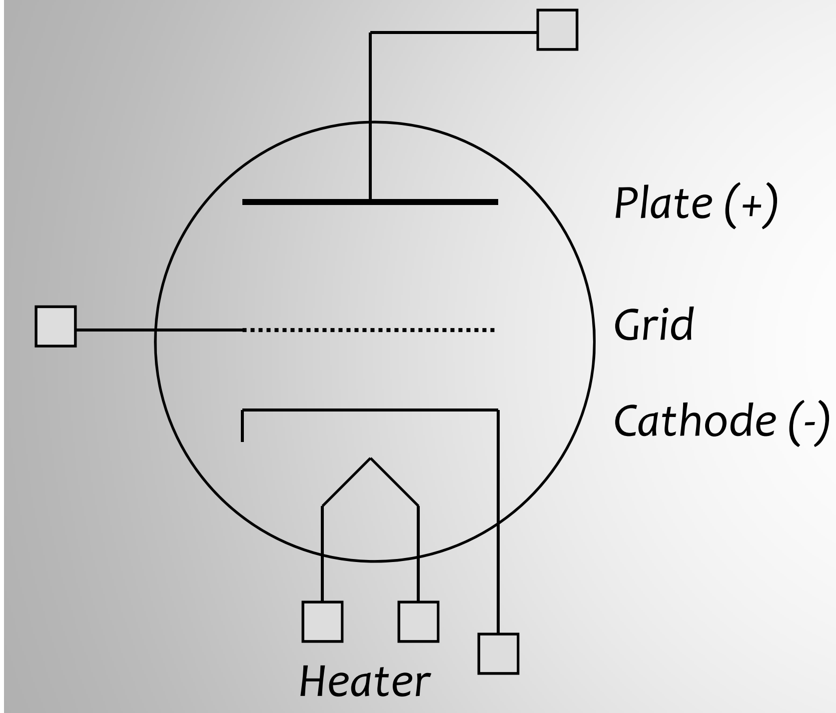
Bruno Rossi - 1930



Geiger tubes

D < 0 – no current flow

1906 – Lee de Forest, the Triode



$I \sim V_G^{x}$

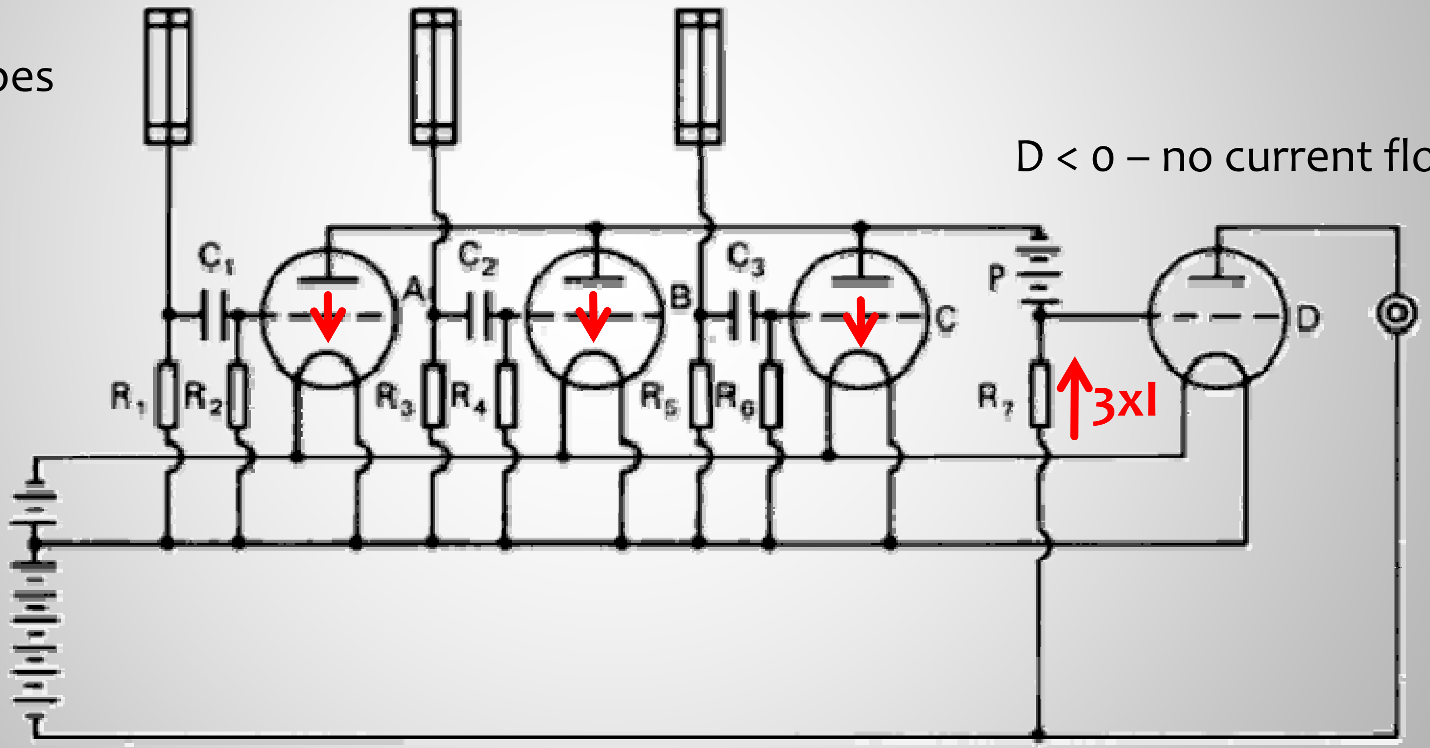
- ◆ Indirectly heated cathode emits electrons
- ◆ Electrons collected by positive anode (plate)
- ◆ If grid is negative, electrons are repelled (reduces or eliminates current flow)

Electronic coincidence circuit

Bruno Rossi - 1930

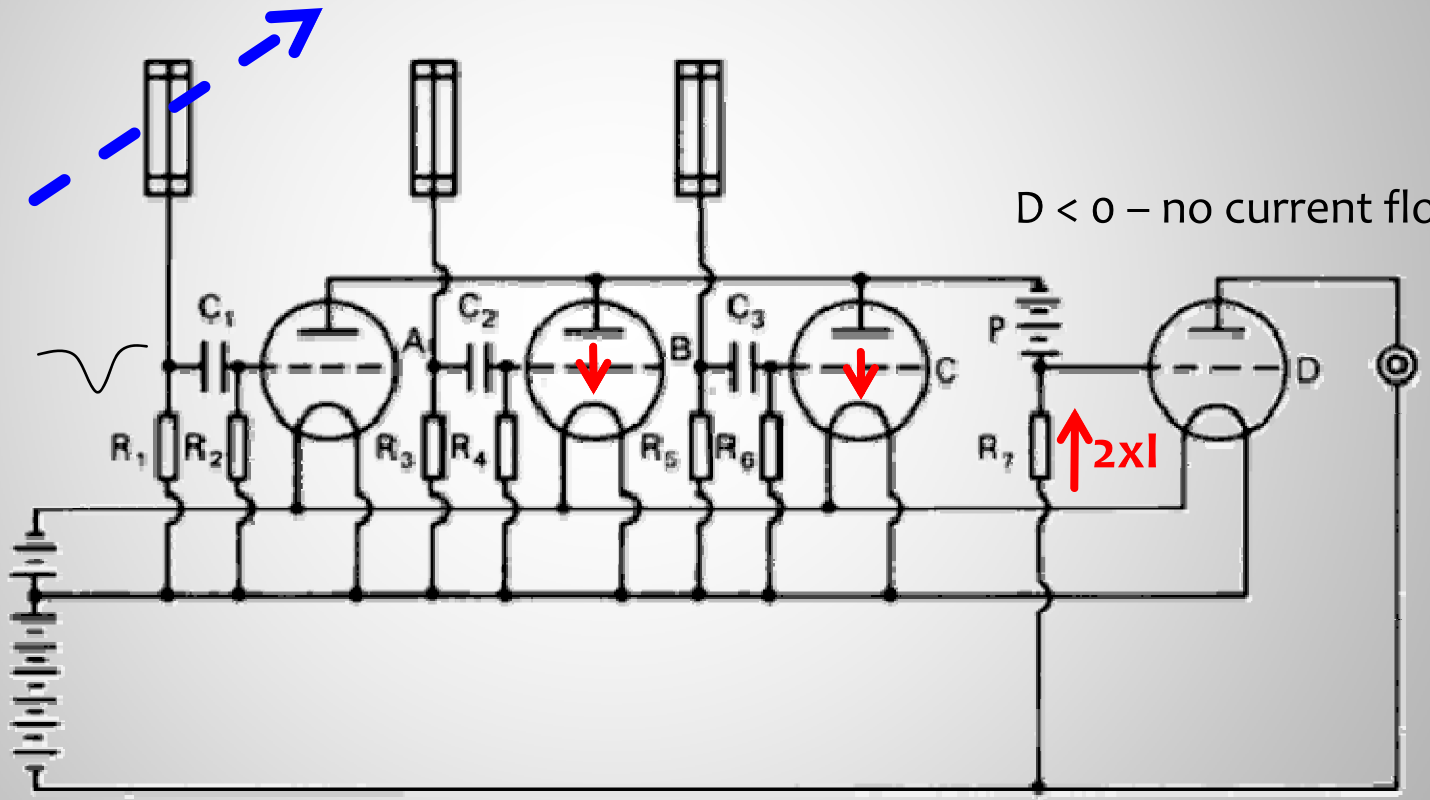
Geiger tubes

D < 0 – no current flow



Electronic coincidence circuit

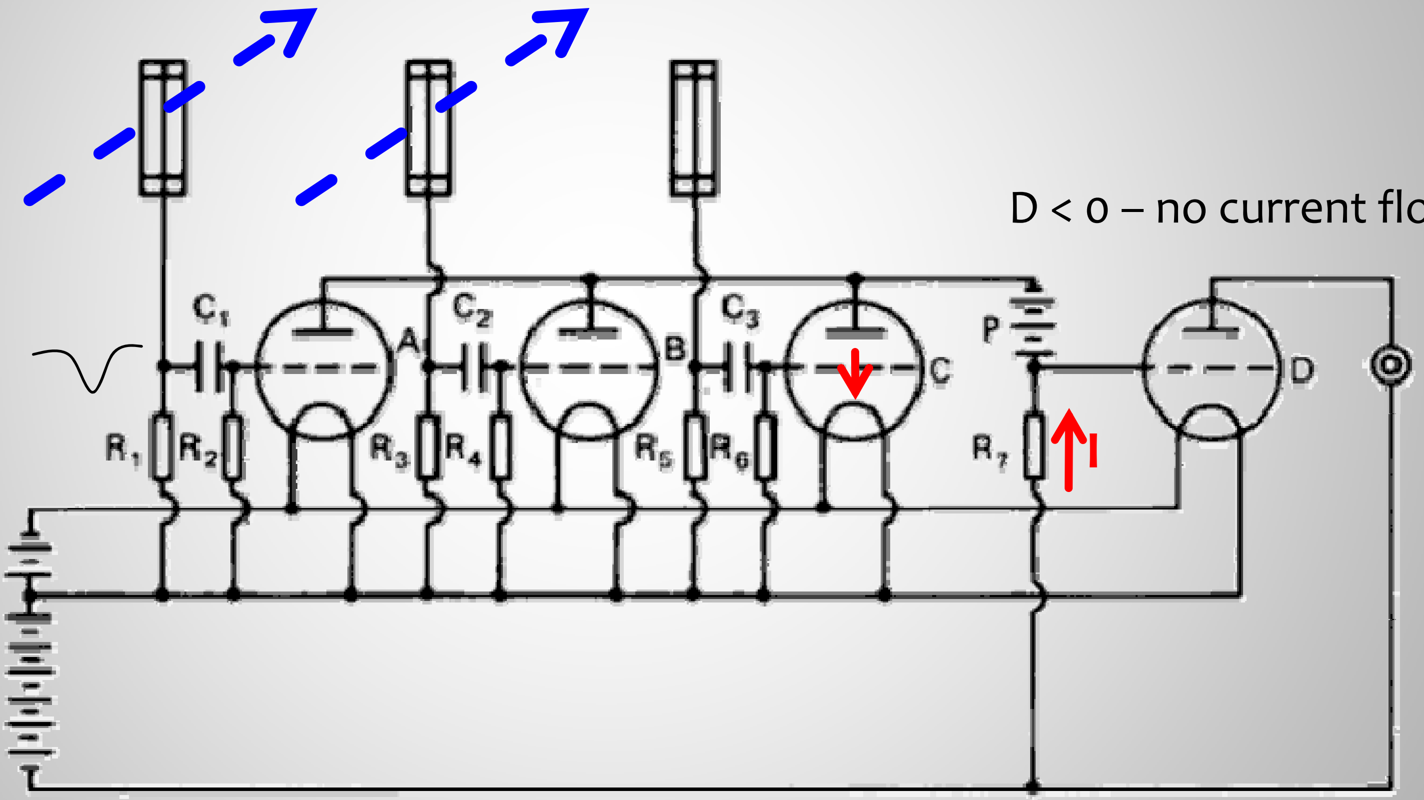
Bruno Rossi - 1930



D < 0 – no current flow

Electronic coincidence circuit

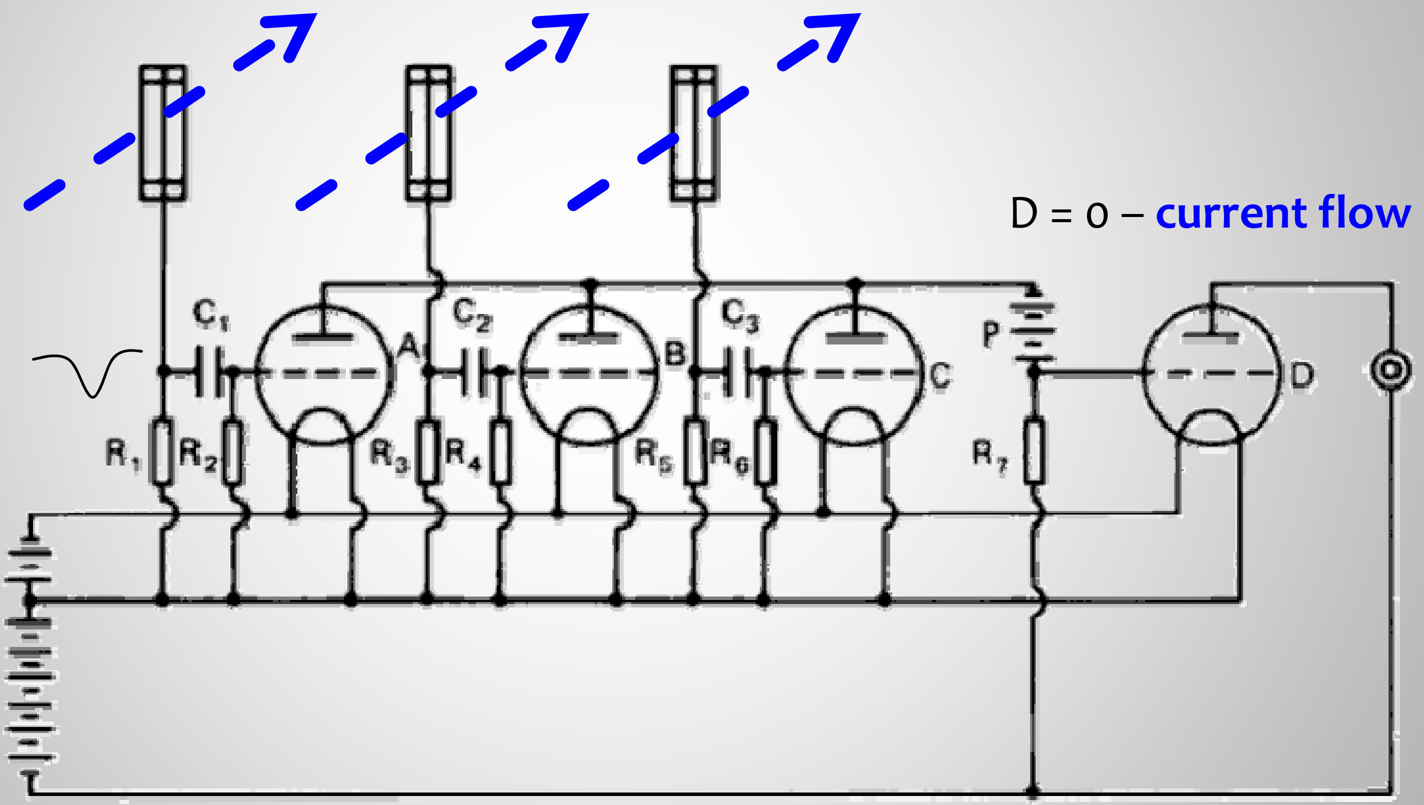
Bruno Rossi - 1930



D < 0 – no current flow

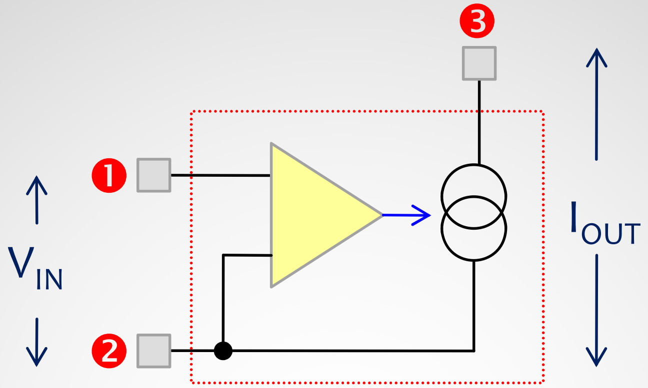
Electronic coincidence circuit

Bruno Rossi - 1930



D = 0 – **current flow**

Generic transconductor



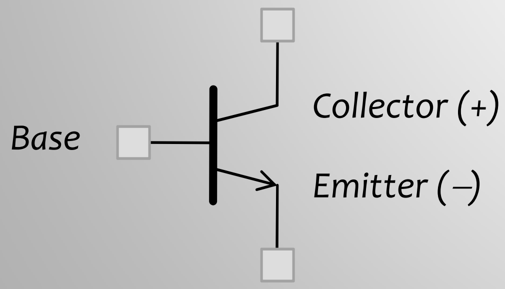
$$g_m = \frac{\partial I}{\partial V}$$

- Three terminal device
- $I_{\text{❸❷}} = f(V_{\text{❶❷}})$
- To first order, I_{OUT} independent of V_{OUT} (but not really)

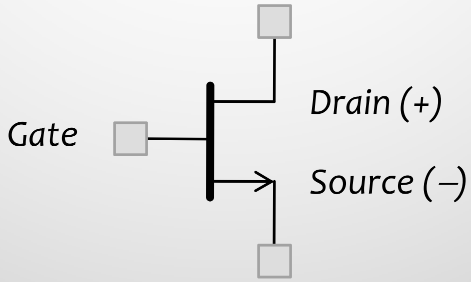
Real transconductors

- Bipolar transistor – $\beta = I_{OUT}/I_{IN}$
- Field effect transistor – $R_{IN} \sim \infty$

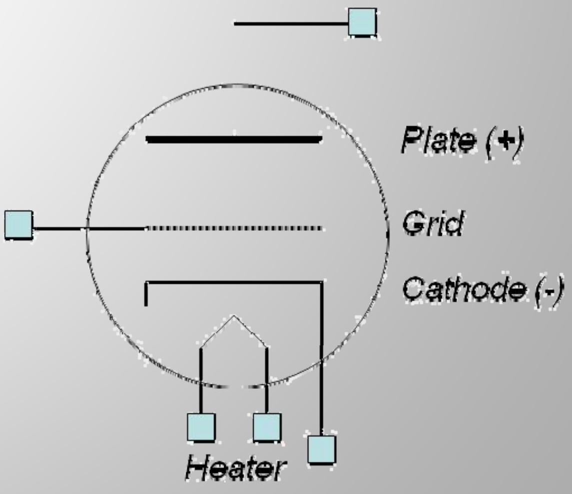
$I \propto \exp(V_{BE})$



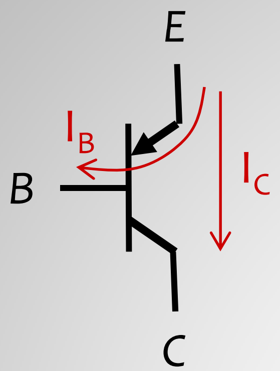
$I \propto V_{GS}^2$



$I \propto V_{GC}^x$

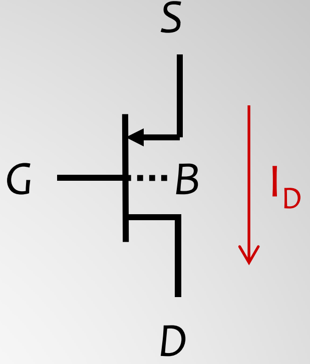


Bipolar Junction vs. Insulated Gate Transistors



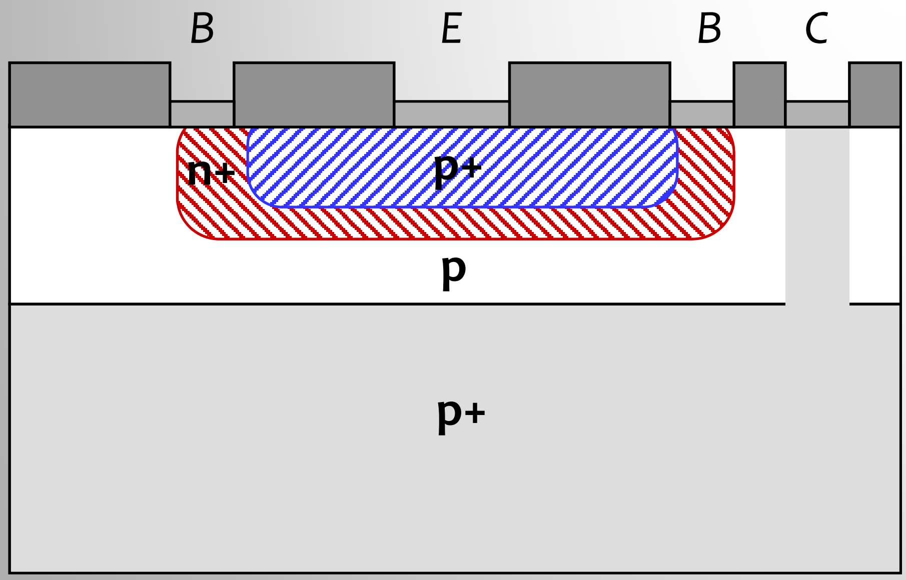
$I_C \sim \beta \, I_B$

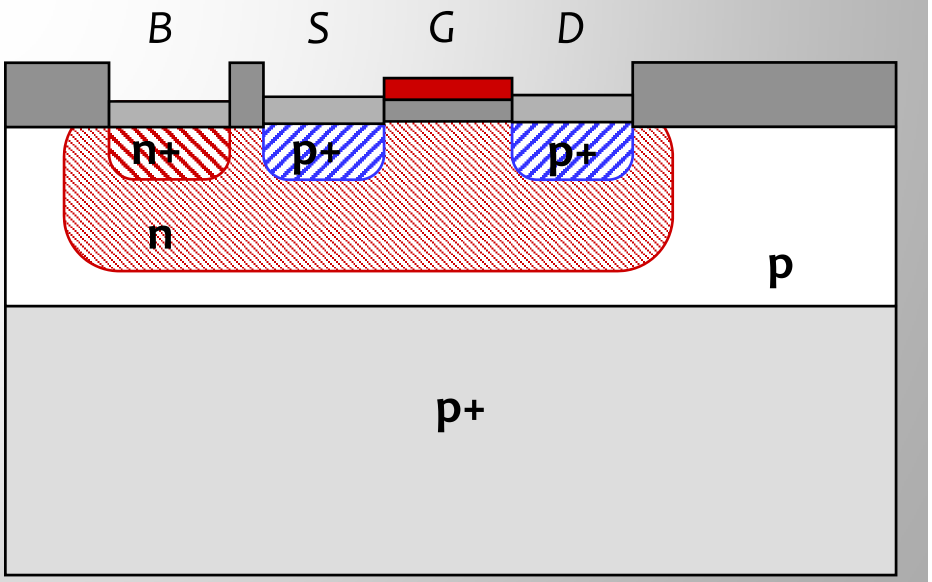
$I_B \sim \exp(V_{BE}/kT)$



$I_D \sim (V_{GS} - V_T)^2 \quad V_{GS}>V_T$

$I_D \sim 0 \quad V_{GS}<V_T$

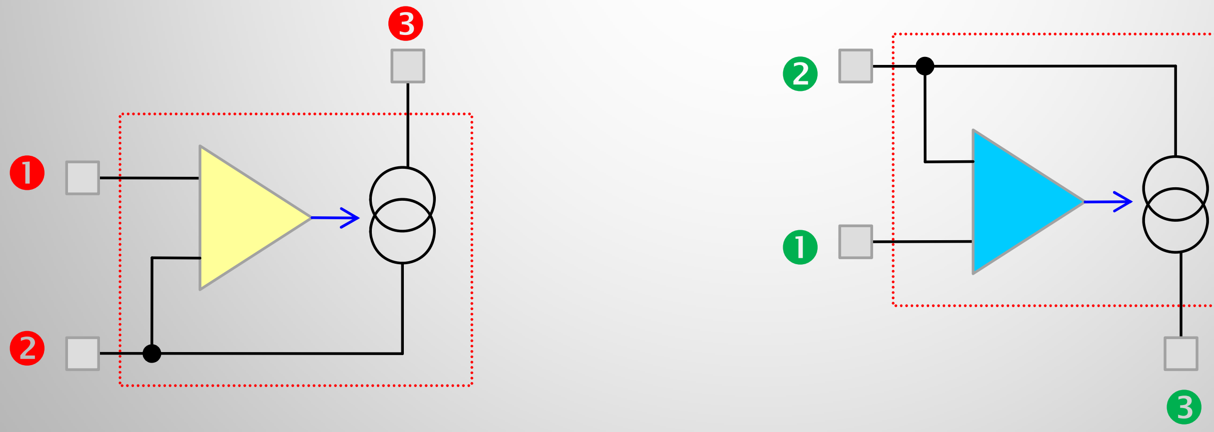




1^{st} MOS on Si - 1960

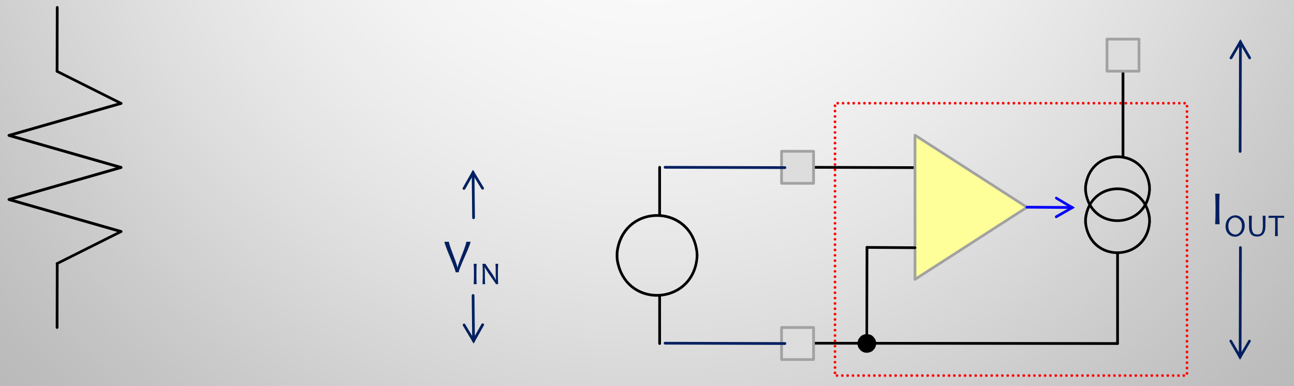
Complementary devices

- V❶ > V❷ in order to have current flow
- Complementary device has V❶ < V❷ in order to have current flow



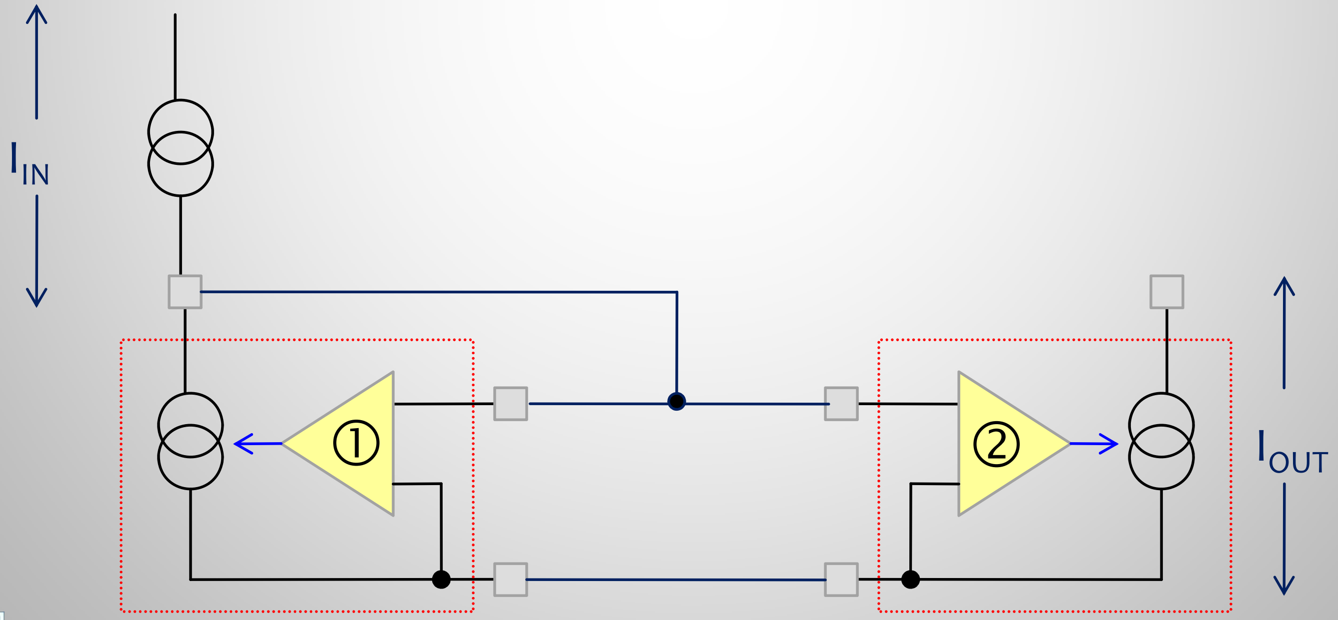
Uses – current source

- $I_{OUT} = g_m V_{IN}$ (resistor, $I_{OUT} = V_{OUT} / R$)
- I_{OUT} independent of V_{OUT} (for a perfect device)



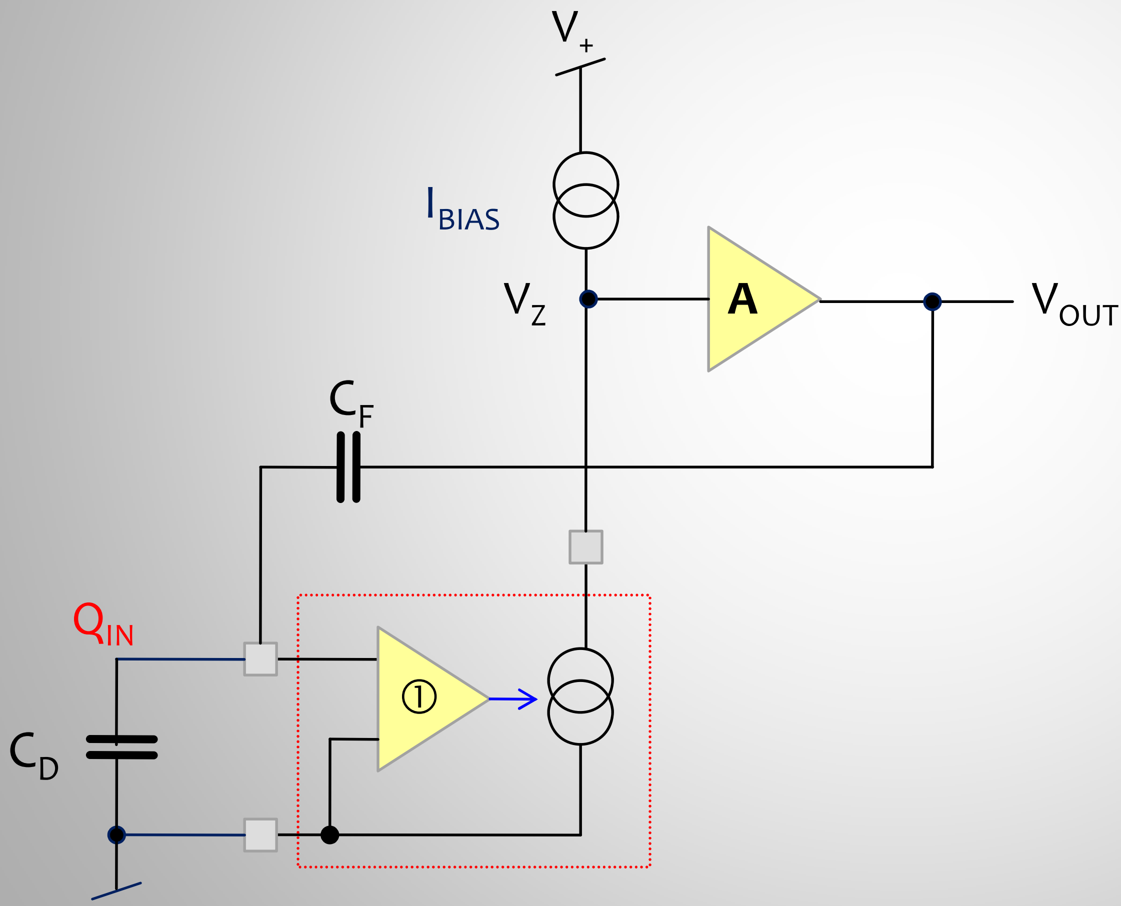
Uses – current mirror

- I_{IN} forces $V_{IN①}$ such that $I_{OUT①} = I_{IN}$
- $V_{IN②} = V_{IN①}$, so that if ② = ①, then $I_{OUT②} = I_{IN}$
- (If ② = Mx①, then $I_{OUT②} = MxI_{IN}$)



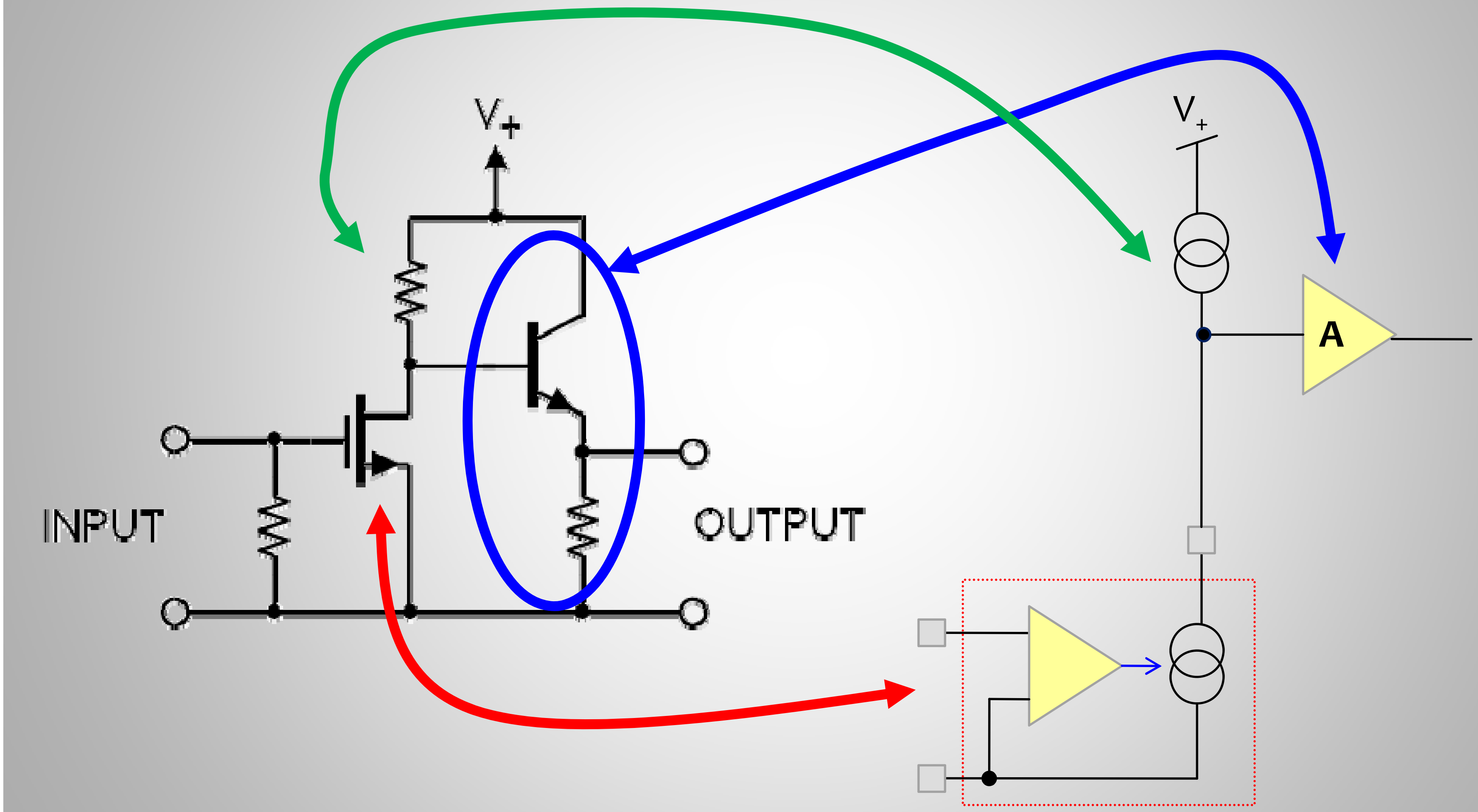
Uses - preamplifier

Quiescent state

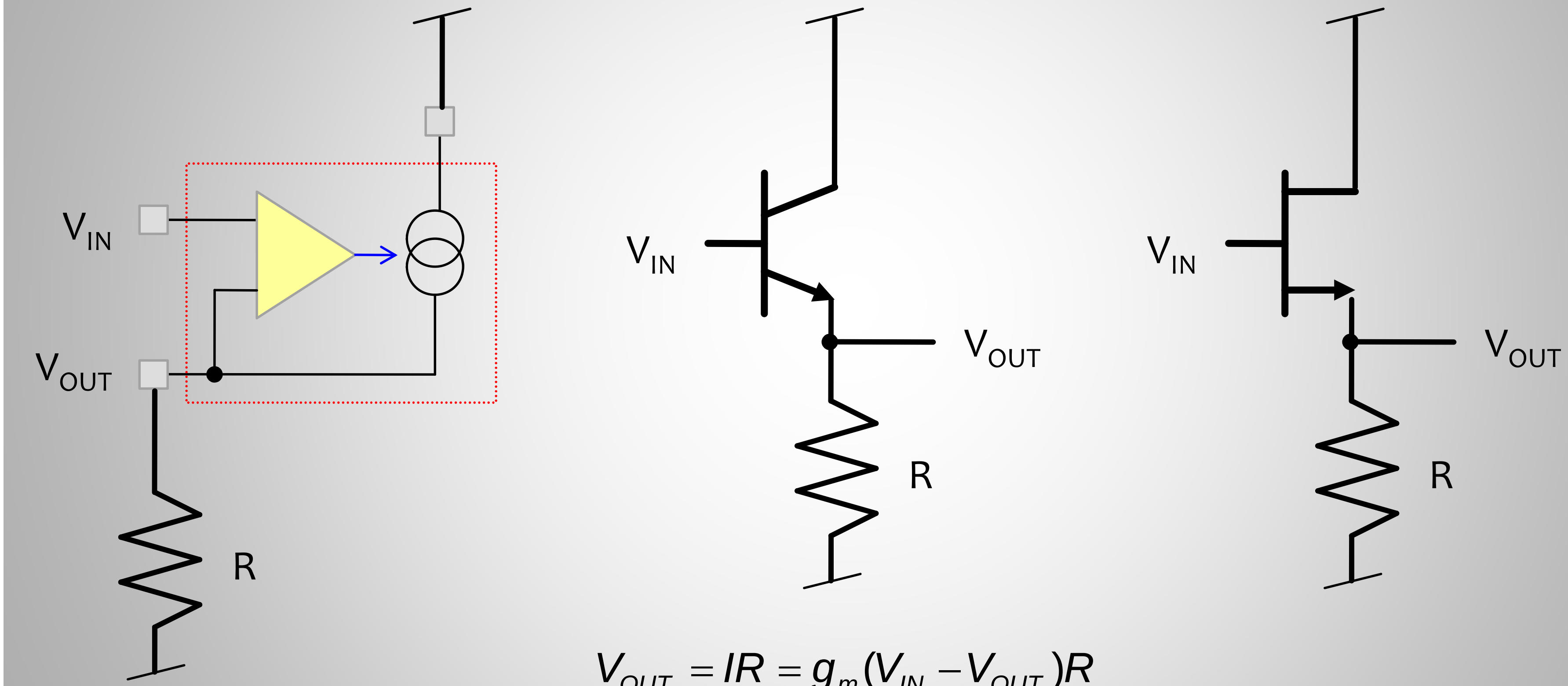


- A has high gain
- $I_{①} = I_{BIAS}$ (quiescent)
    - $V_Z = V_+ / 2$
- Q_{IN} arrives (δ fn.)
    - $\Delta V_{IN} = Q_{IN} / C_D$
- $I_{①} \rightarrow I_{BIAS} + g_m \Delta V_{IN}$
    - $V_Z \rightarrow$ rail
- Feedback current $C_F \frac{dV_{OUT}}{dt}$ replenishes charge

Helmuth's Example



Emitter/Source Follower



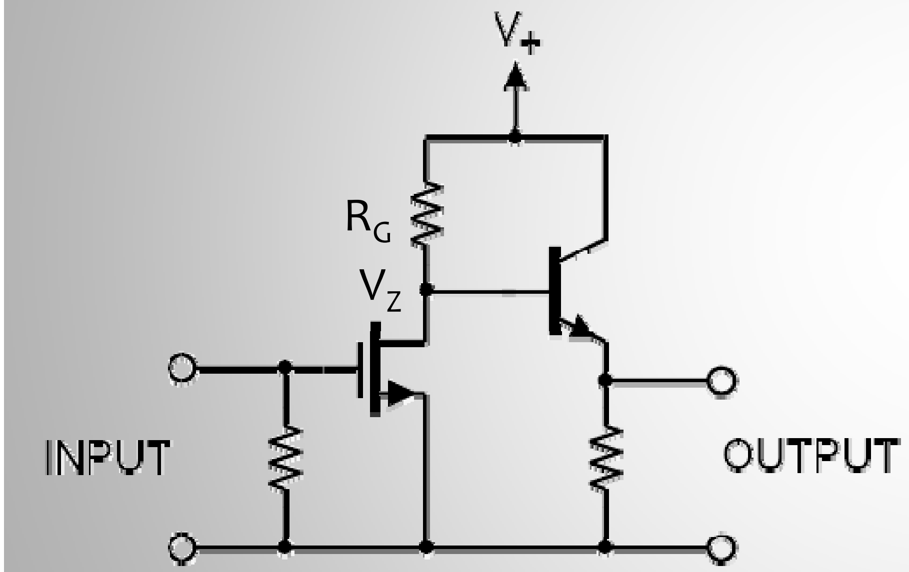
$$V_{OUT} = IR = g_m(V_{IN} - V_{OUT})R$$

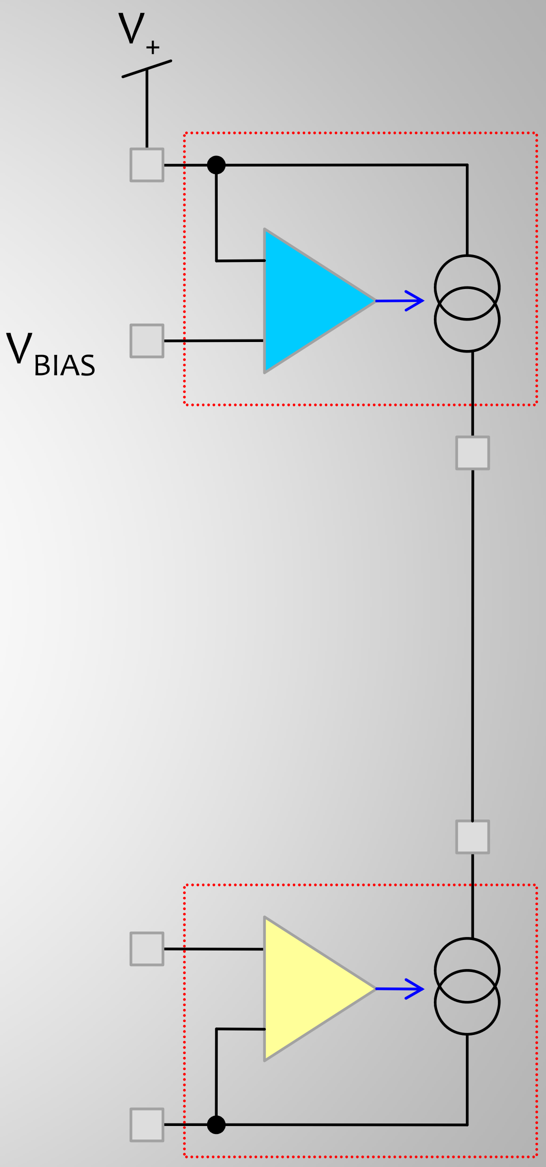
$$A = \frac{g_m R}{1+g_m R} < 1$$

Improve

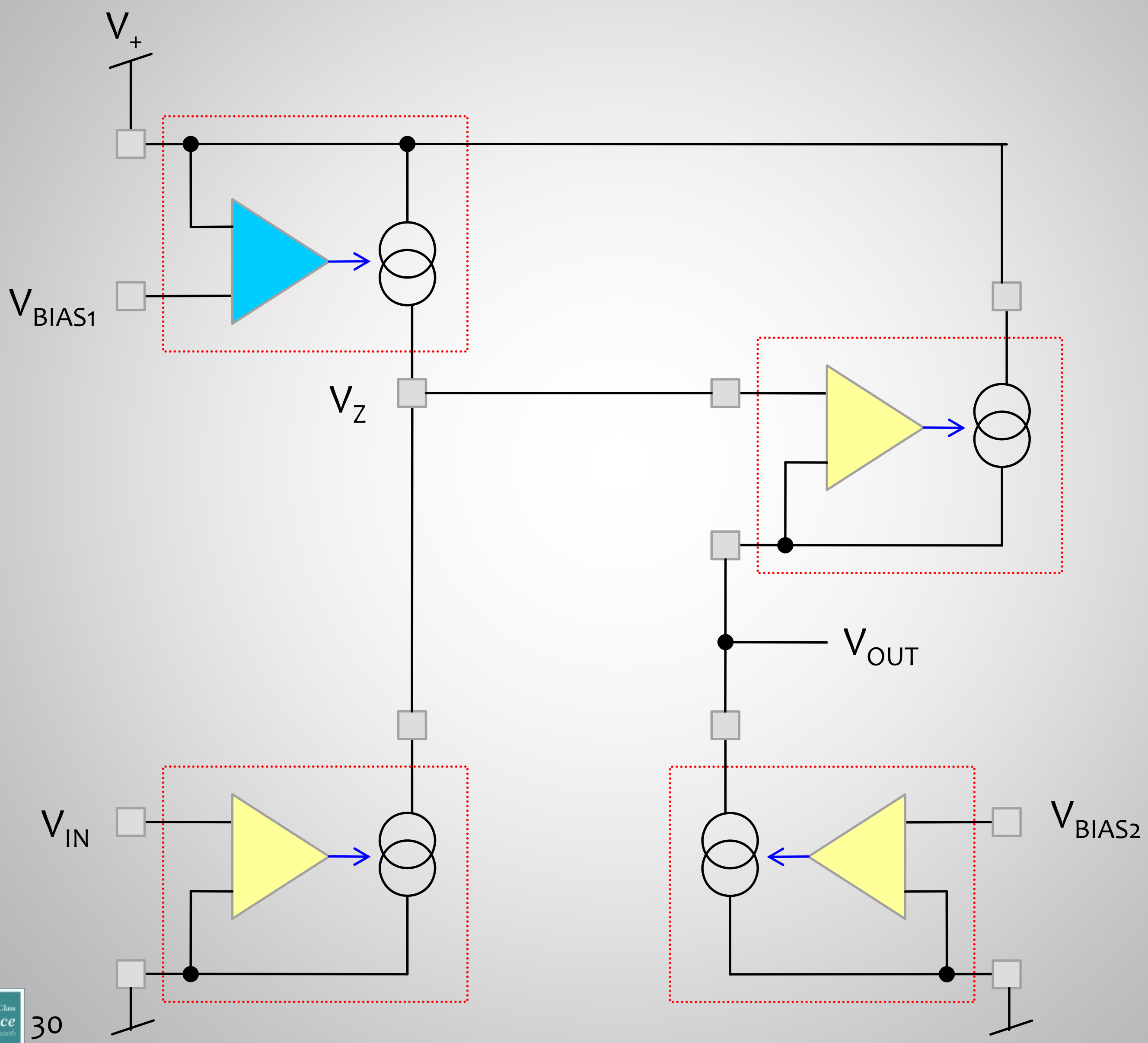
$\Delta V_Z = R_G g_m \Delta V_{IN}$

Maximize V_Z by making R_G big

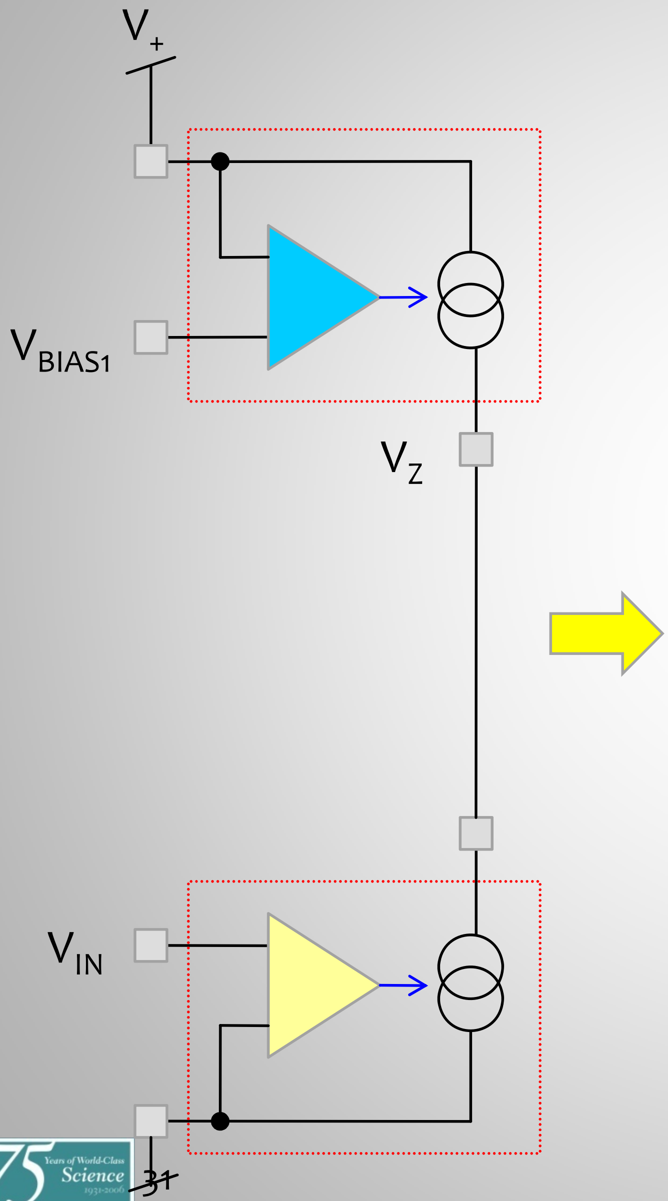


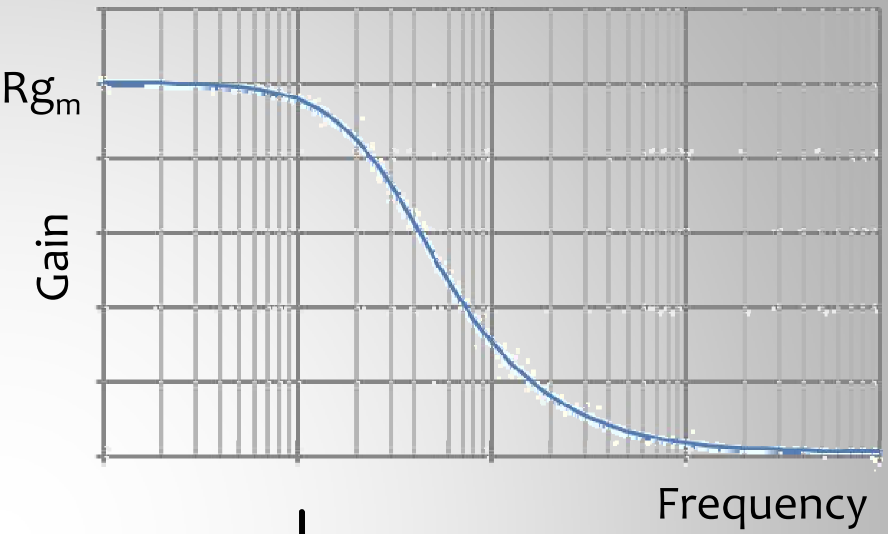


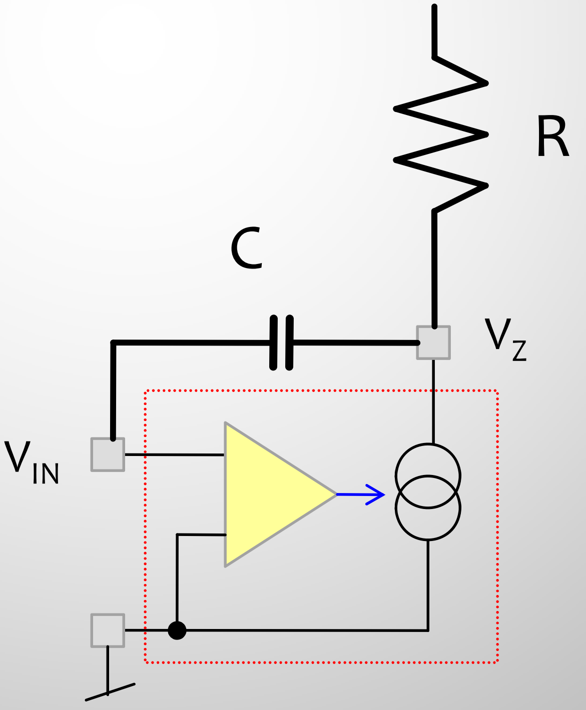
How about this?



Small problem



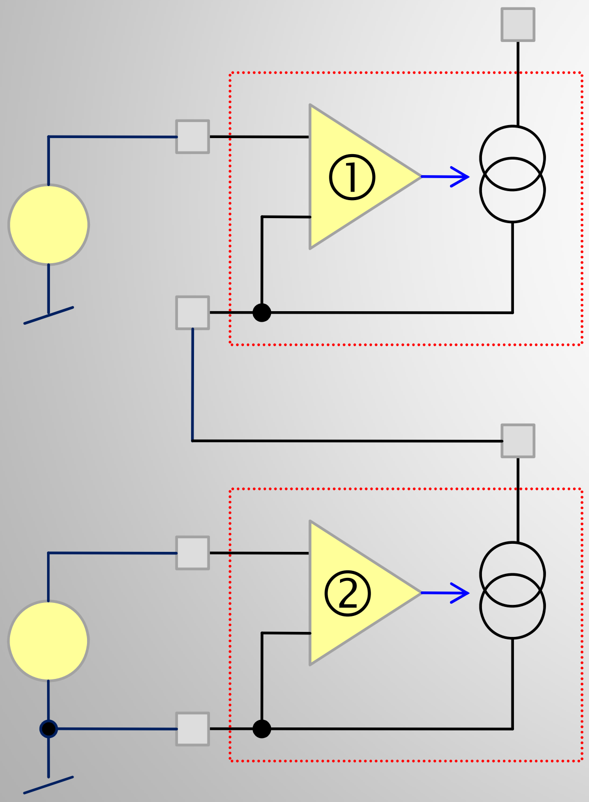




Even small C
kills gain
(Miller effect)

Uses - cascode

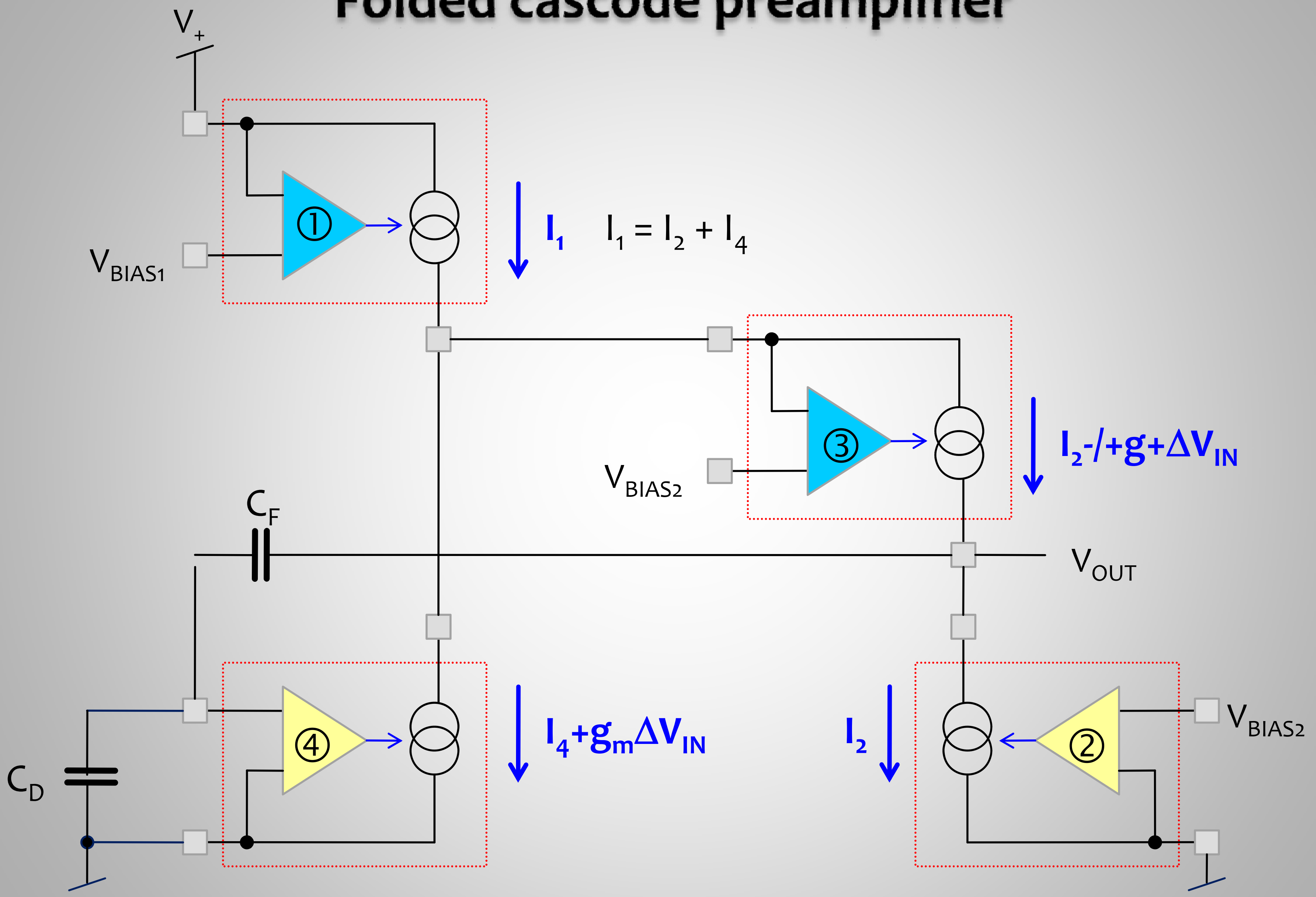
"cascade to cathode"



- $I_{②} = g_m V_{②}$
- $I_{①} = I_{②}$
- $V_{OUT②} = V_{①} - g_m I_{①}$

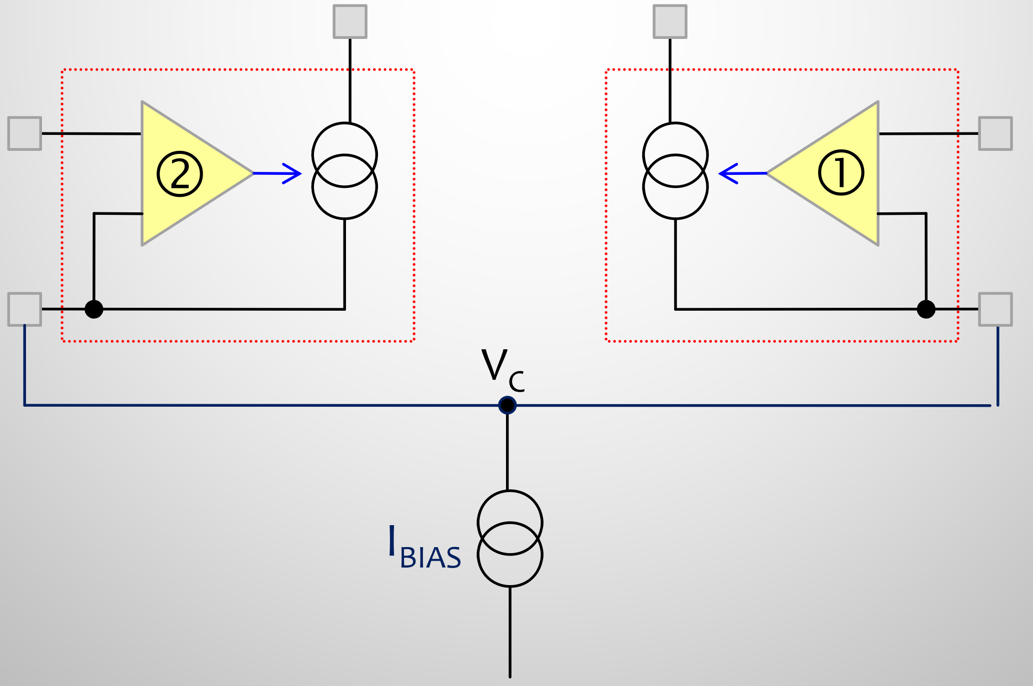
- Output of ② doesn't move

Folded cascode preamplifier

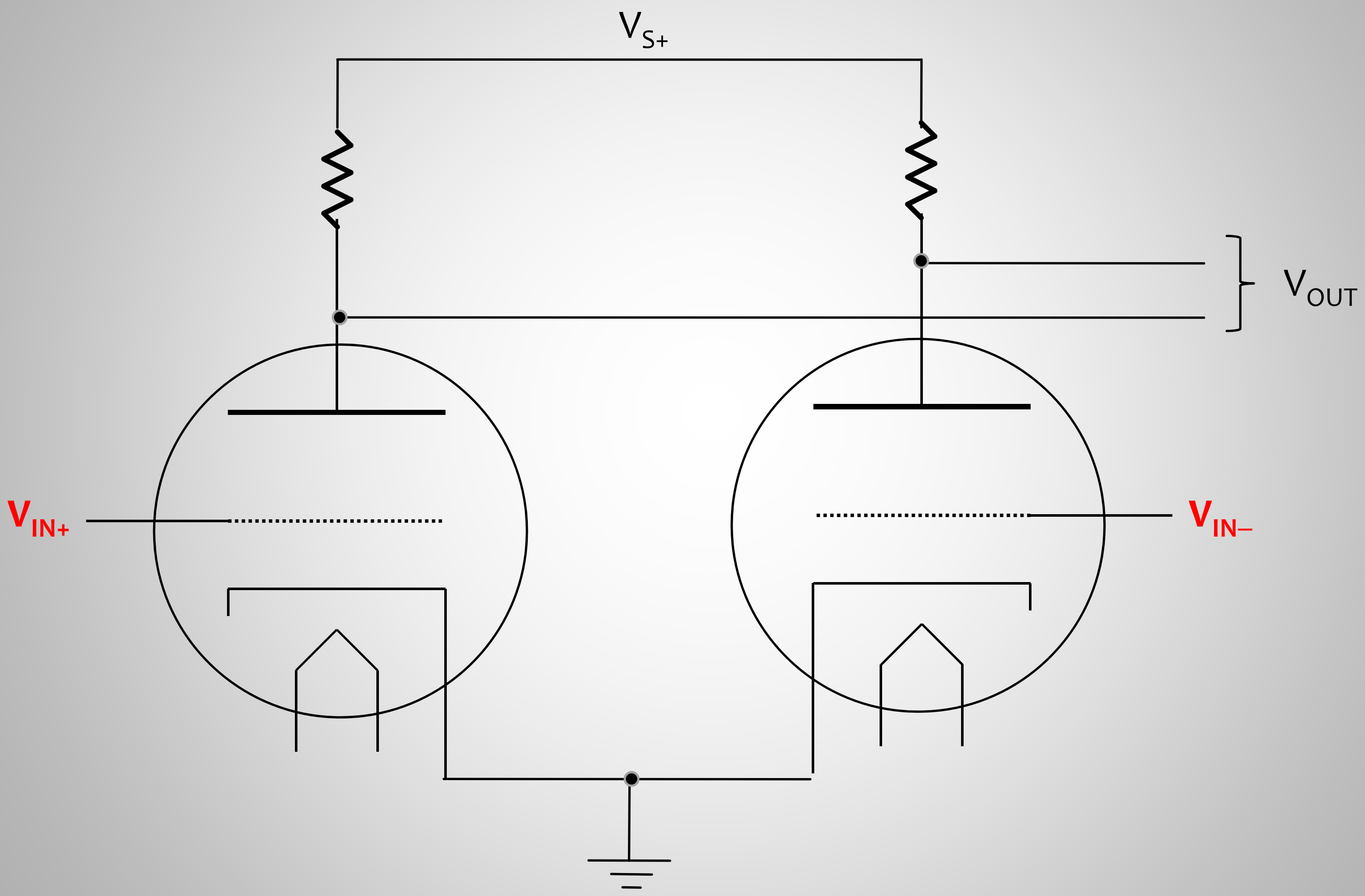


Uses – differential stage

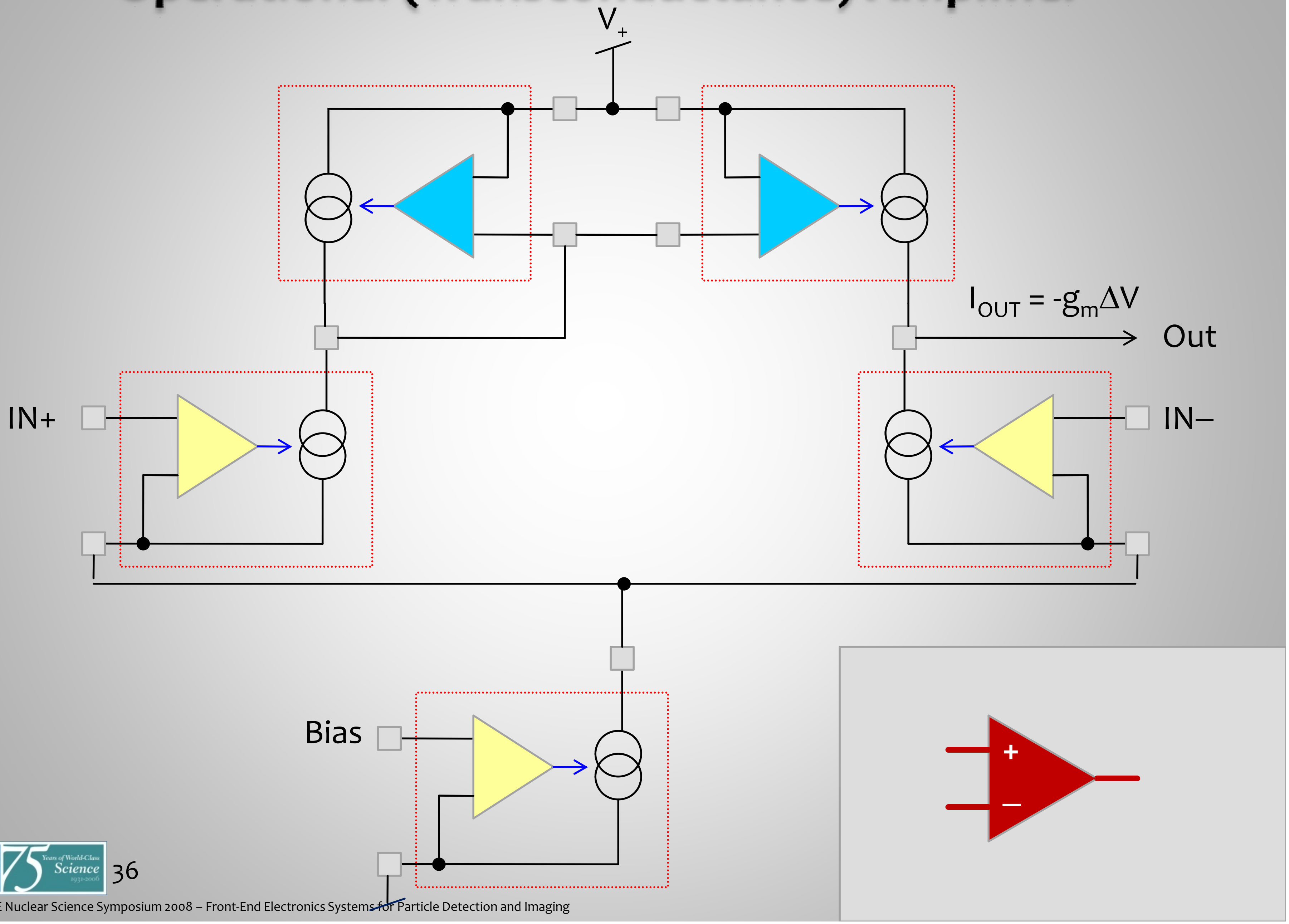
- $I_{②} = g_m(V_{IN②}-V_C)$, $I_{①} = g_m(V_{IN①}-V_C)$
- $I_{①} - I_{②} = g_m(V_{①} - V_{②})$
- $I_{BIAS} = I_{①} + I_{②}$



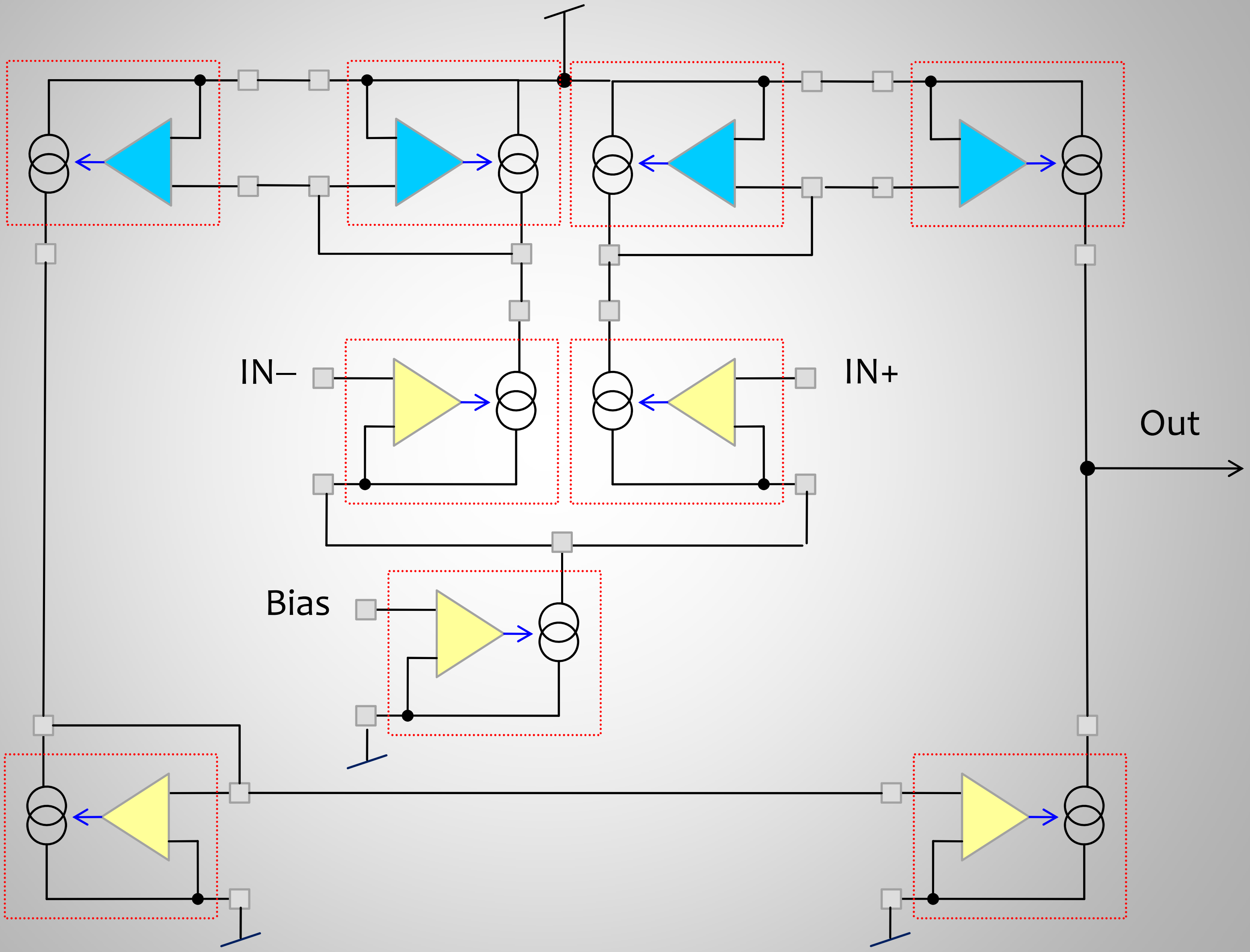
1938 – J.F. Toennies – The Long-Tailed Pair



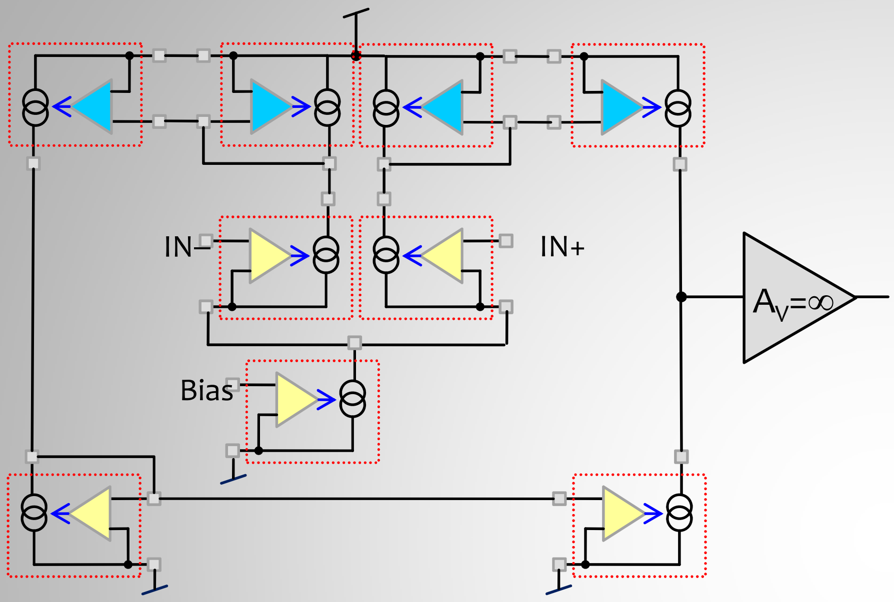
Operational (Transconductance) Amplifier

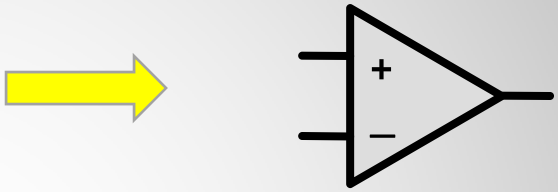


Rail-to-Rail OTA

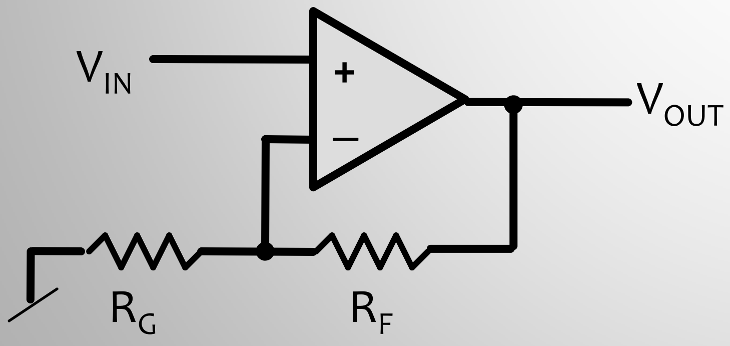


Operational amplifier

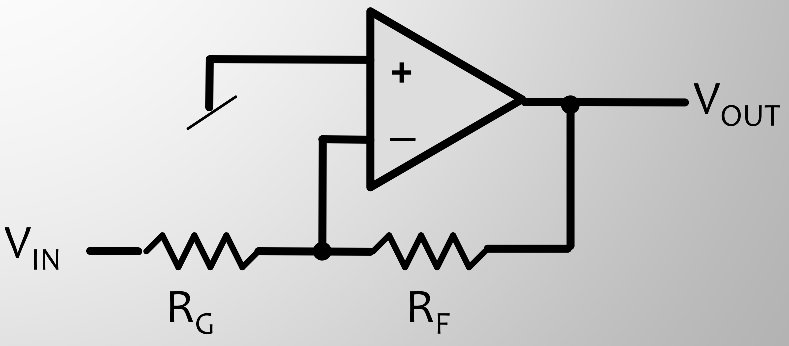




$V_{OUT} = A_V\,(V+ - V–)$
(Assume $A_V = \infty$)



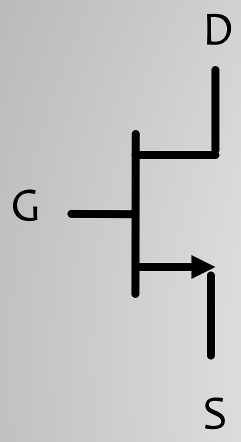
$V_{OUT} = (1 + R_F/R_G)V_{IN}$

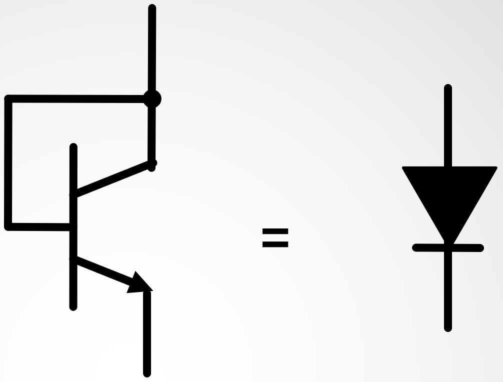


$V_{OUT} =– (R_F/R_G)V_{IN}$

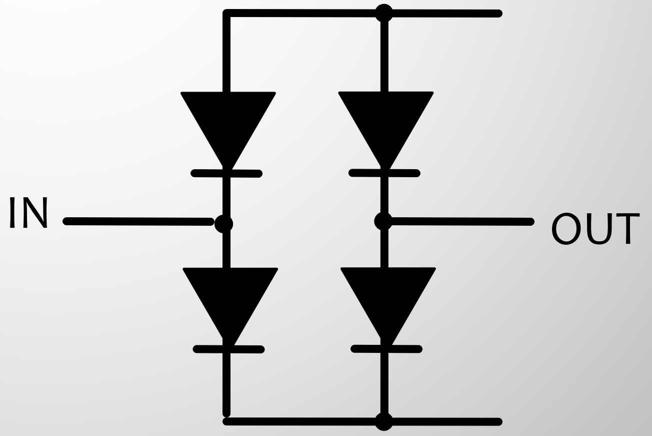
Uses - switch

No more “generic” transconductor



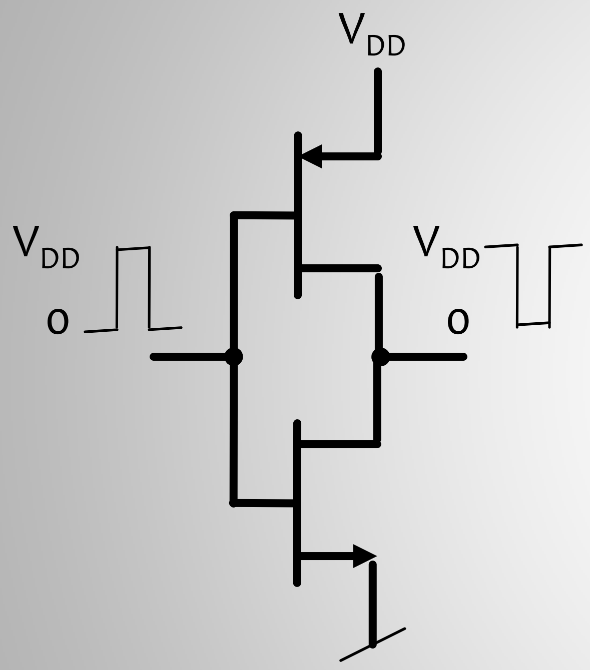


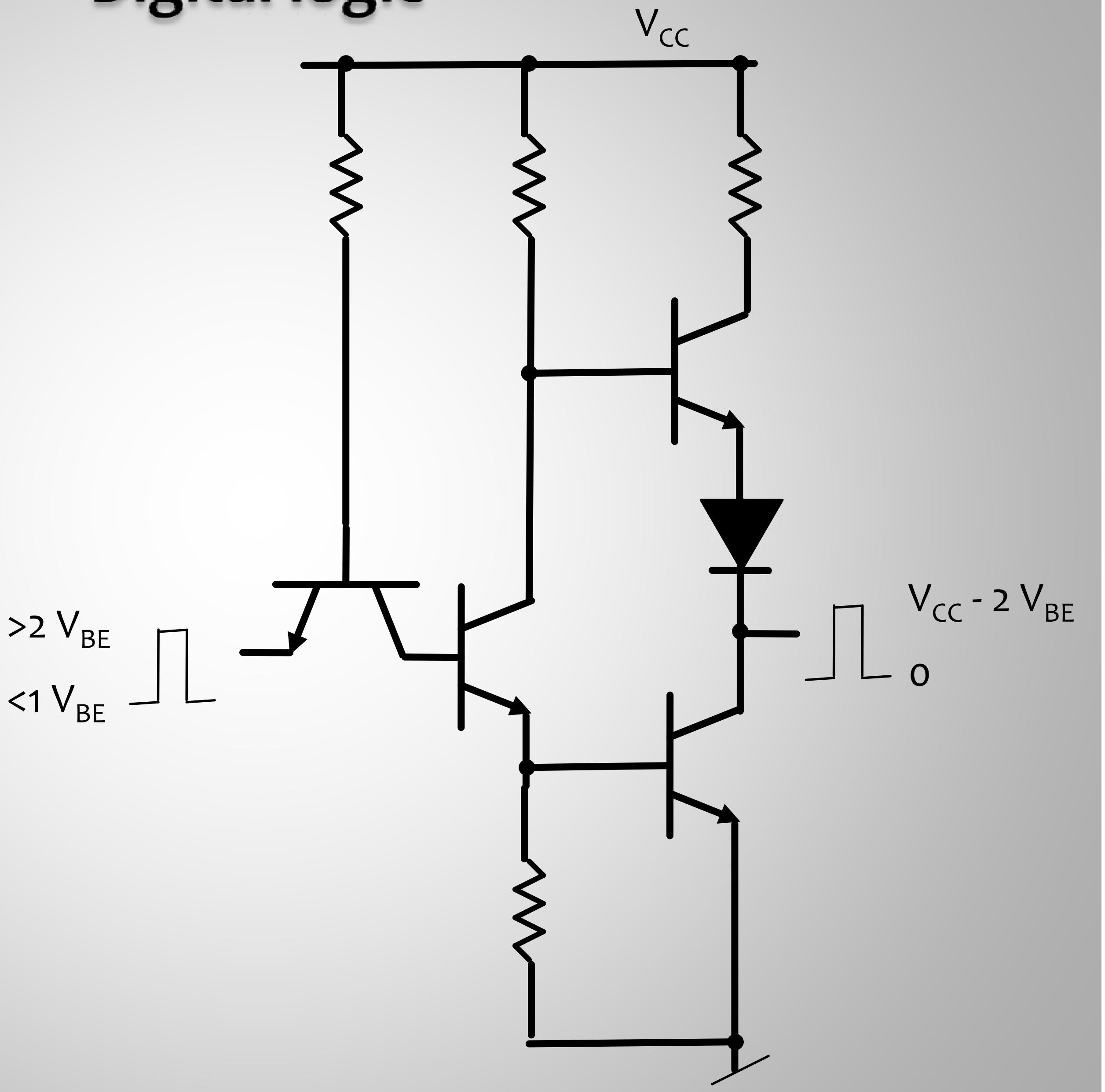
$I_{DS} = k(V_{GS} - V_T)^2$ for $V_{DS} > V_{GS} - V_T$
$I_{DS} = 2k(V_{GS} - V_T)V_{DS}$
→ $R_{DS} = V_{DS} / I_{DS}$



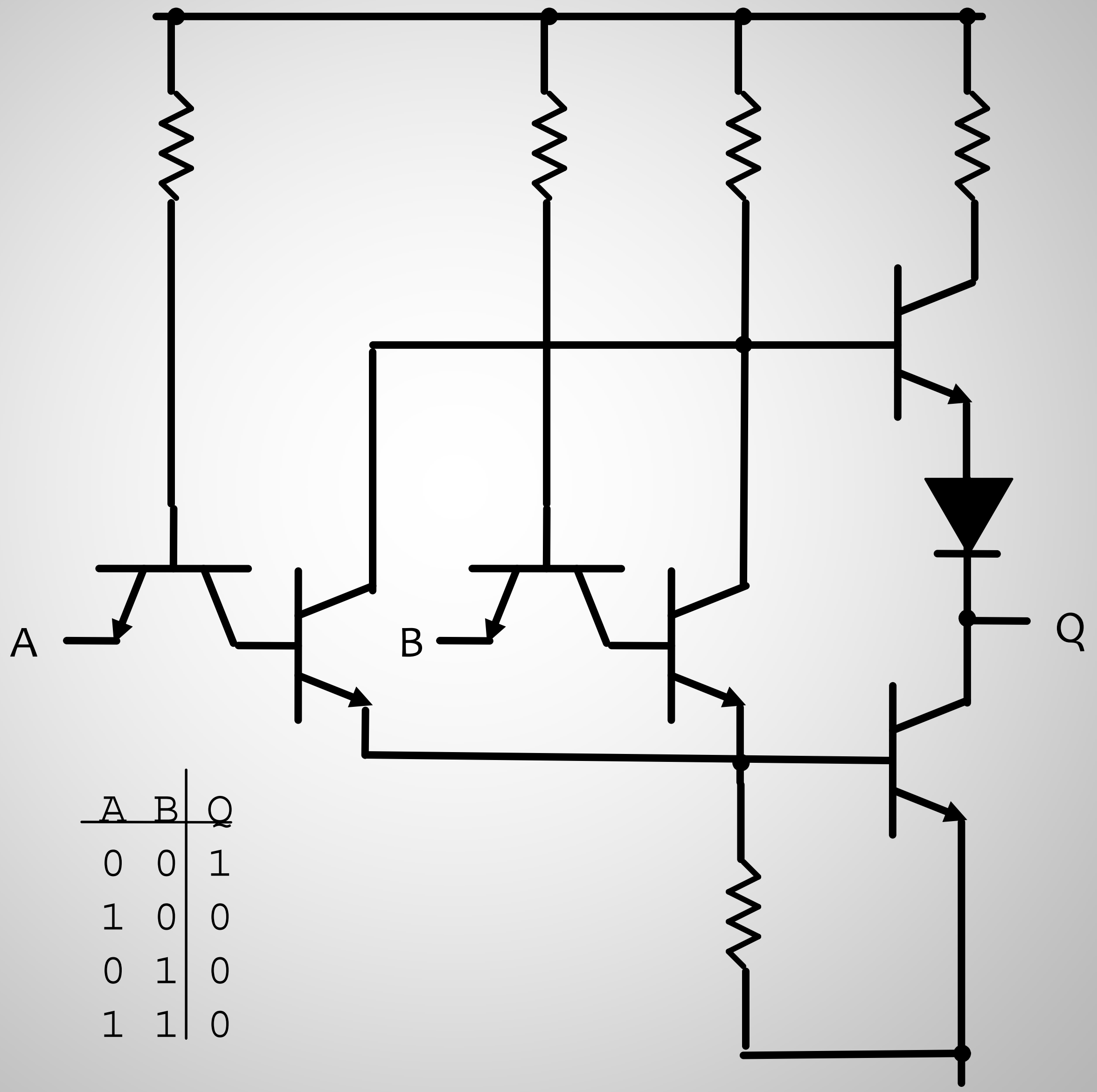
More on this below!

Digital logic



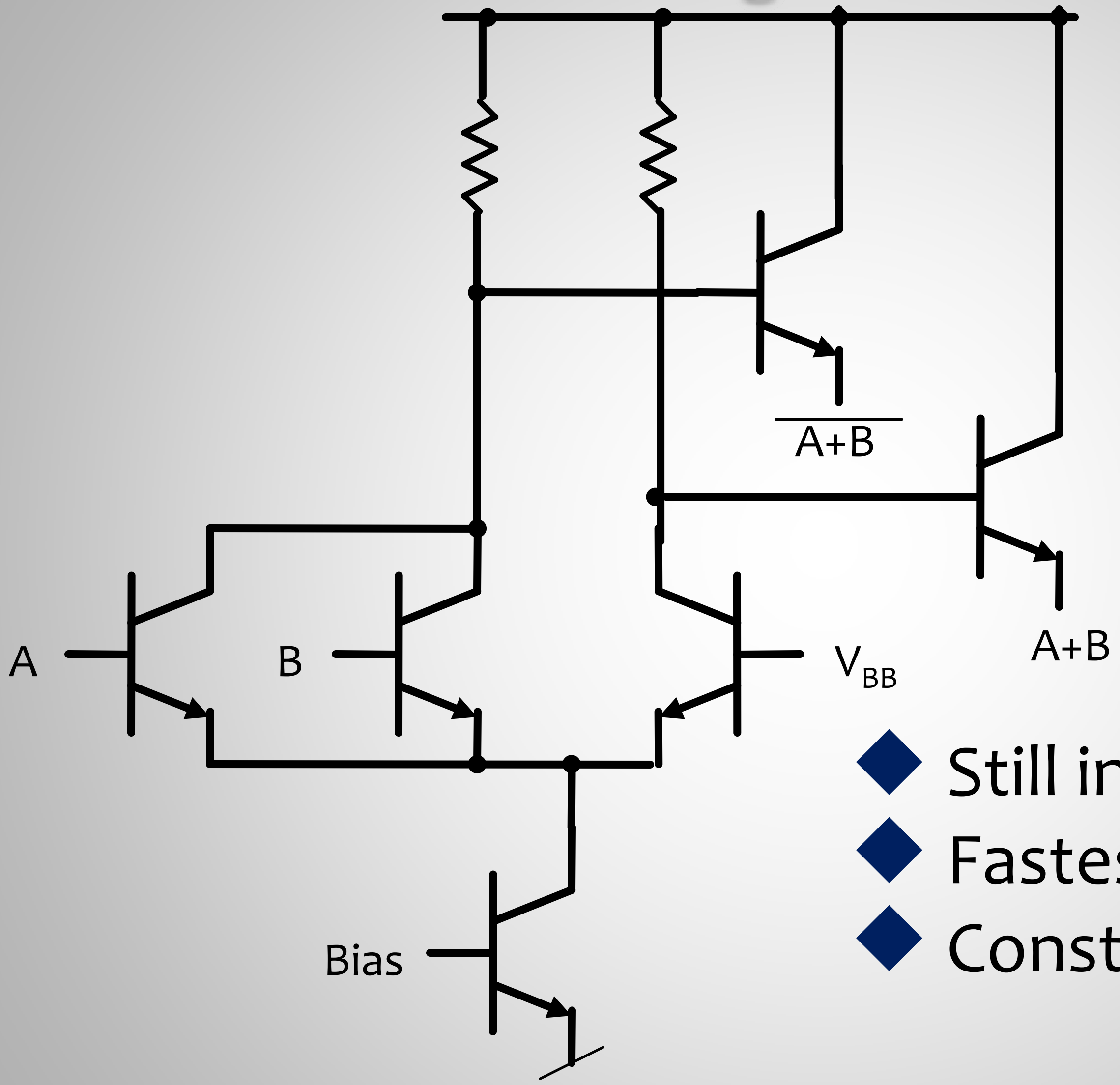


NOR gate – TTL



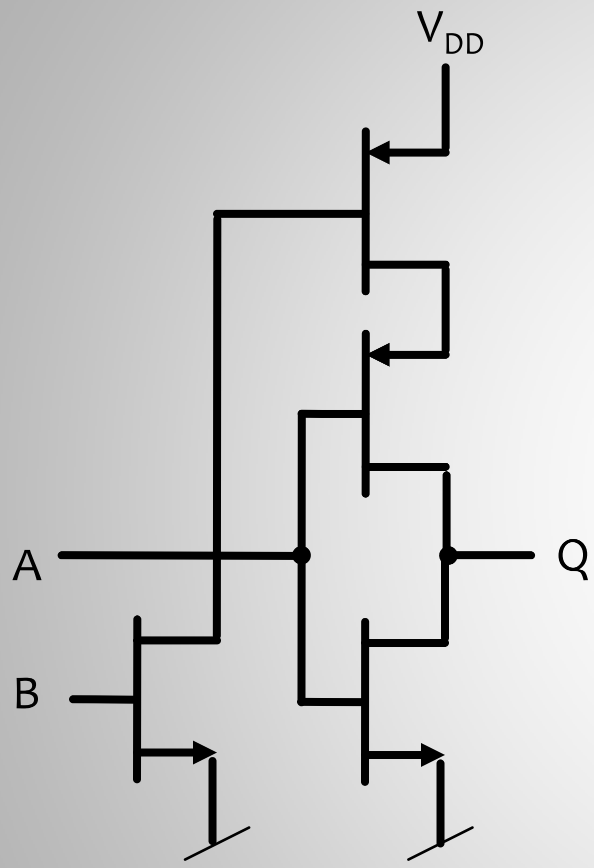
A	B	Q
0	0	1
1	0	0
0	1	0
1	1	0

NOR gate – ECL



- Still in use
- Fastest logic family
- Constant current

NOR gate - CMOS

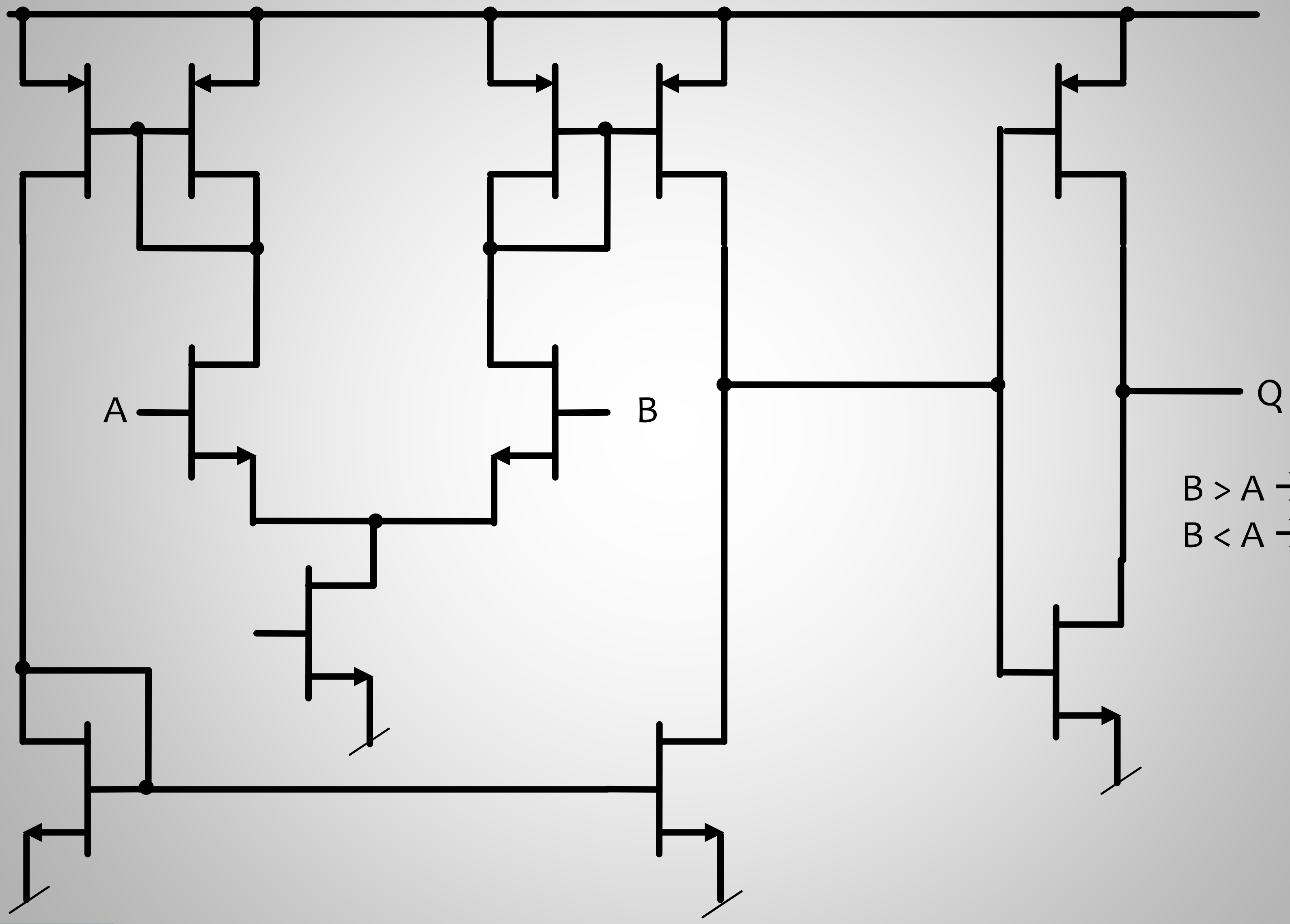


- CMOS logic dominant
  - Easiest to manufacture
  - No static power
- Dynamic power:

$I \sim fCV_{DD}^2$

- CMOS scaling
  - Feature size reduction
  - V_{DD} ↓
  - Transistors/Area ↑
  - Microprocessor fans are a good business

Comparator

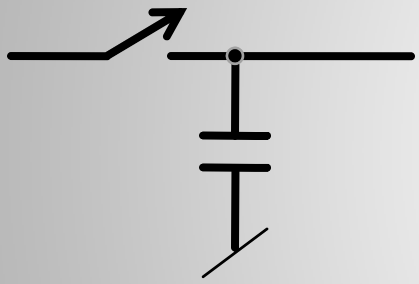


B > A → Q = 0
B < A → Q = 1

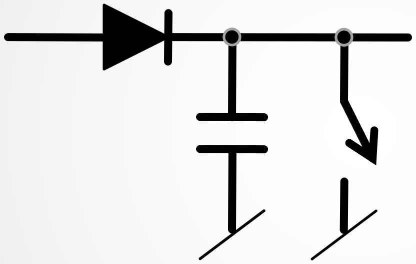
“Mixed-mode” circuit – analog and digital

Mixed-mode design

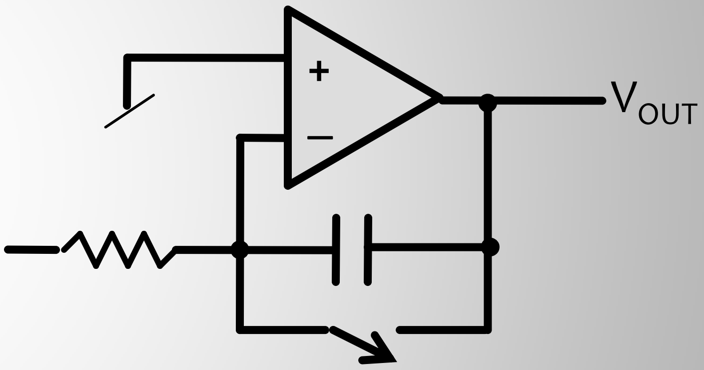
- The majority of “Front-end electronics for detectors and imagers”
- Switches are key components



Sample / hold
(track / hold)



Peak detector

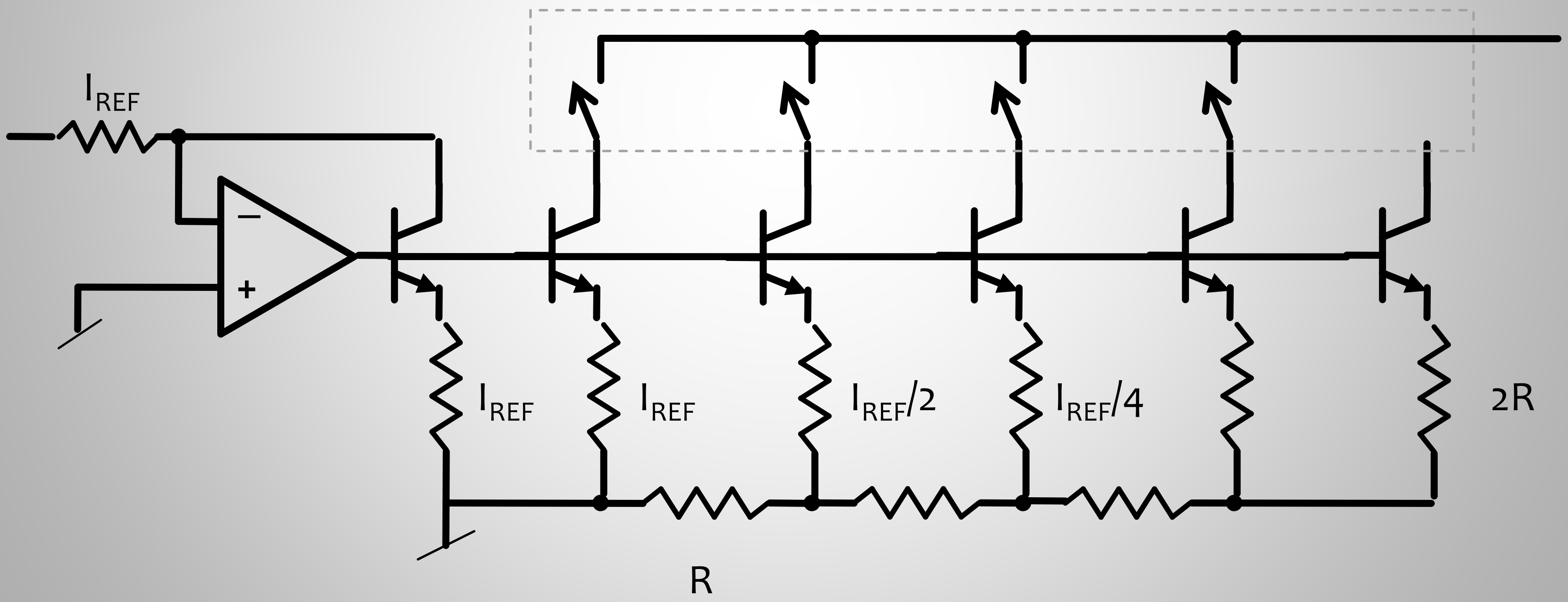


Gated integrator

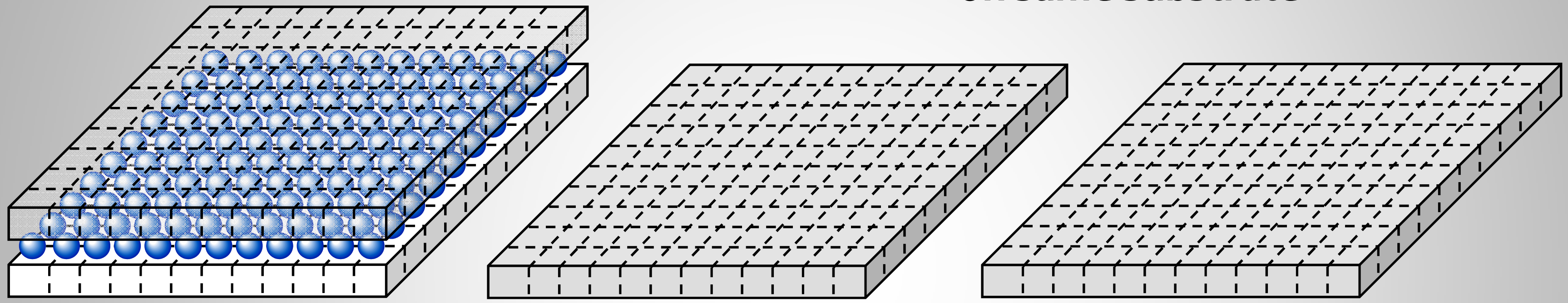
DAC

R-2R ladder

Bipolar or CMOS
Laser trimming of R-2R ladder



Consider 3 examples which can be either "detectors" or "imagers"



Hybrid

Monolithic
sensor+readout
on same substrate

APS

CCD

Increasing complexity

- Particle *tracking* (x, y, t)
- Particle *spectroscopy* (x, y, E)
- Imaging N(x,y)
    - Optical photons, x-rays, electrons, neutrons (with convertor)

Scientific CCDs

National Optical Astronomy Observatory

Cerro Tololo ◦ Kitt Peak ◦ U.S. Gemini Program

National Solar Observatory

GONG ◦ Kitt Peak ◦ Sacramento Peak

Newsletter 67

September 2001

Operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation

Dumbbell nebula - LBNL CCD

Blue: H-α at 656 nm

Green: SIII at 955 nm

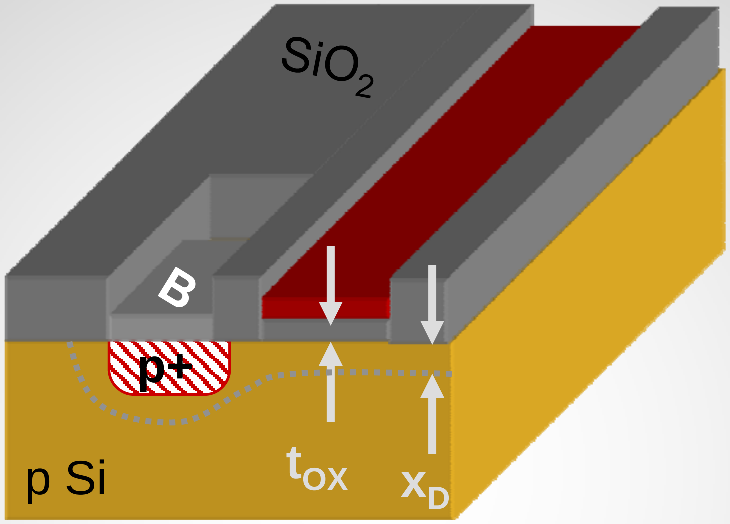
Red: 1.02 mm

◆CCD invented in 1969 by Boyle and Smith (Bell Labs) as alternative to magnetic bubble memory storage

◆LST ("Large Space Telescope" – later Hubble) 1965 – how to image?

- Film was obvious choice, but -
  It would "cloud" due to radiation damage in space
  Changing the film in the camera not so trivial
- 1972 CCD proposed

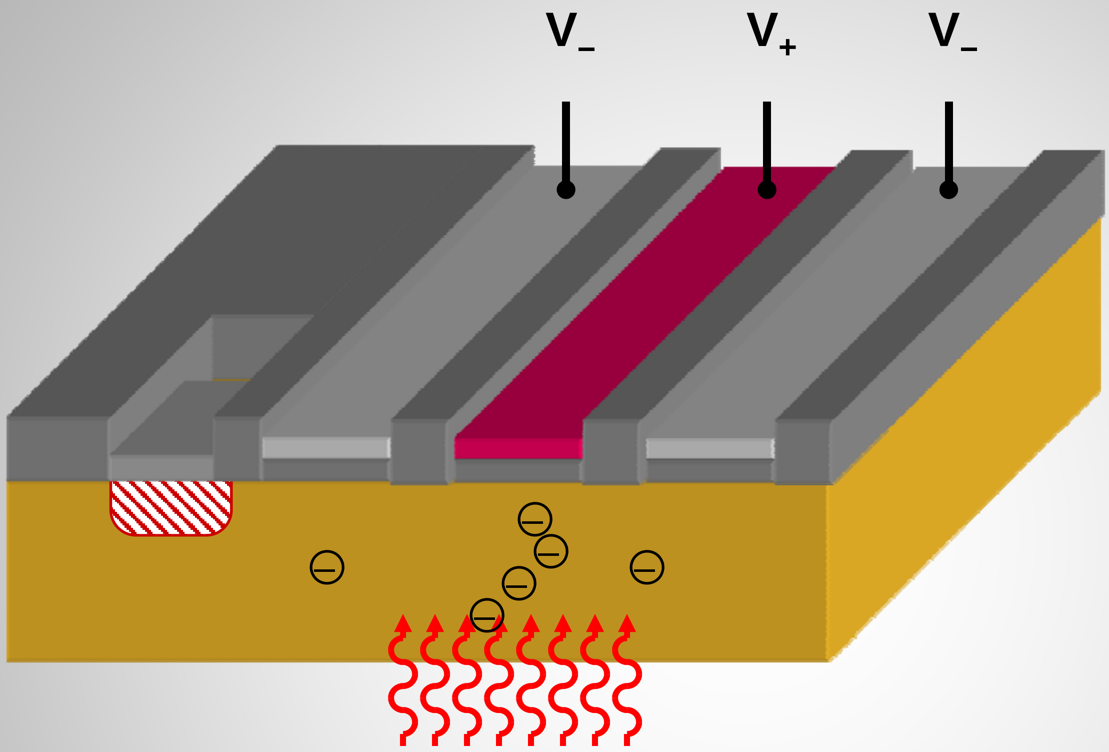
Integrated Circuit Elements



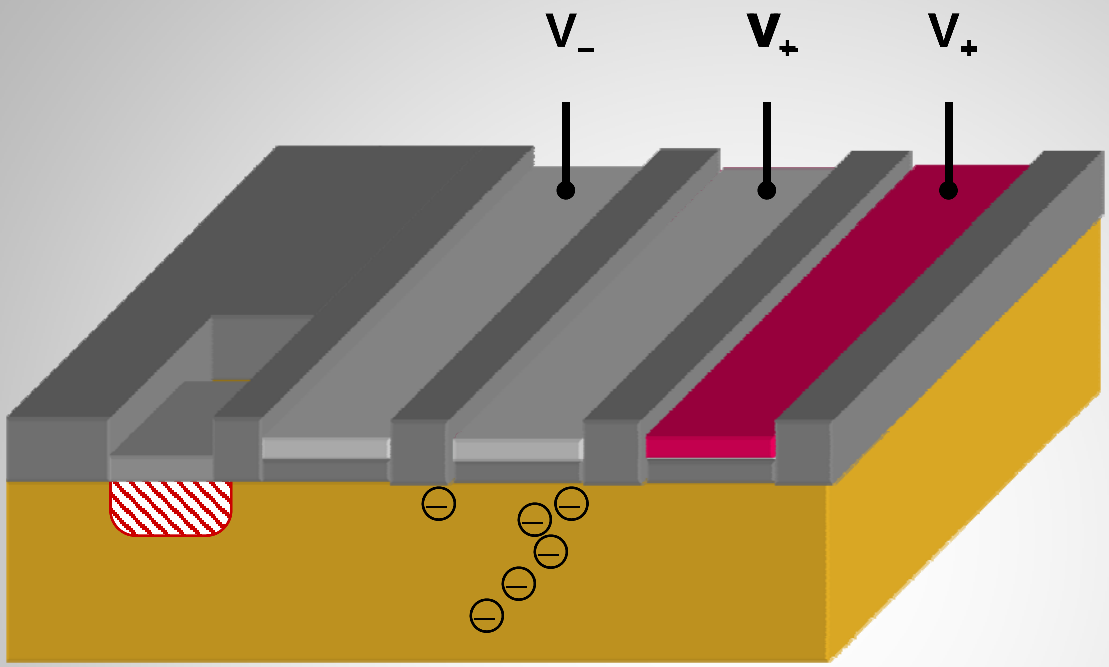
$$C = \frac{1}{\frac{1}{C_{OX}} + \frac{1}{C_{DEP}}}, \quad C_{OX} = \frac{\varepsilon_{SiO_2}}{t_{OX}}, C_{DEP} = \frac{\varepsilon_{Si}}{x_D}$$

MOS Capacitor

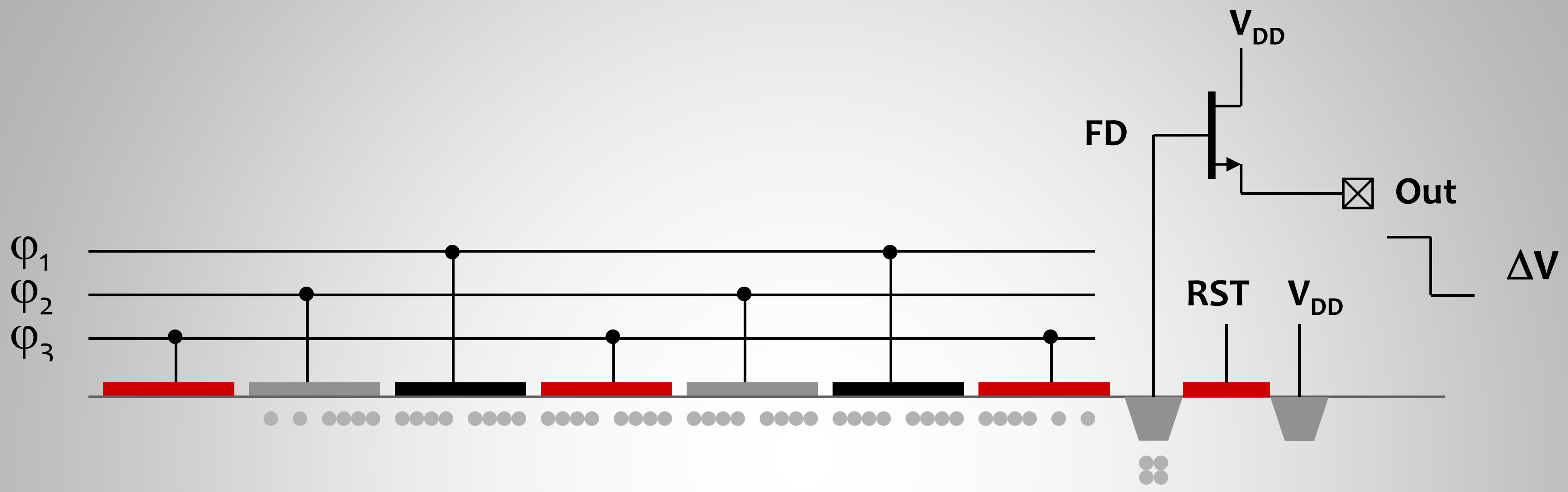
Accumulate Charge



Accumulate and Transfer Charge

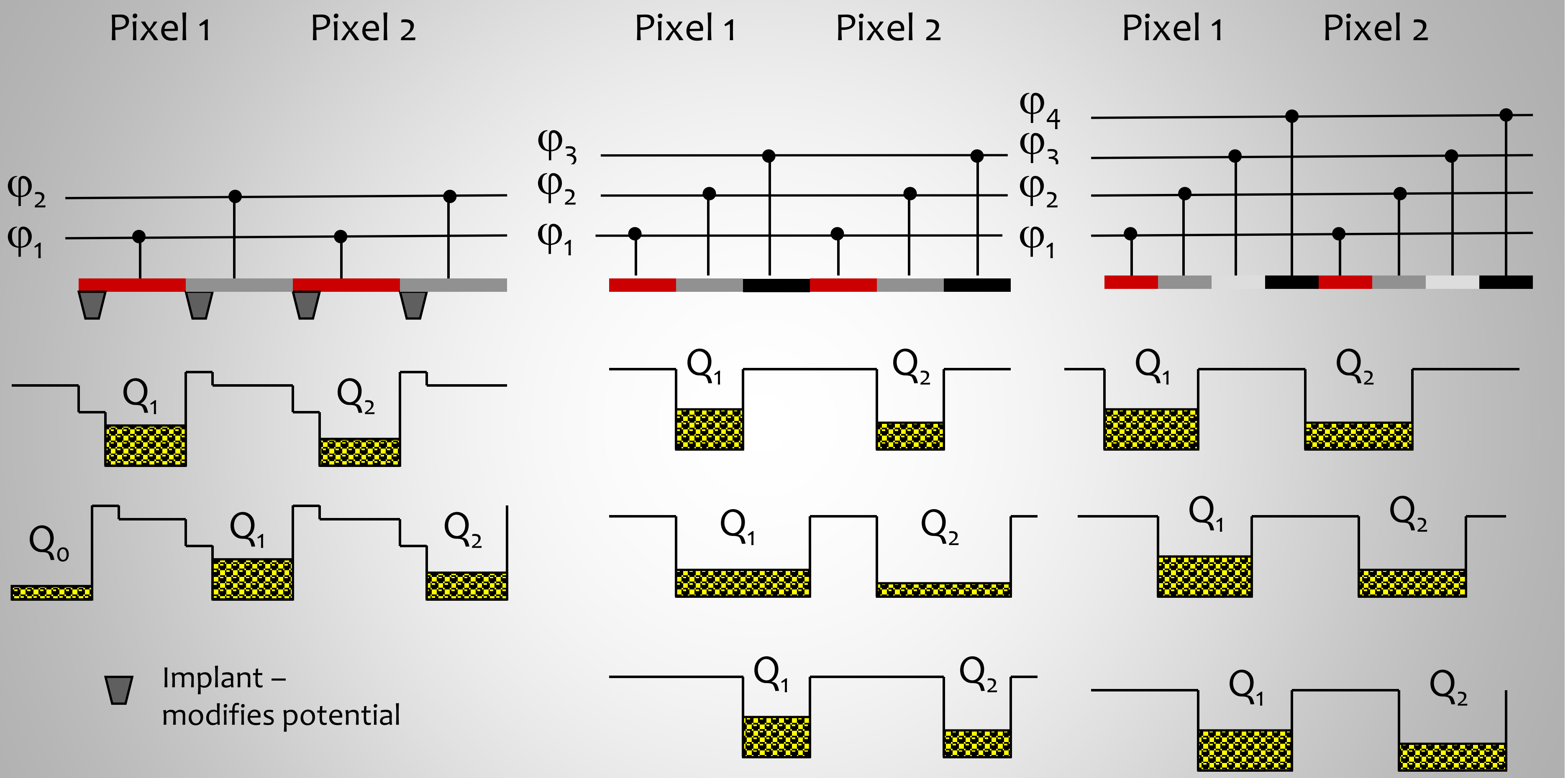


Conventional 3-Phase CCD



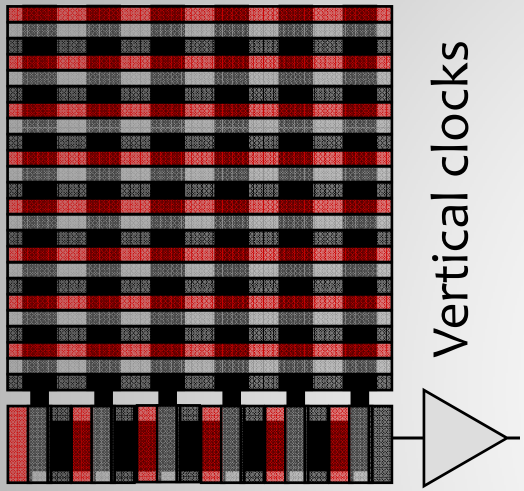
- Noiseless, ~lossless charge transfer
- High gain charge-to-voltage conversion $\Delta V = q/C_{FD}$
- Output amplifier (source follower, or …) on-chip

Many ways to do this

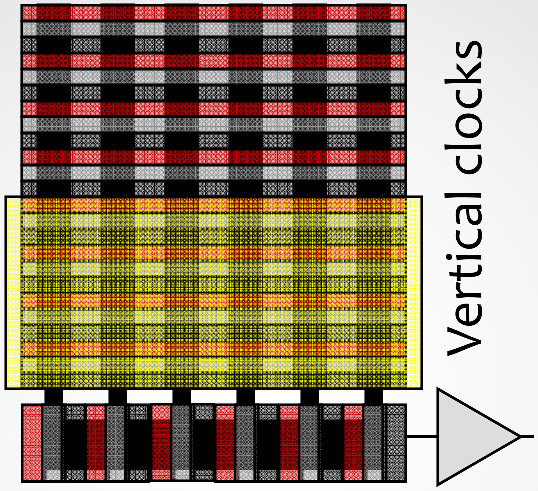


Implant –
modifies potential

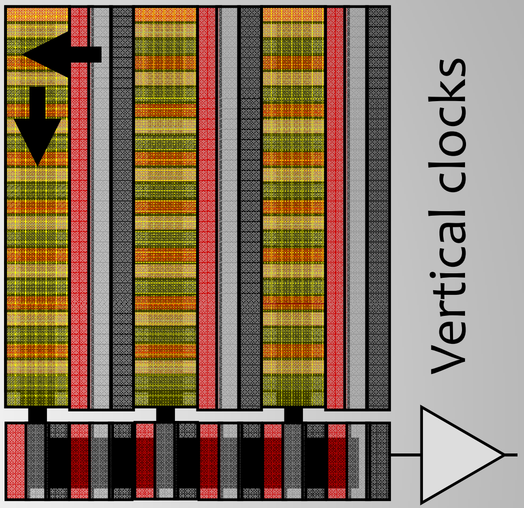
Several architectures



Full frame



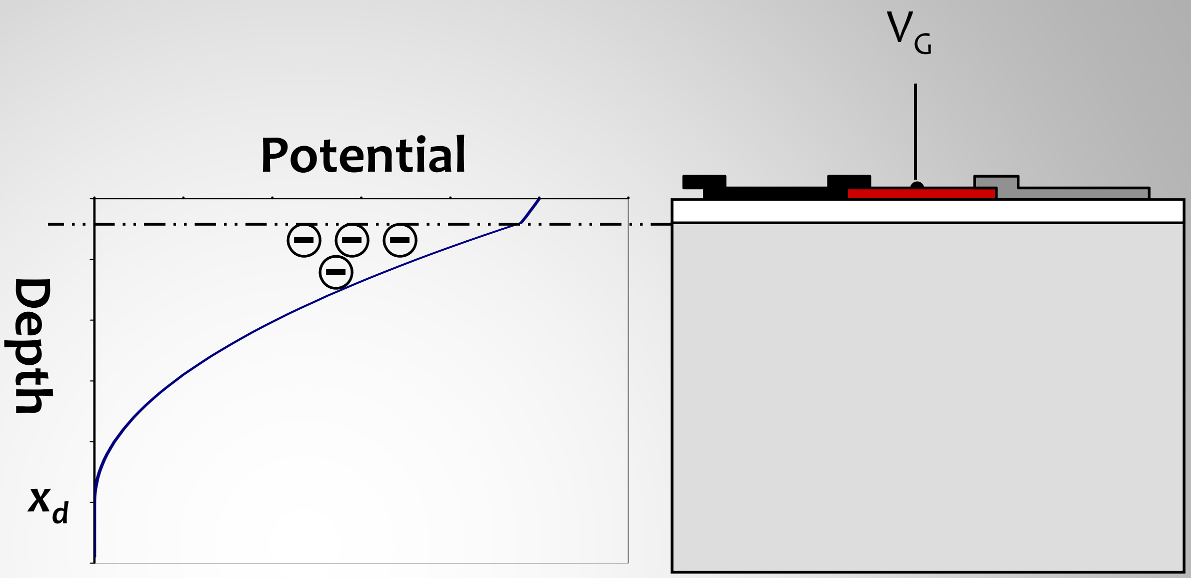
Frame transfer
Rapid shift from image
to storage
Slower readout of
storage during integration



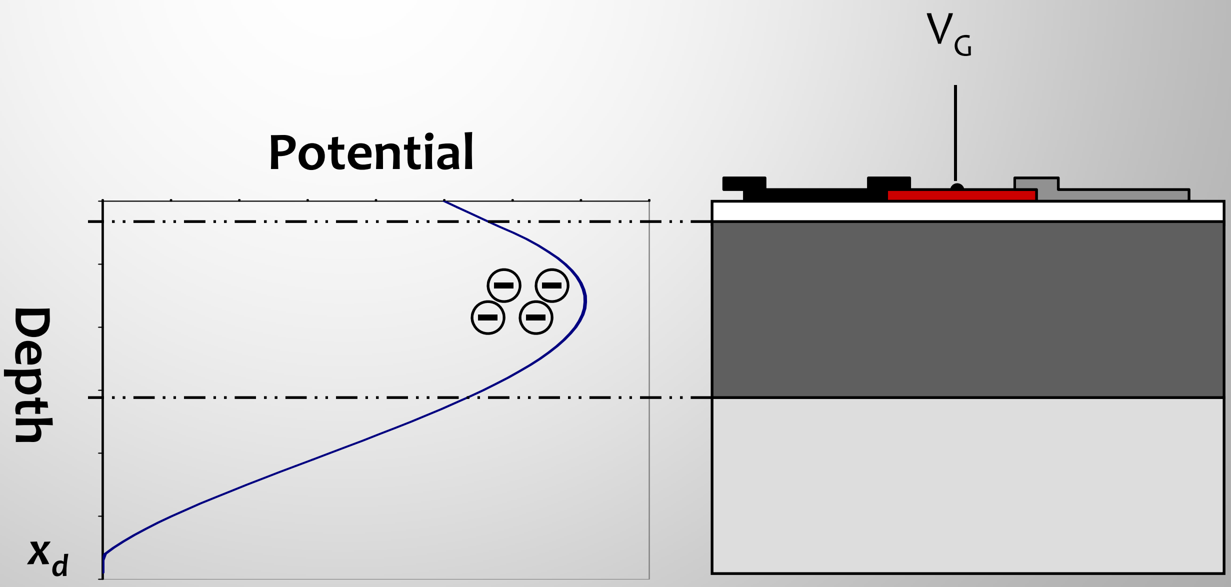
Interline

Surface vs buried channel CCD

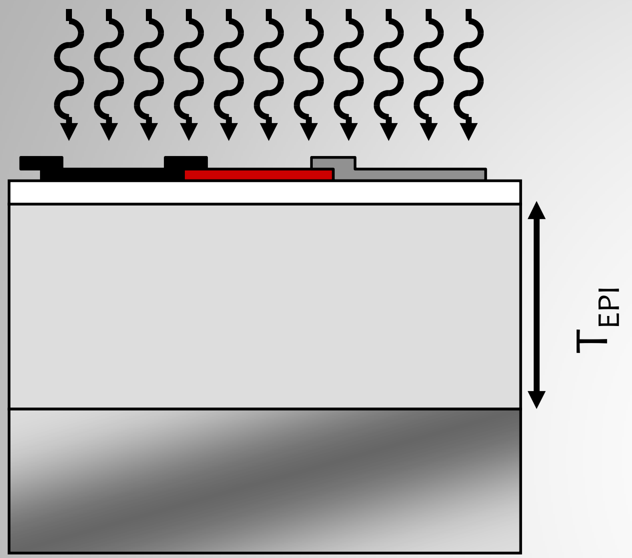
- MOS capacitor
- Potential maximum at Si – SiO_2 interface
    - CTE < 1 due to trapping at interface



- Potential maximum not at Si – SiO_2 interface
    - *CTE typically > 99.9999%*



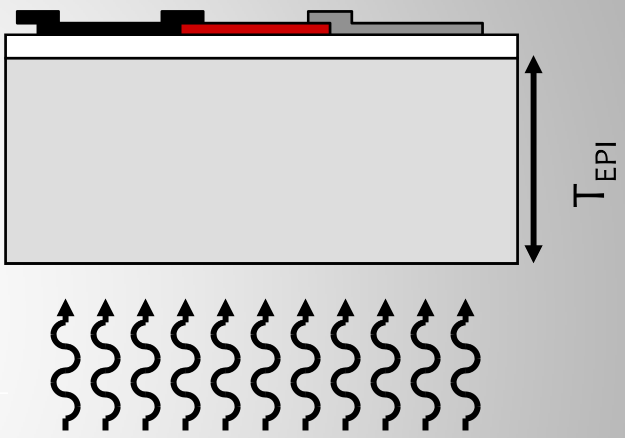
Frontside/Backside Illumination



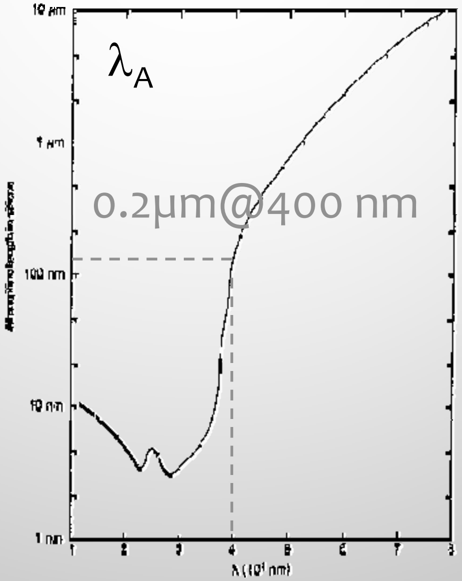
$$\varepsilon \propto e^{-T_{POLY}/\lambda_A}\left(1-e^{-T_{EPI}/\lambda_A}\right)$$

Fill factor < 1

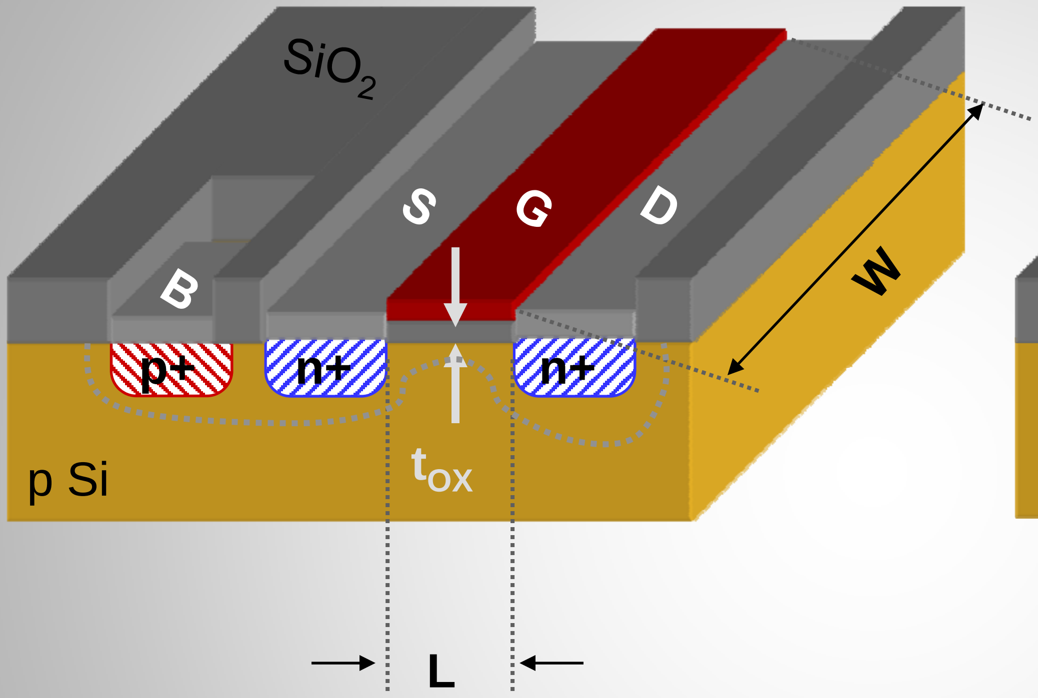
$$\varepsilon \propto \left(1-e^{-T_{EPI}/\lambda_A}\right)$$

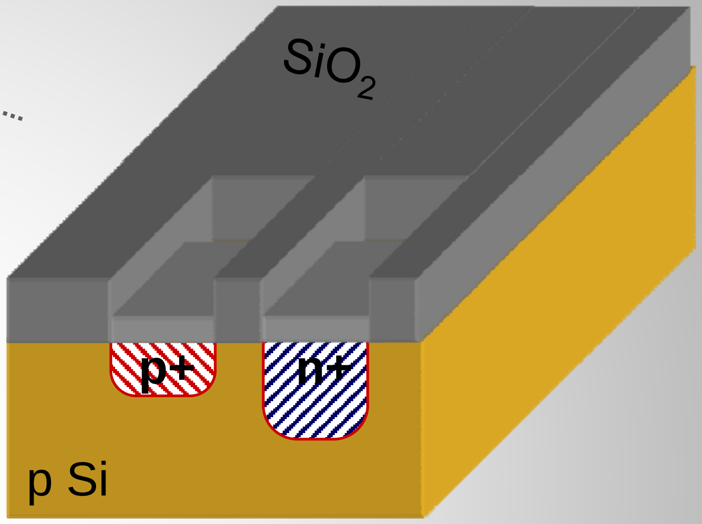


Fill factor = 1



Integrated Circuit Elements

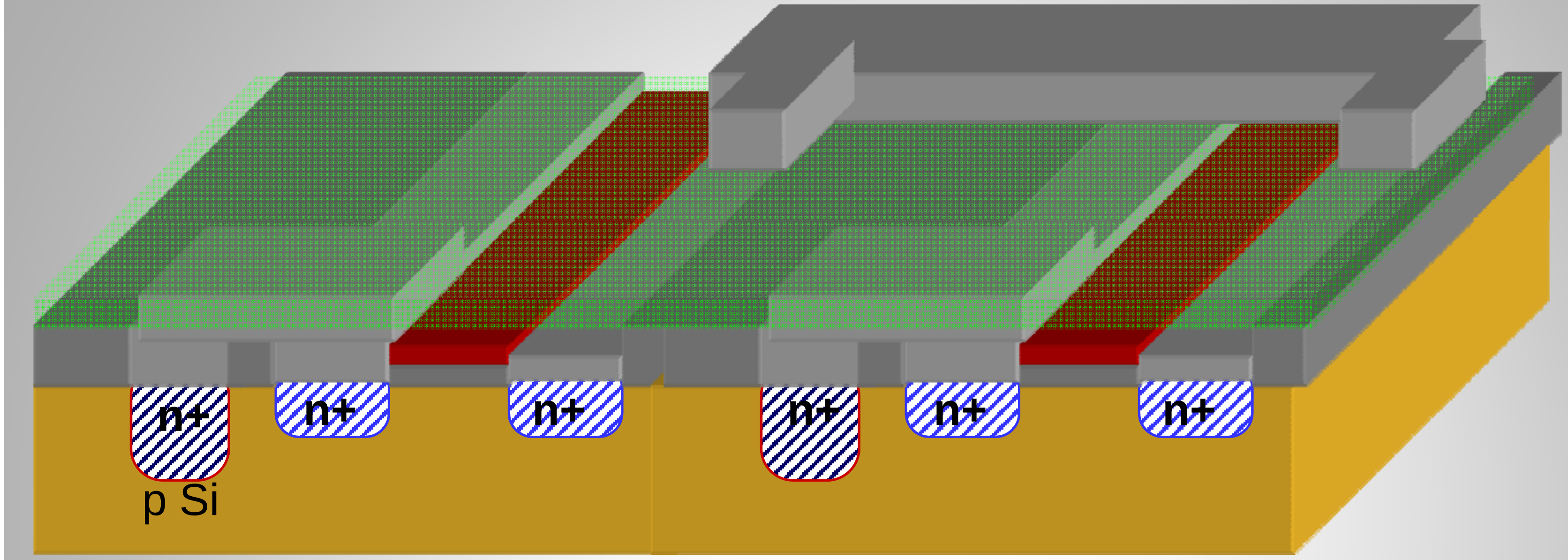


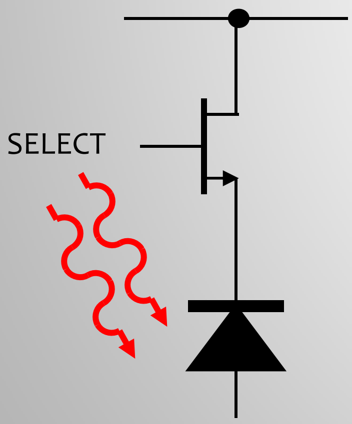


MOS Transistor

pn Diode

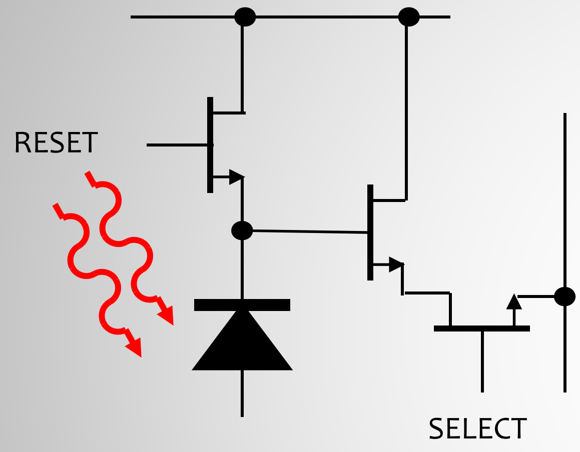
Conventional Semiconductor Processing

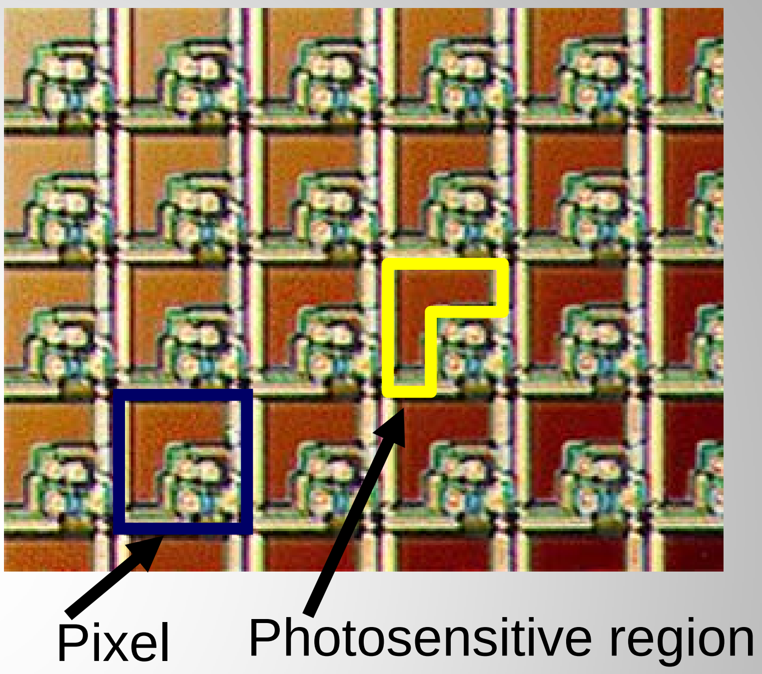




- Passive Pixel Sensor
- Proposed 1968
- No in-pixel reset
- Poor performance due to capacitive load (nothing buffers the photodiode)

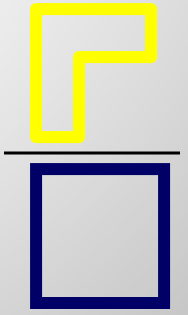
Active Pixel Sensor



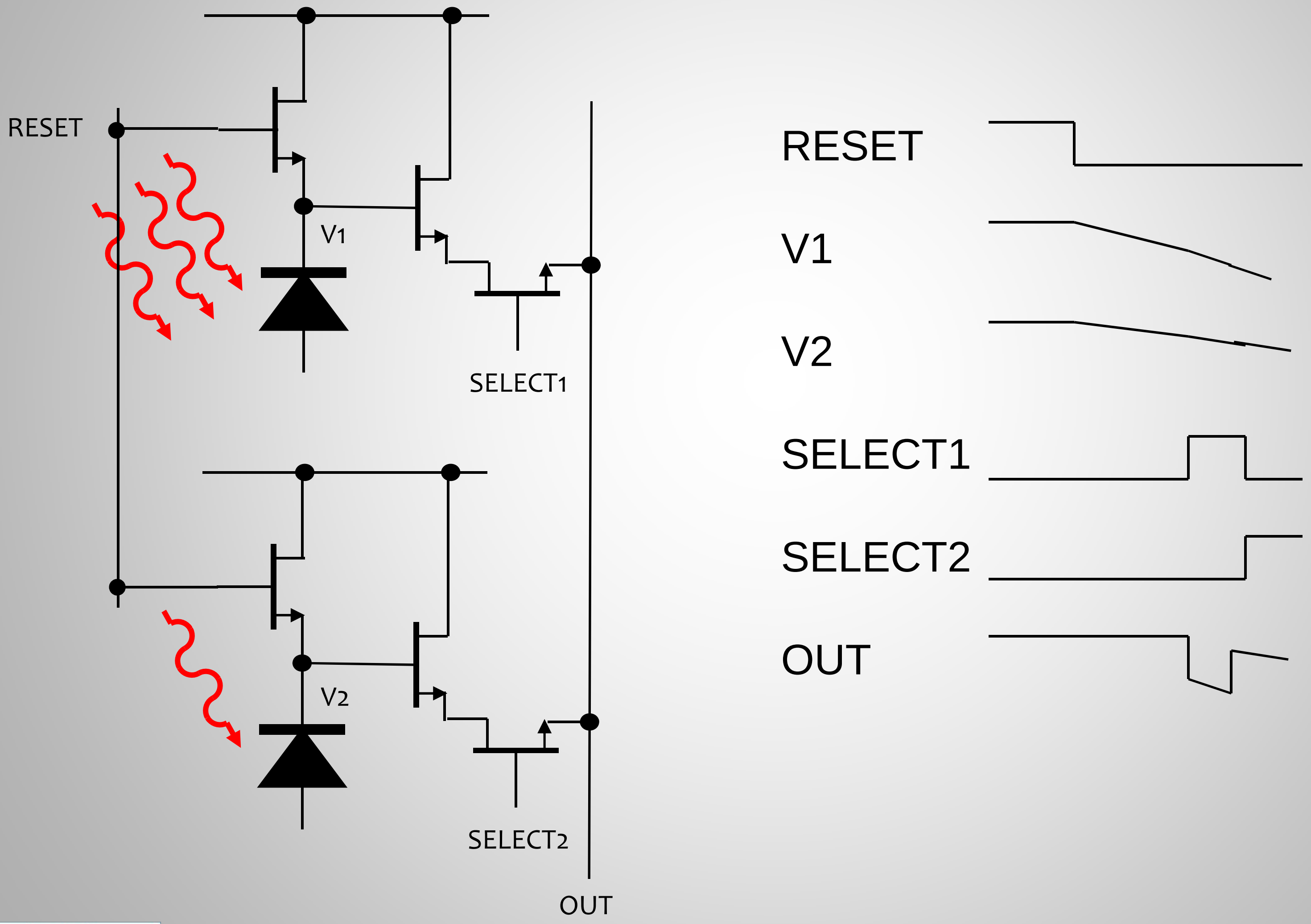


- Active Pixel Sensor
- *Also* proposed 1968
- Many ways to make the photodiode

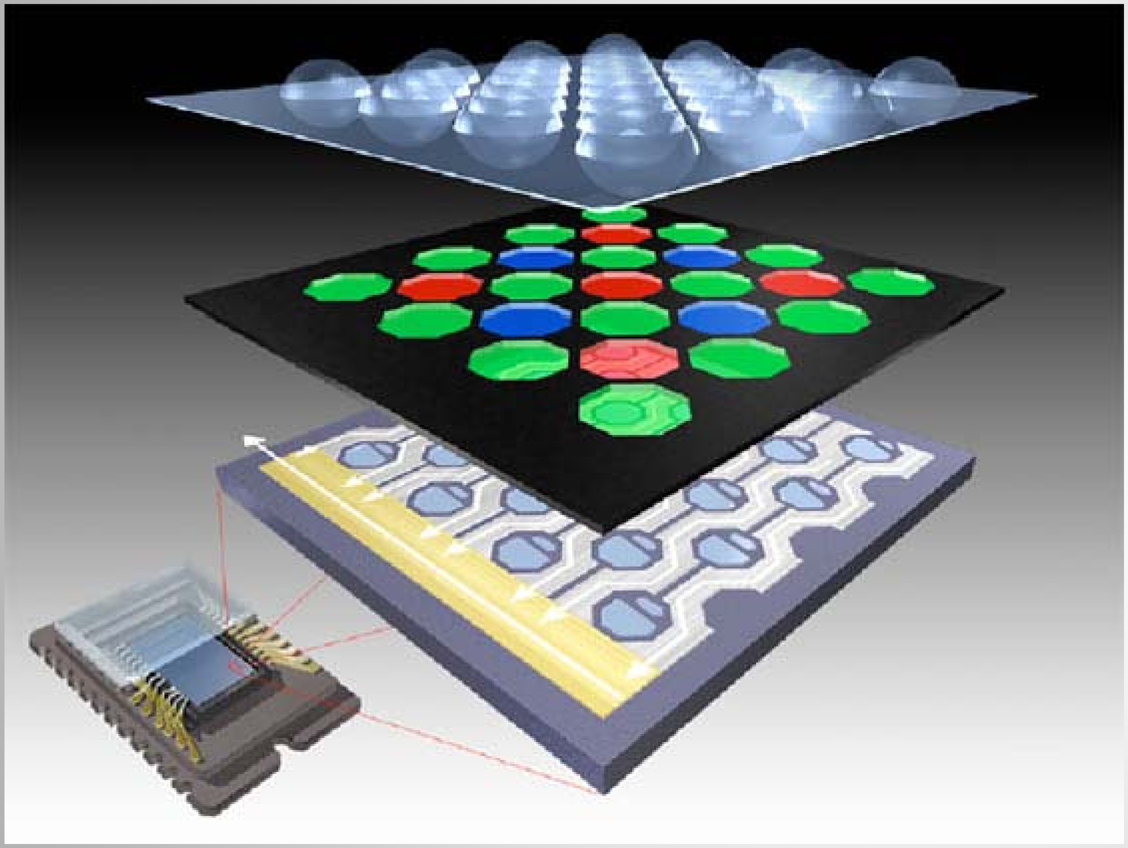
Fill factor =



How It Works


RESET
V1
SELECT1
V2
SELECT2
OUT
RESET
V1
V2
SELECT1
SELECT2
OUT

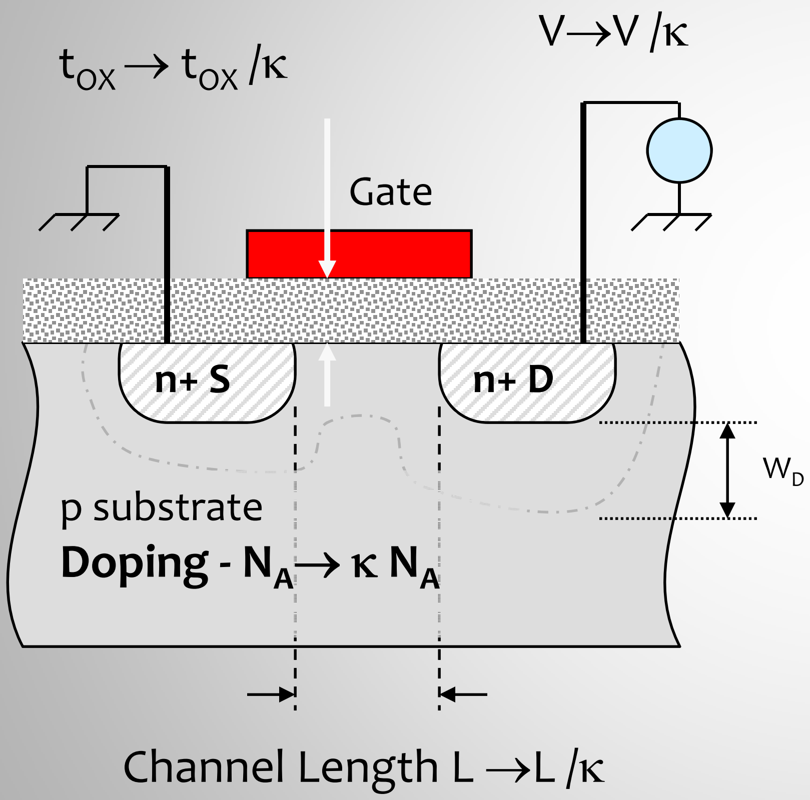
Add Microlens and Color Filter



- Microlens array recovers some of the fill factor
- Opaque walls between cells reduces cross-talk
- Color pattern matched to algorithm

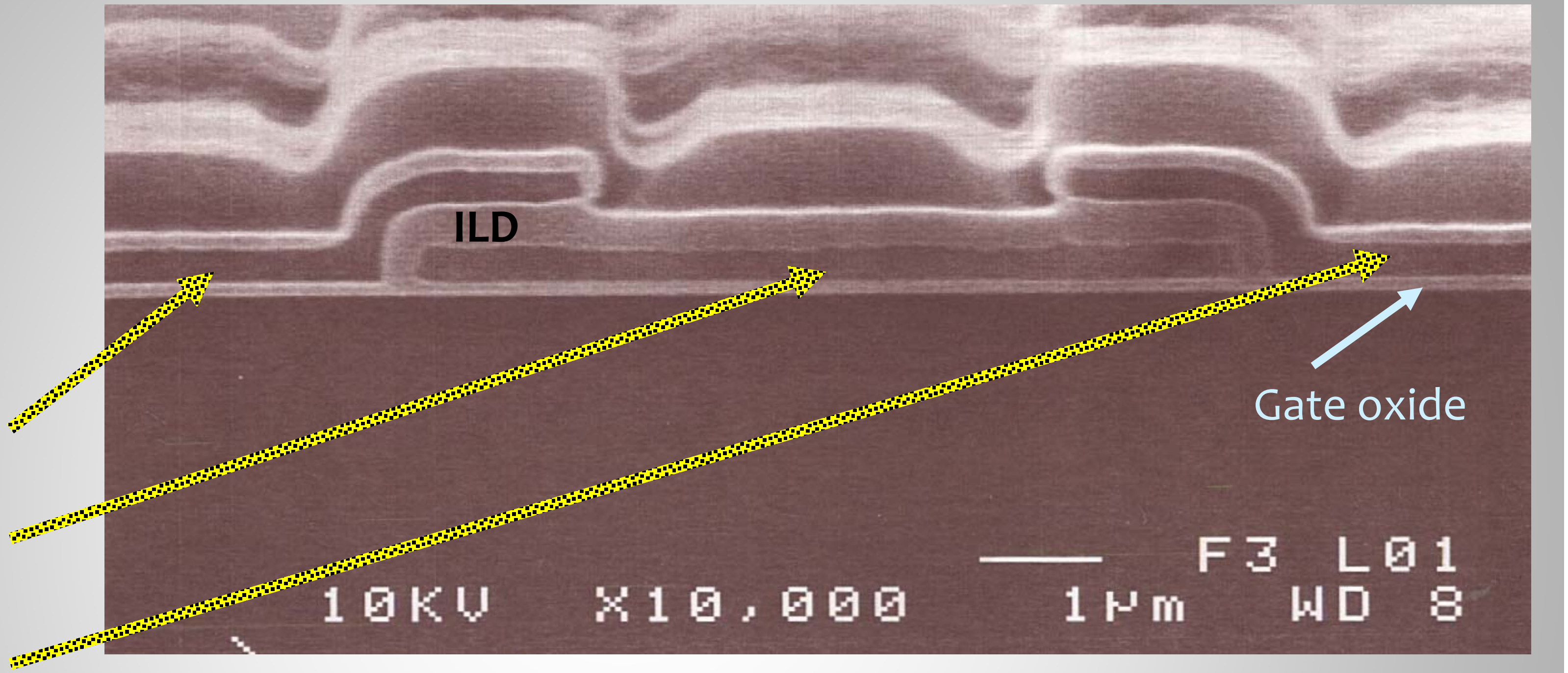
CMOS, CMOS “opto” and CCD processes

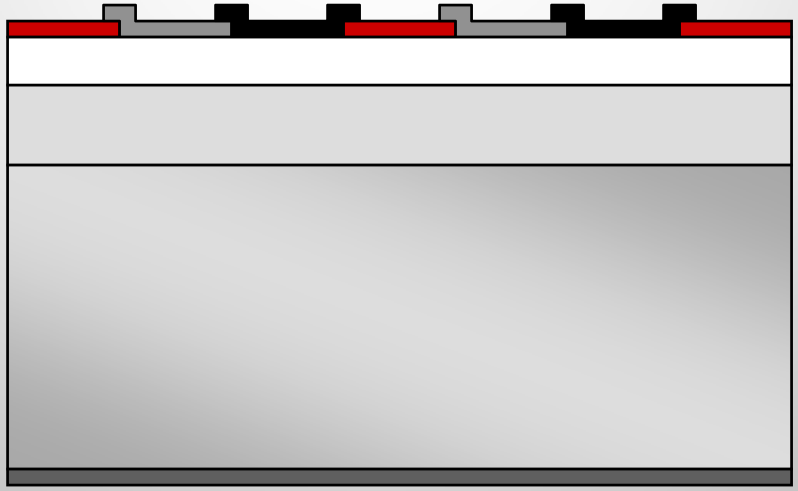
CMOS driven by
constant field scaling



	CCD	CMOS
t_{OX} (Å)	500 - 1000	50
Well depth (µm)	2.5	0.5 deeper for RF
Implant (µm)	~1 channel stop	0.1 S/D implants
V	≥10	<3.3 <2.5 <1.x ...
Poly layers	3 (2)	1 2 for analog
Subst. quality	Low leakage	Don’t care Except opto

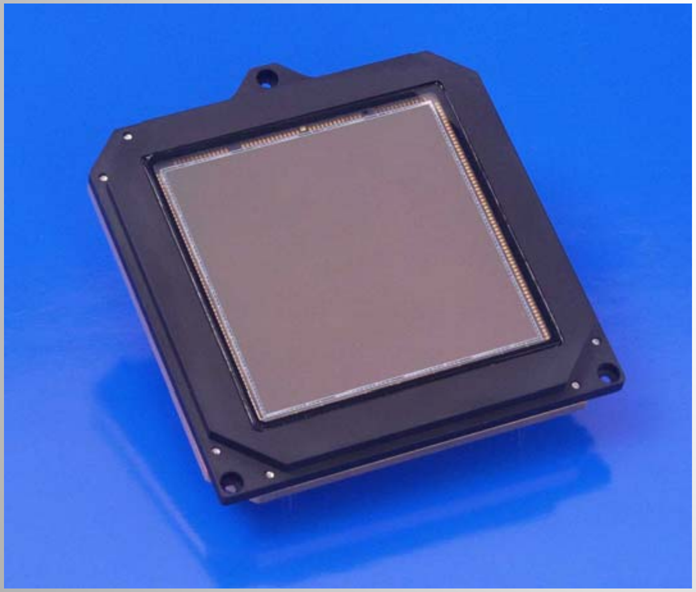
Triple Poly CCD Process



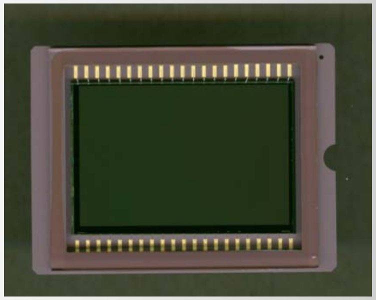


Very Large Format CCDs (and CMOS imagers)

- Fairchild Wafer Scale Full Frame CCD
  - 9216 x 9216 x 8.75 μm pixel
  - 80.64 x 80.64 mm² size CCD
  - Eight 3-stage output amplifiers
  - Readout noise < 30e- @ 2/fps



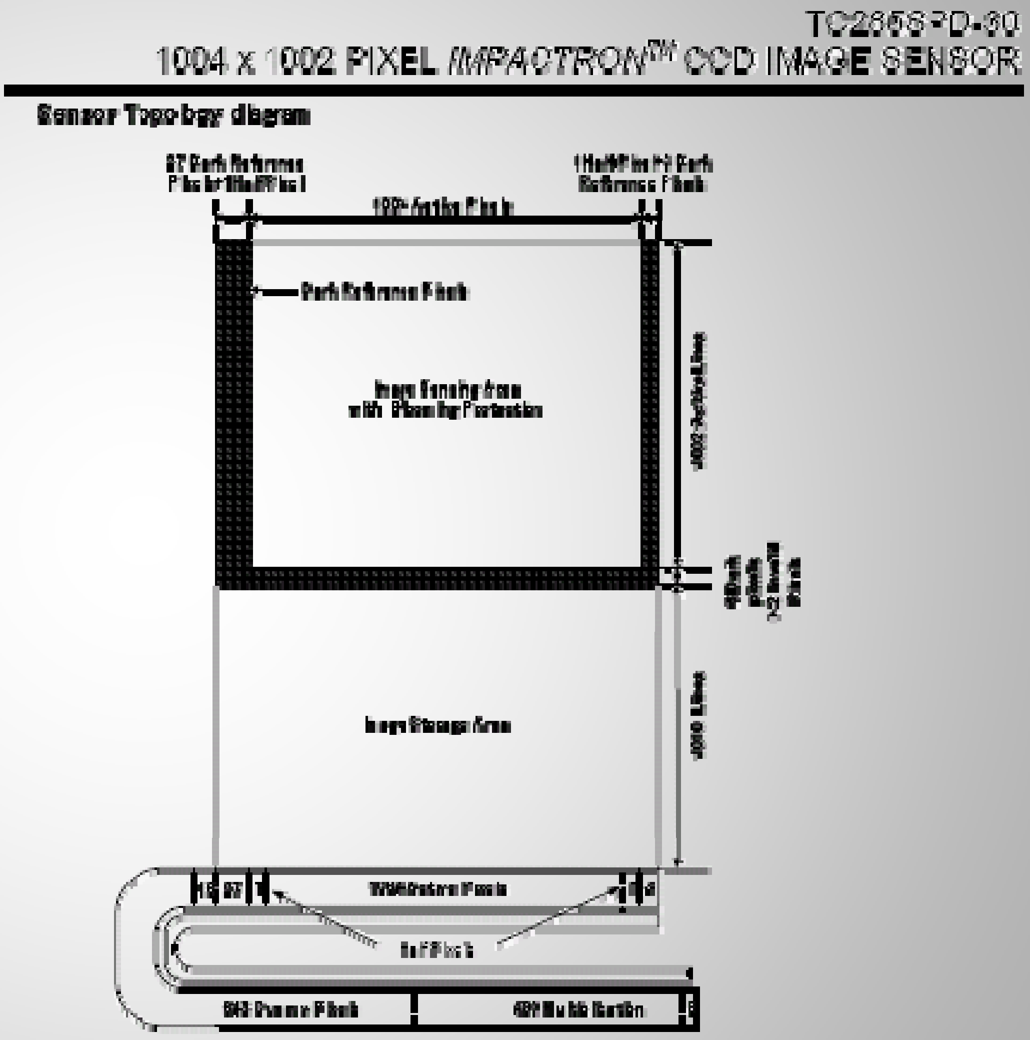
- Cypress CYIHDS9000
  - 3710 x 2434 x 6.4 μm pixel
  - 23.3 x 15.5 mm² size APS
  - 0.13 μm imaging CMOS process



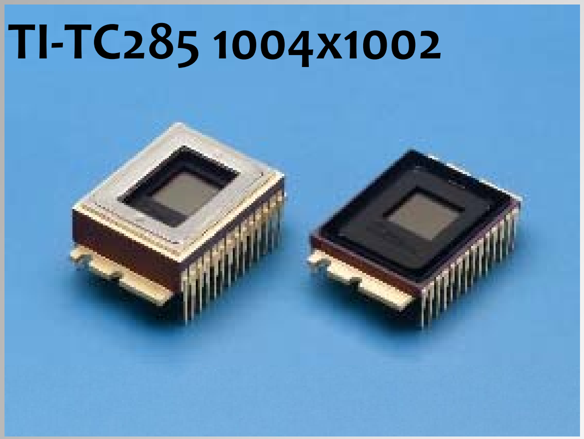
- Canon 16.7 MPix
  - *36 x 24 mm² 4992 x 3328*
- Kodak 39 MPix
  - *36 x 48 mm²*

Electron-Multiplying CCDs

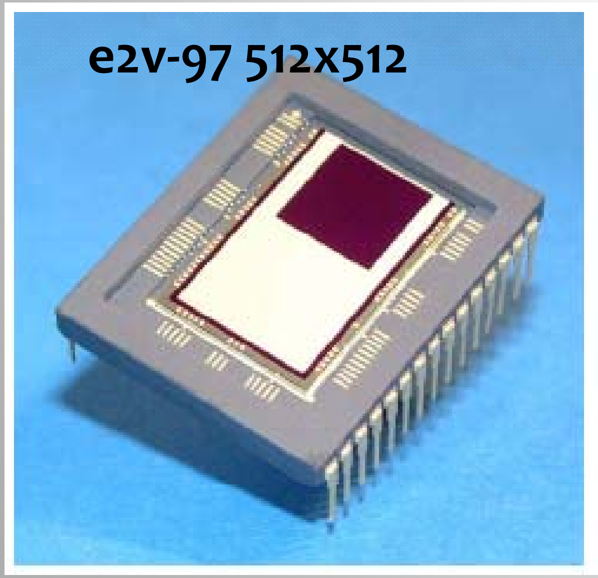
- Long serial register with avalanche multiplication pixels
- Gain $(1+\varepsilon)^N$ $\varepsilon \sim 1\%$
- Good for single-photon sensitivity
- Nonetheless, current devices have limited ($\leq$ 12 bit) dynamic range
- Excess noise factor, F



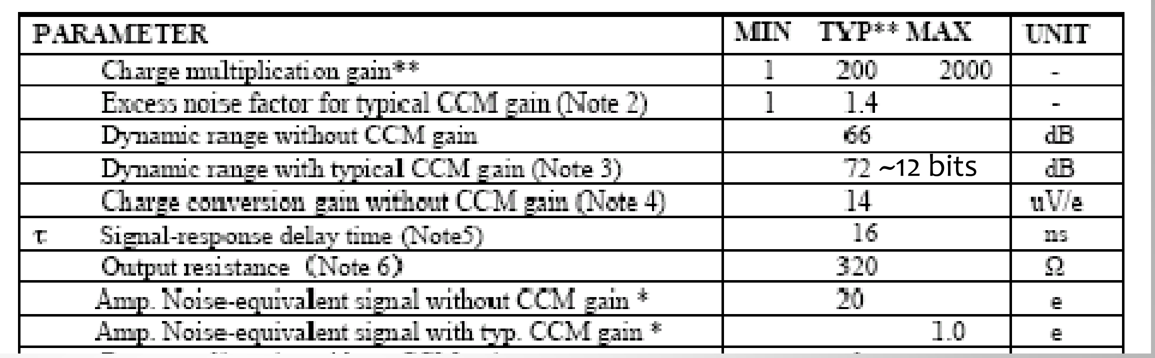
EM CCD



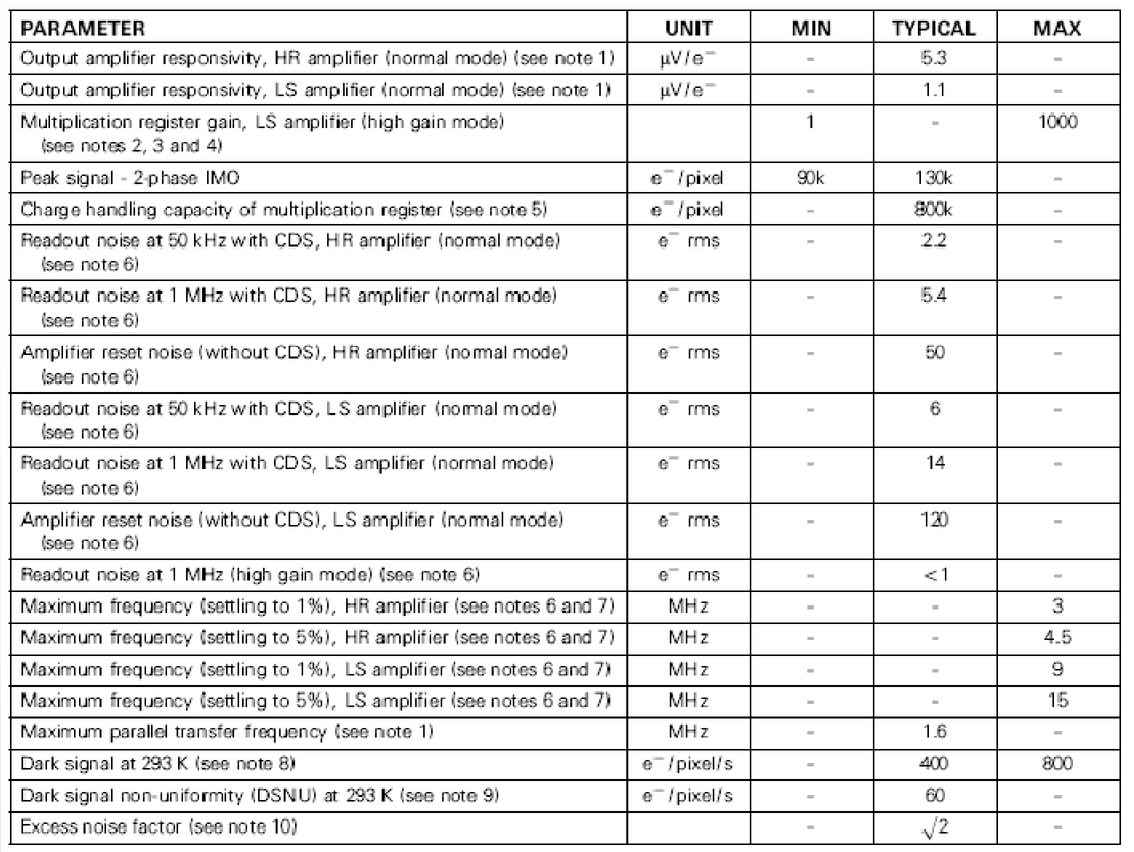
TI-TC285 1004x1002



e2v-97 512x512

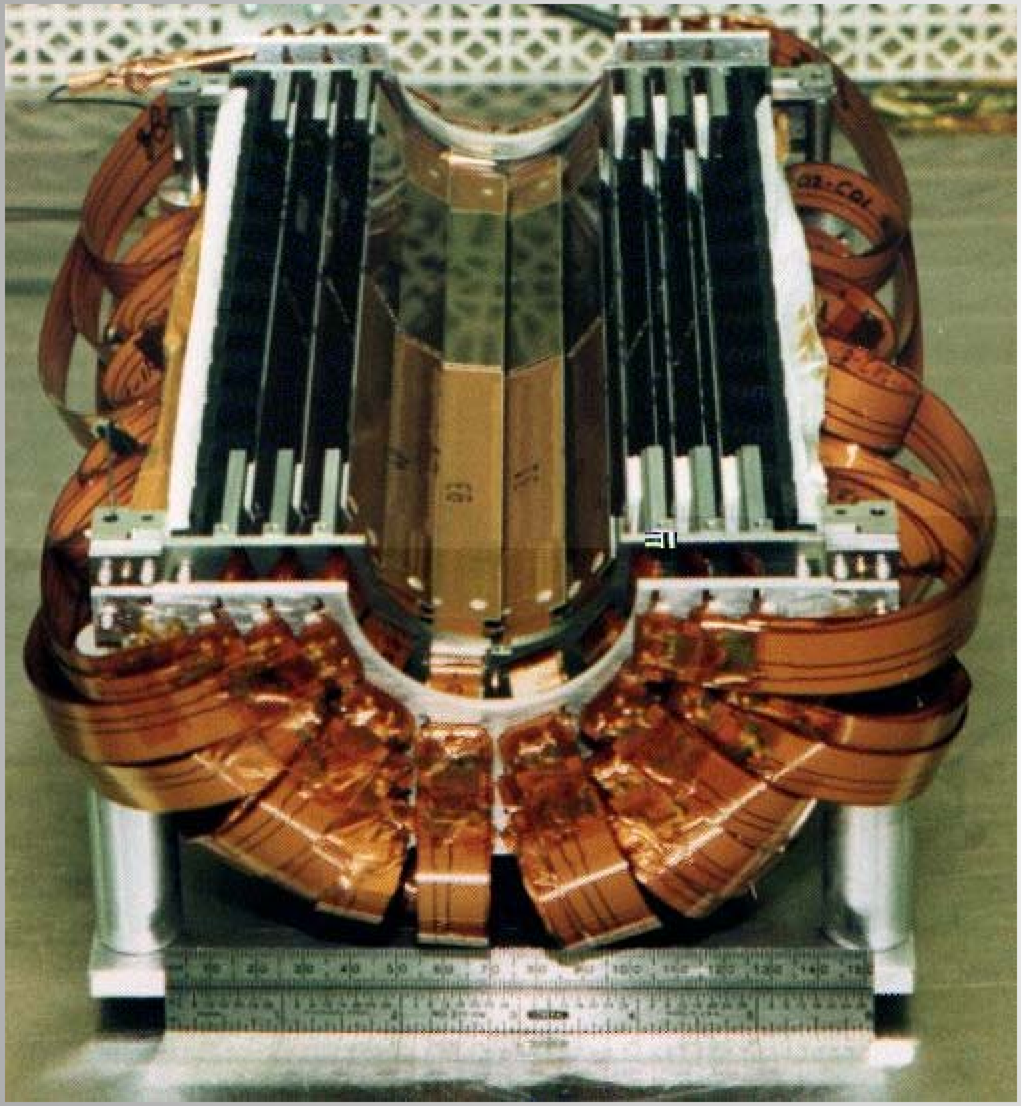


PARAMETER	MIN	TYP**	MAX	UNIT
Charge multiplication gain**	1	200	2000	-
Excess noise factor for typical CCM gain (Note 2)	1	1.4		-
Dynamic range without CCM gain		66		dB
Dynamic range with typical CCM gain (Note 3)		72 ~12 bits		dB
Charge conversion gain without CCM gain (Note 4)		14		uV/e
τ Signal-response delay time (Note5)		16		ns
Output resistance (Note 6)		320		Ω
Amp. Noise-equivalent signal without CCM gain *		20		e
Amp. Noise-equivalent signal with typ. CCM gain *			1.0	e



PARAMETER	UNIT	MIN	TYPICAL	MAX
Output amplifier responsivity, HR amplifier (normal mode) (see note 1)	μV/e⁻	-	5.3	-
Output amplifier responsivity, LS amplifier (normal mode) (see note 1)	μV/e⁻	-	1.1	-
Multiplication register gain, LS amplifier (high gain mode) (see notes 2, 3 and 4)		1	-	1000
Peak signal - 2-phase IMO	e⁻/pixel	90k	130k	-
Charge handling capacity of multiplication register (see note 5)	e⁻/pixel	-	800k	-
Readout noise at 50 kHz with CDS, HR amplifier (normal mode) (see note 6)	e⁻ rms	-	2.2	-
Readout noise at 1 MHz with CDS, HR amplifier (normal mode) (see note 6)	e⁻ rms	-	5.4	-
Amplifier reset noise (without CDS), HR amplifier (normal mode) (see note 6)	e⁻ rms	-	50	-
Readout noise at 50 kHz with CDS, LS amplifier (normal mode) (see note 6)	e⁻ rms	-	6	-
Readout noise at 1 MHz with CDS, LS amplifier (normal mode) (see note 6)	e⁻ rms	-	14	-
Amplifier reset noise (without CDS), LS amplifier (normal mode) (see note 6)	e⁻ rms	-	120	-
Readout noise at 1 MHz (high gain mode) (see note 6)	e⁻ rms	-	<1	-
Maximum frequency (settling to 1%), HR amplifier (see notes 6 and 7)	MHz	-	-	3
Maximum frequency (settling to 5%), HR amplifier (see notes 6 and 7)	MHz	-	-	4.5
Maximum frequency (settling to 1%), LS amplifier (see notes 6 and 7)	MHz	-	-	9
Maximum frequency (settling to 5%), LS amplifier (see notes 6 and 7)	MHz	-	-	15
Maximum parallel transfer frequency (see note 1)	MHz	-	1.6	-
Dark signal at 293 K (see note 8)	e⁻/pixel/s	-	400	800
Dark signal non-uniformity (DSNU) at 293 K (see note 9)	e⁻/pixel/s	-	60	-
Excess noise factor (see note 10)		-	$\sqrt{2}$	-

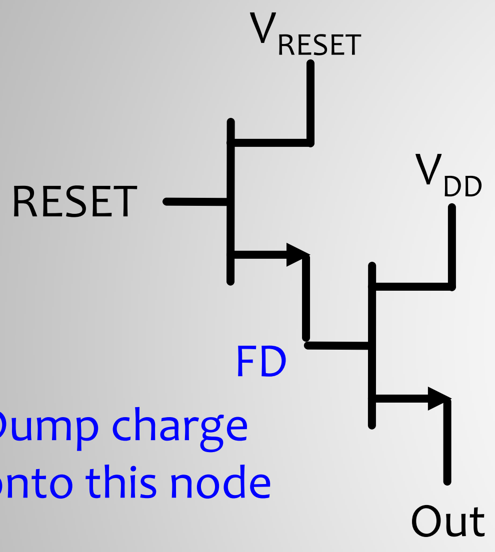
Particle physics example



- ◆1996 - SLD Vertex Detector
- ◆3 x 10^8 pixels
- ◆96 x 3.2 MPix x 20 μm CCD

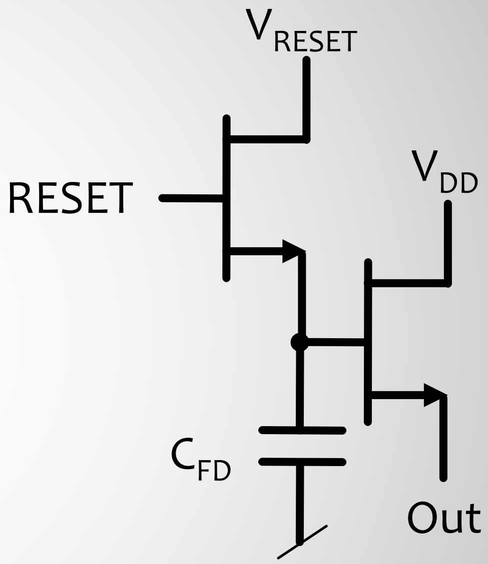
Reading out CCDs

CCD Output Stage



Dump charge
onto this node

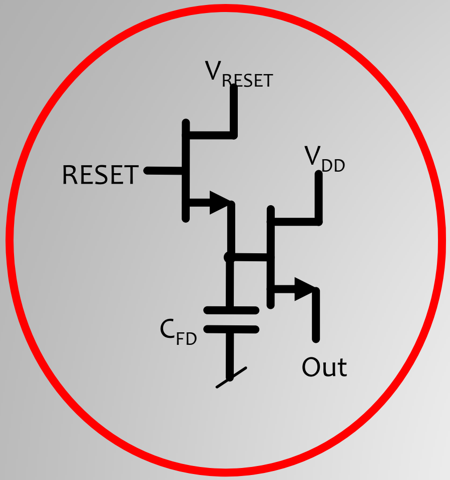
CCD Output Stage

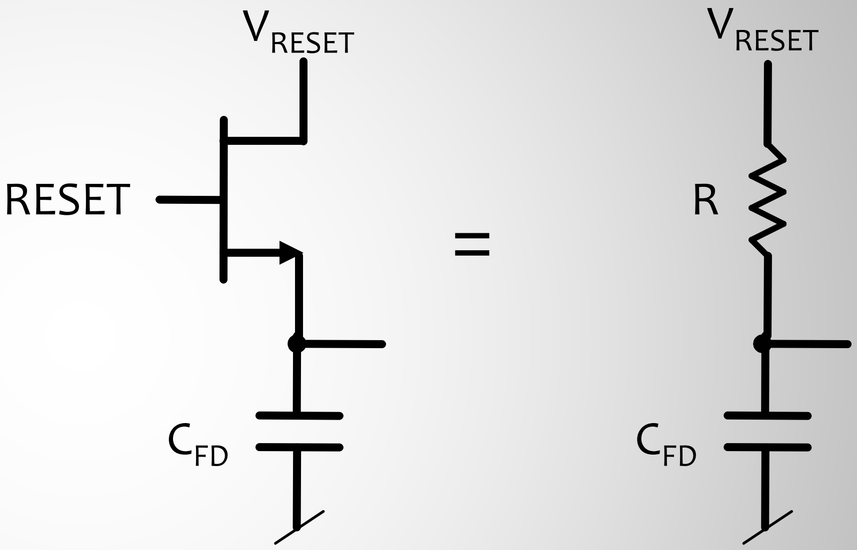


Each transistor is a noise source

C_{FD} "converts" the charge into a voltage: $V = Q / C_{FD}$

kT/C noise





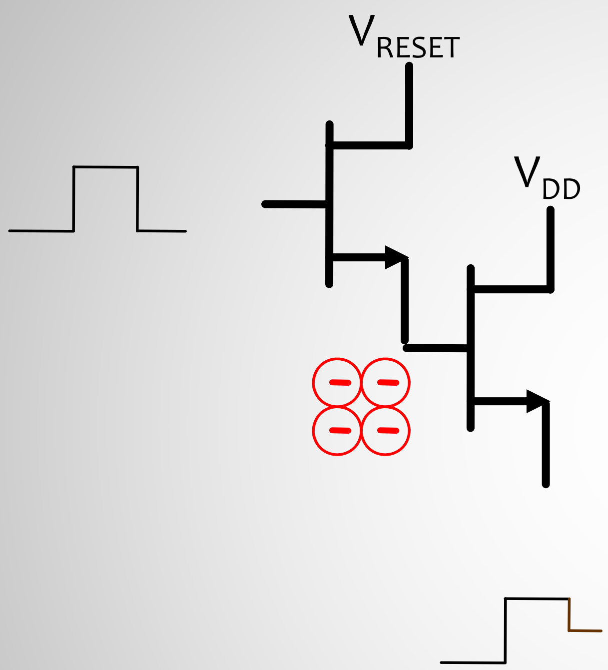
Reset transistor is a switch whose resistance is a function of the gate voltage

Voltage noise = $\sqrt{4kTR \times BW}$

Bandwidth $\propto 1/\tau$, $\tau = RC$ → Voltage noise = $\sqrt{4kT/C}$

$V = Q/C_{FD}$ → e.n.c. = $\sqrt{4kTC}$

Correlated double sampling

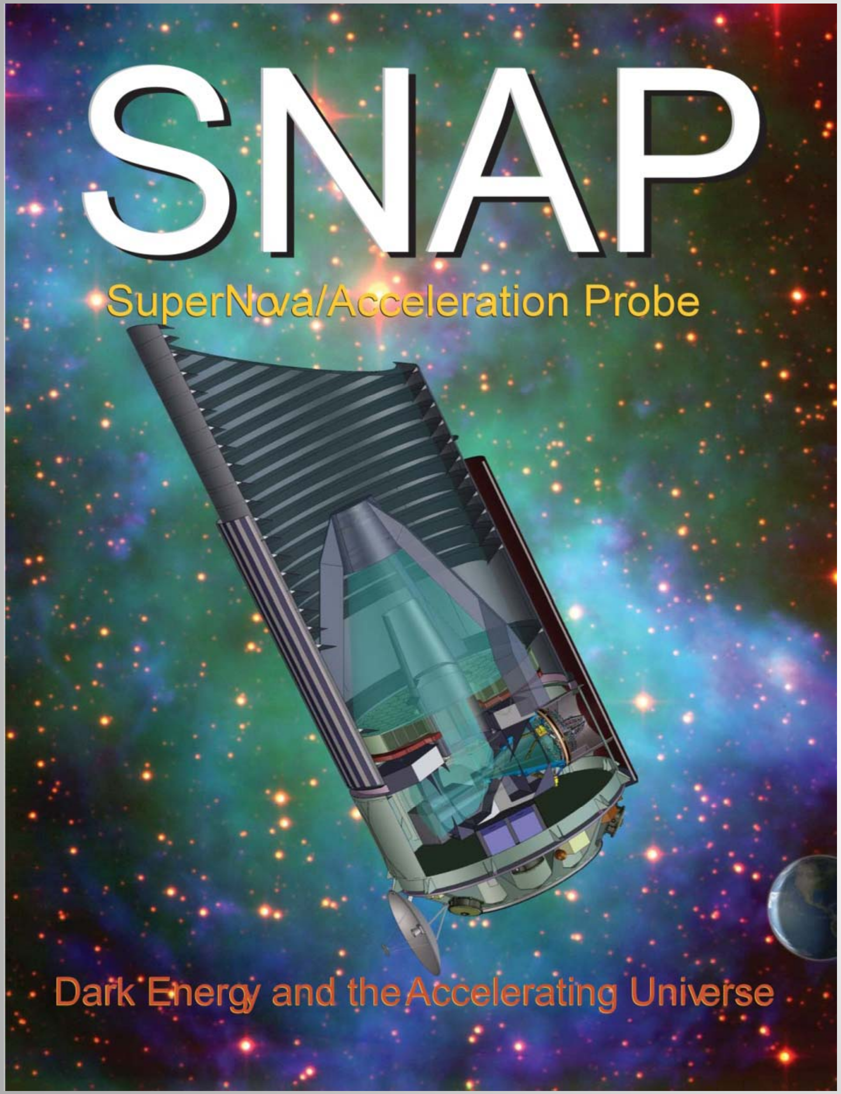


1. Turn on RESET
2. Measure
3. Turn off RESET
4. Dump charge on to FD
5. Measure

Signal = difference

Cancels kT/C noise
Helps to remove low frequency (1/f) noise

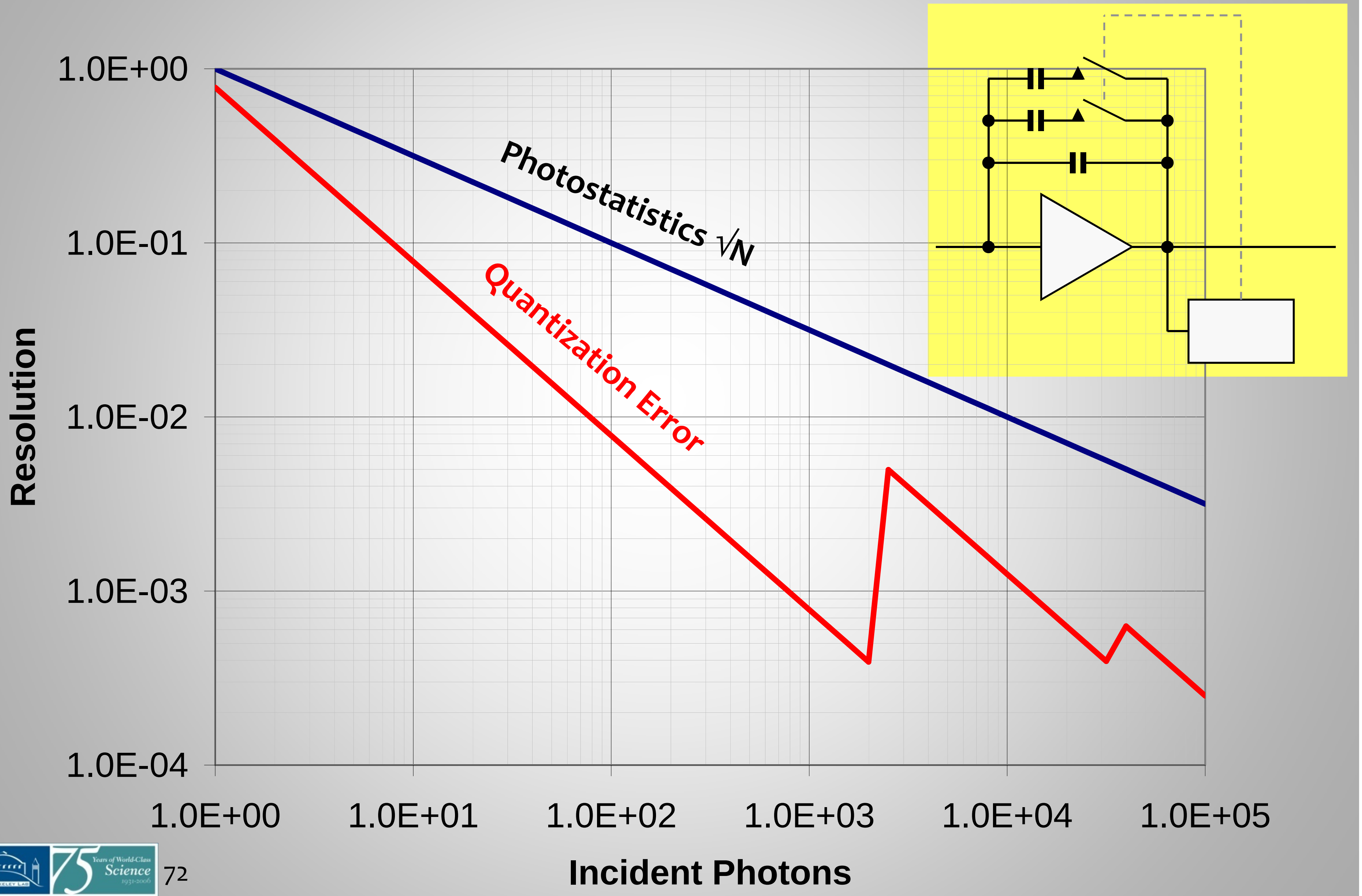
A practical example



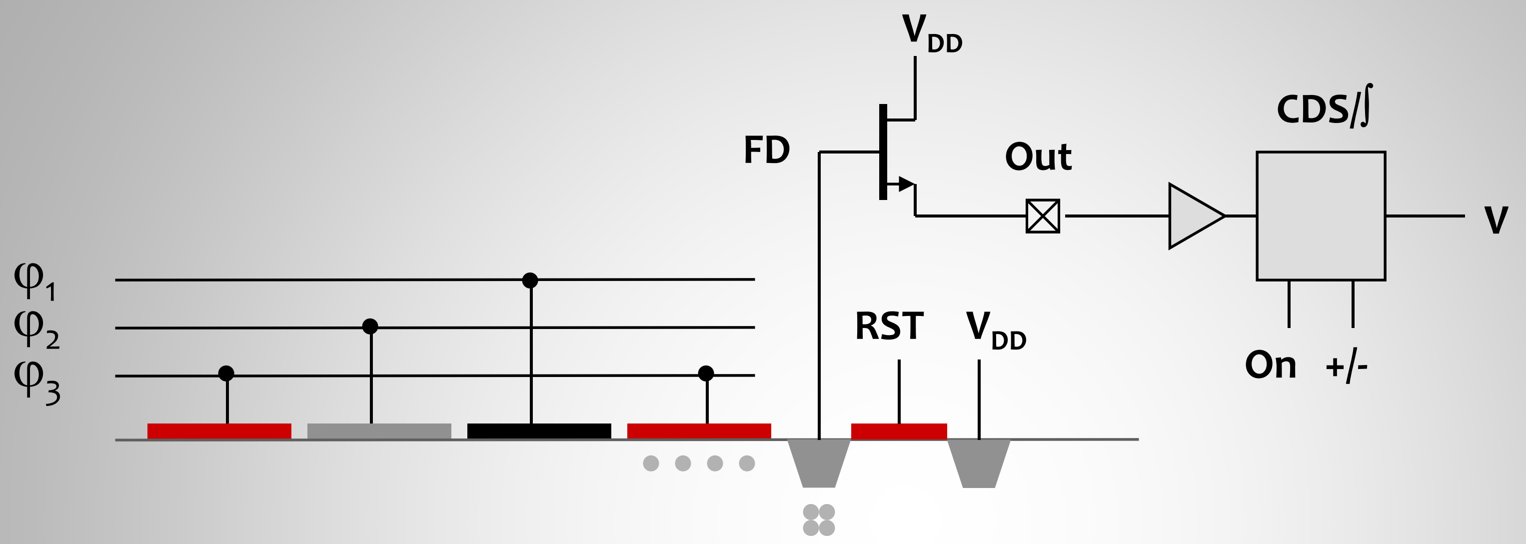
◆ Satellite experiment to look at supernovae
  - Uses CCDs in the focal plane

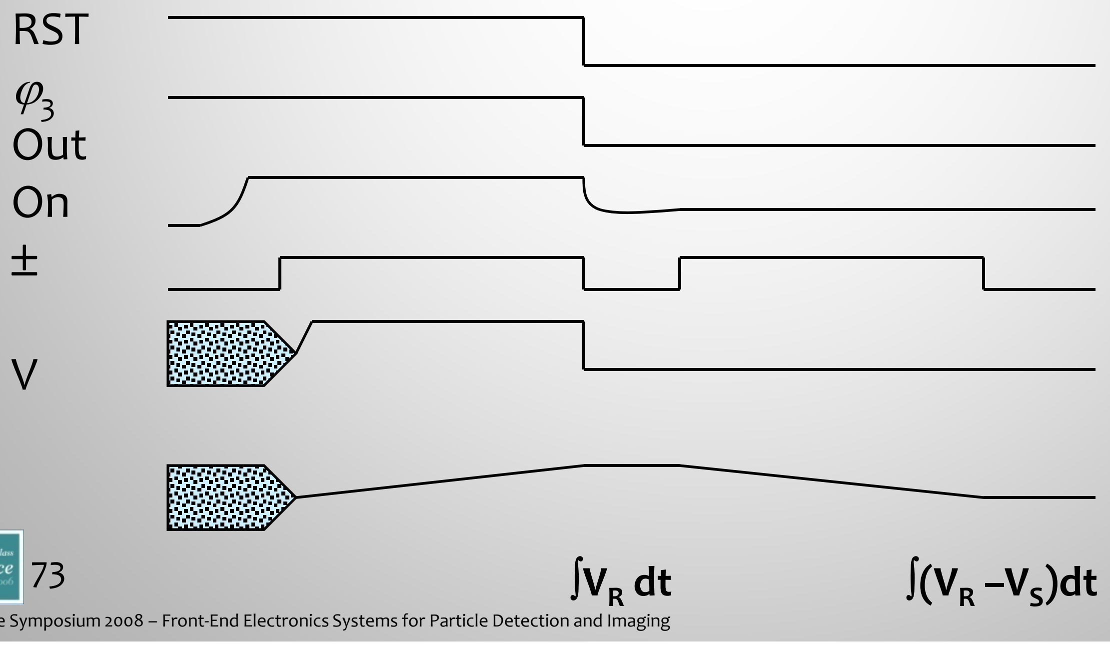
◆SNAP requirements
  - 16 bit dynamic range at 100 kHz
  - 4 channels per chip
  - low power
  - space qualified

Floating point readout



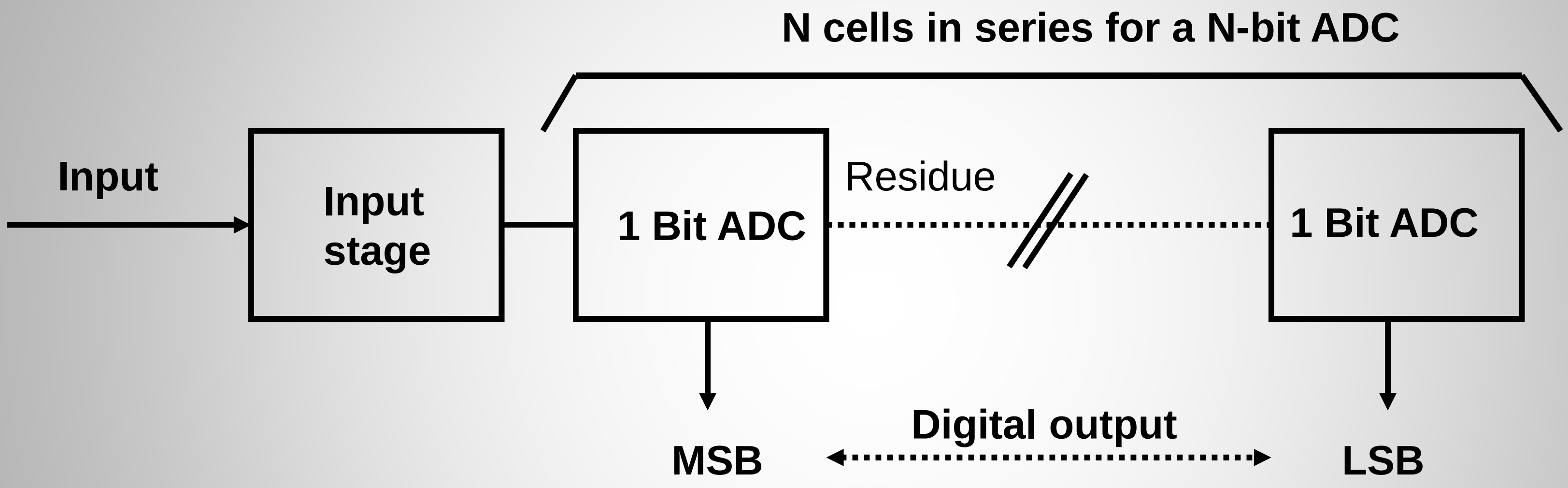
Digitize cycle





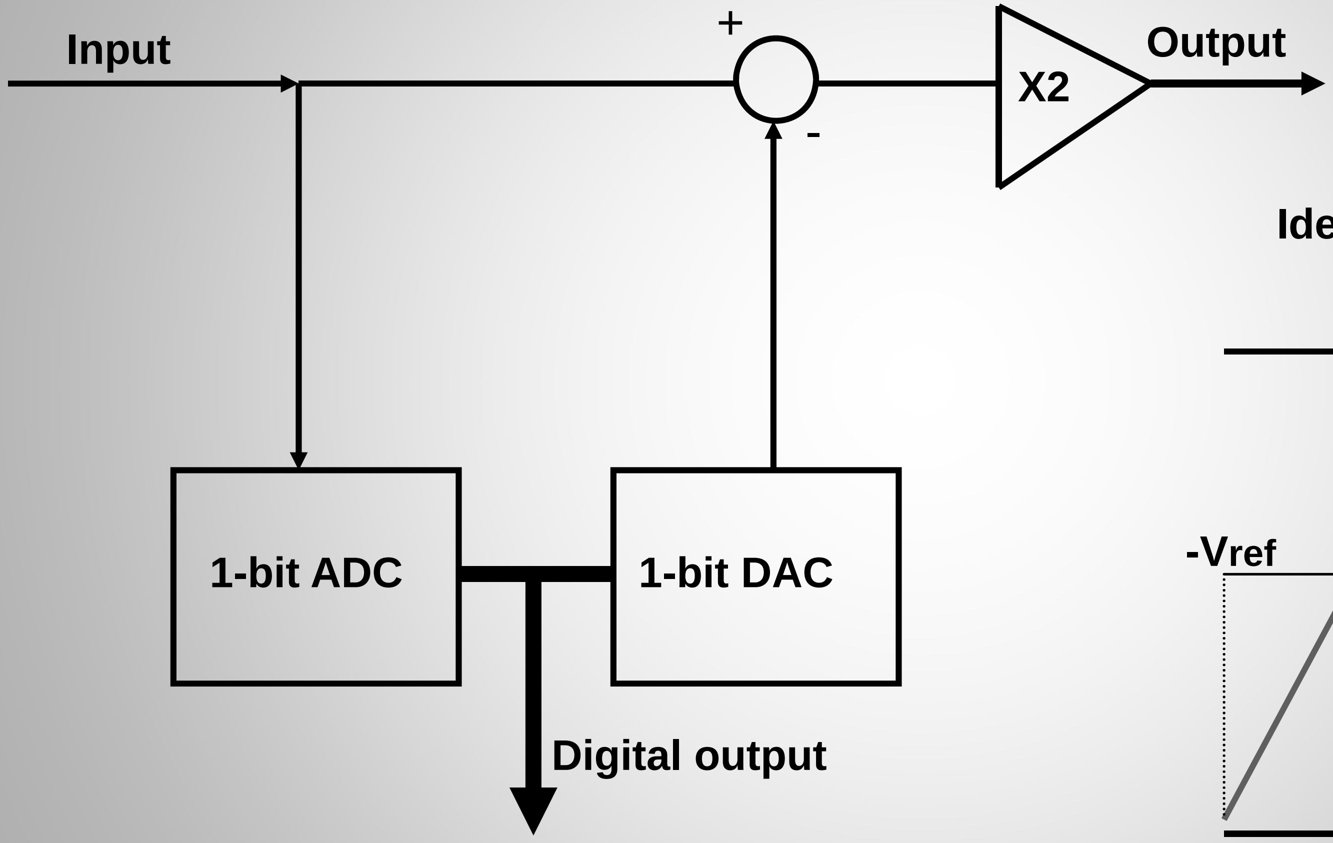
Pipelined ADC

Helmuth mentioned the pipelined ADC – here's a practical implementation

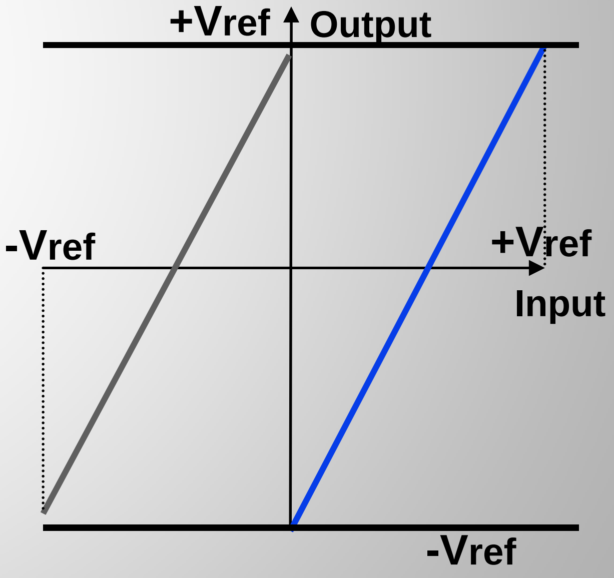


- Sub ranging architecture: Each stage determines one bit.
- The first stage residue is digitized by a (N-1) bit ADC and so on…
- Digitization rate = ADC clock frequency
- Latency = Digitization rate x number of bits /2

1-Bit Cell



Ideal transfer function (residue)

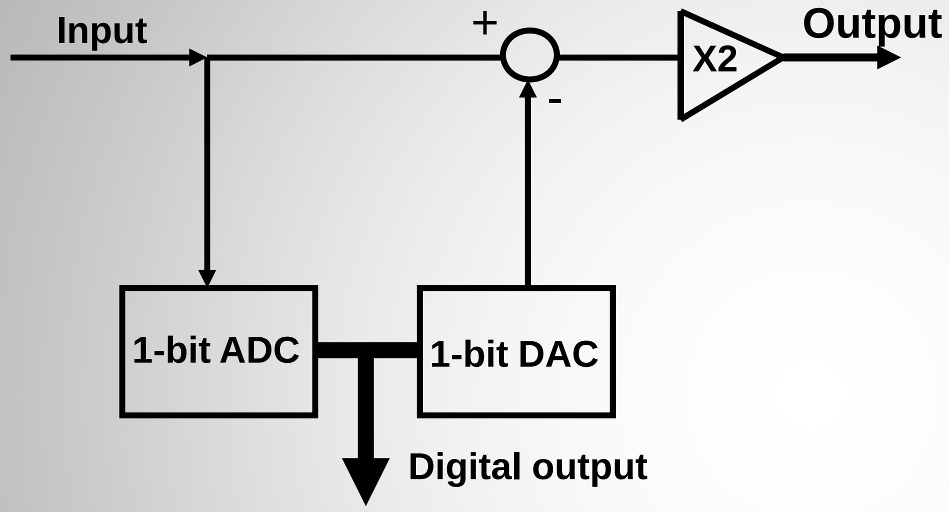


D0

0 Vout = 2xVin + Vref

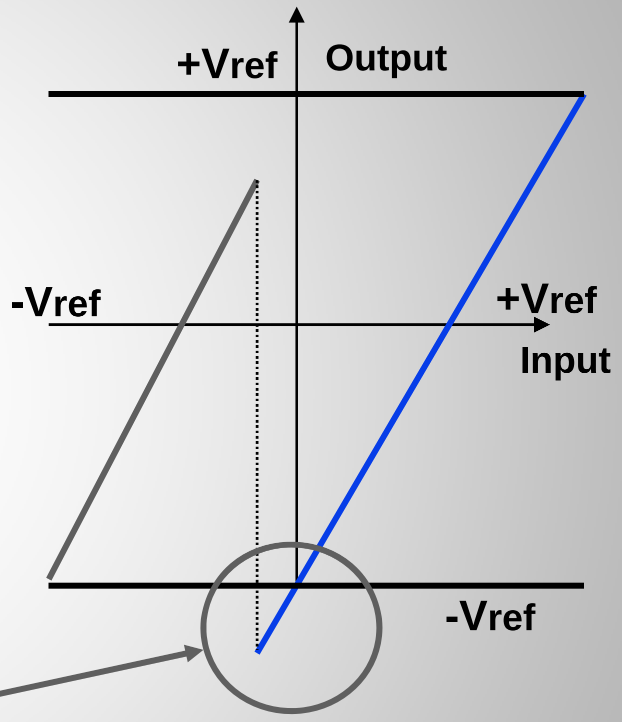
1 → Vout = 2xVin - Vref

Limitation of the 1-Bit Cell



D0		
0	→	Vout = 2xVin + Vref
1		Vout = 2xVin - Vref

Transfer function (residue)

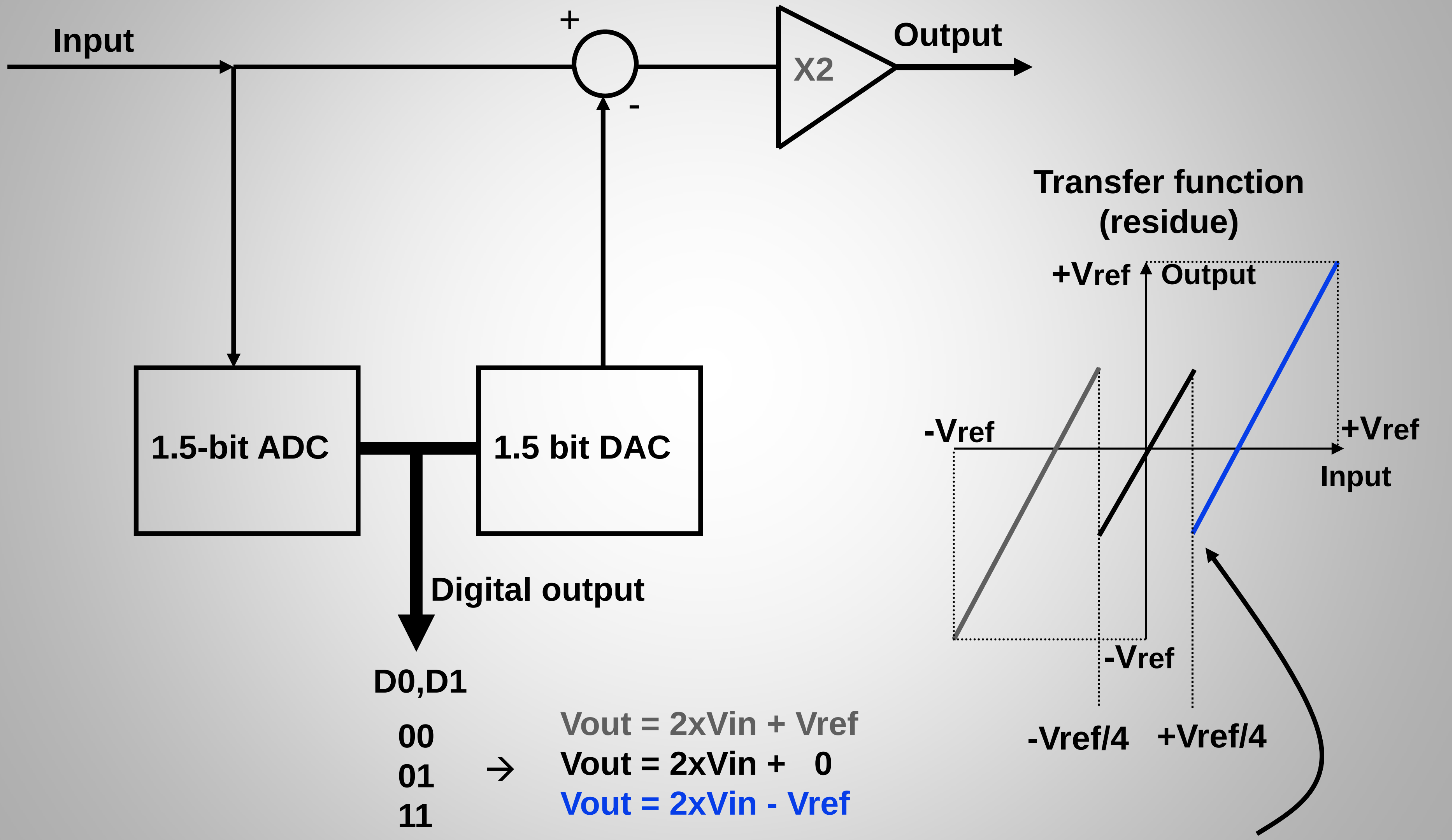


Missing codes due to comparator offset for example

Loss of information when the larger residues saturate the next stage. It could come from charge injection, capacitance mismatch or comparator offset.

Errors can be corrected by digital correction if the conversion range of the next stage is increased to handle the larger residues.

1.5-Bit Cell

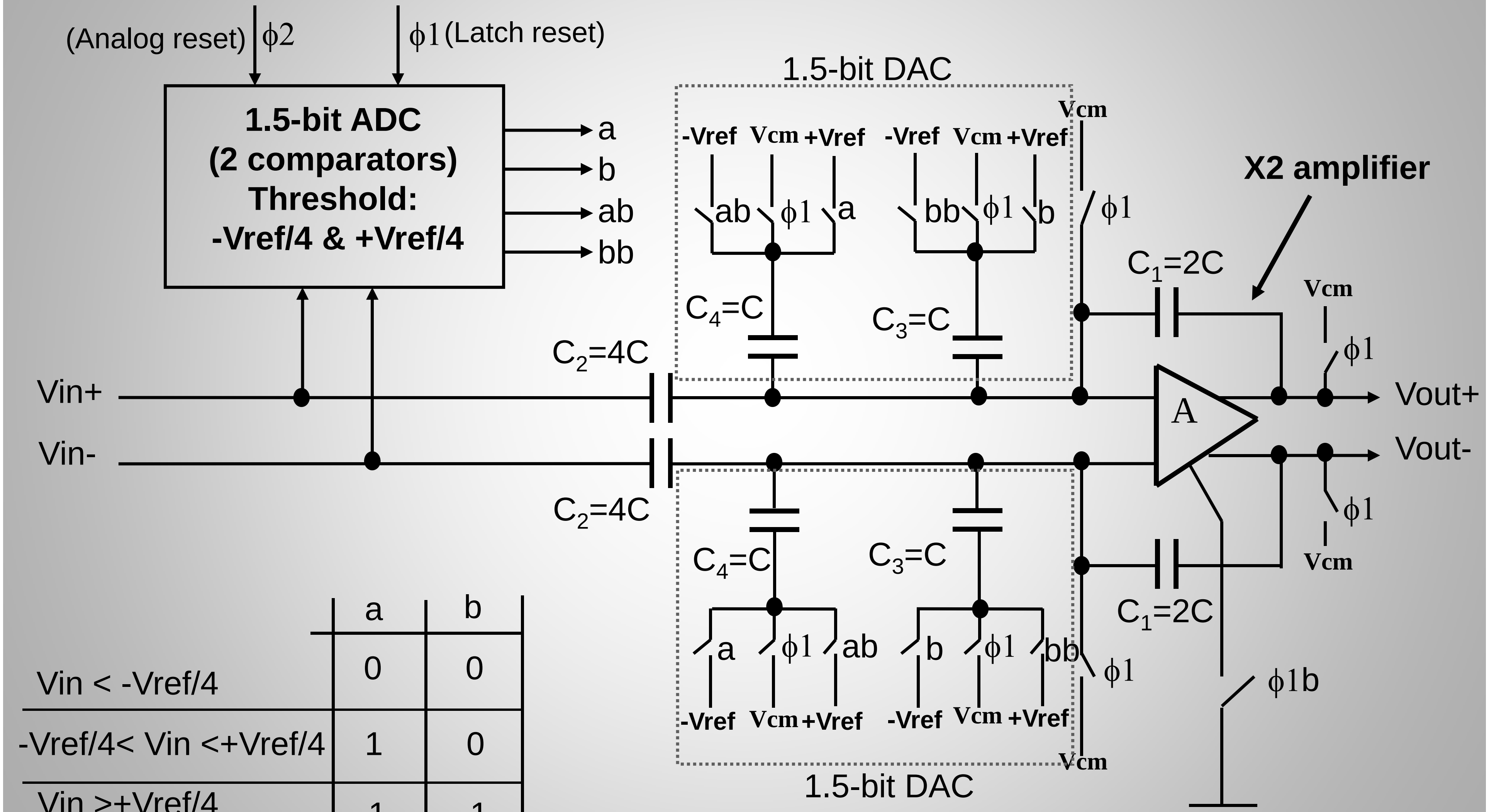


D0,D1

00 Vout = 2xVin + Vref
01 → Vout = 2xVin + 0
11 Vout = 2xVin - Vref

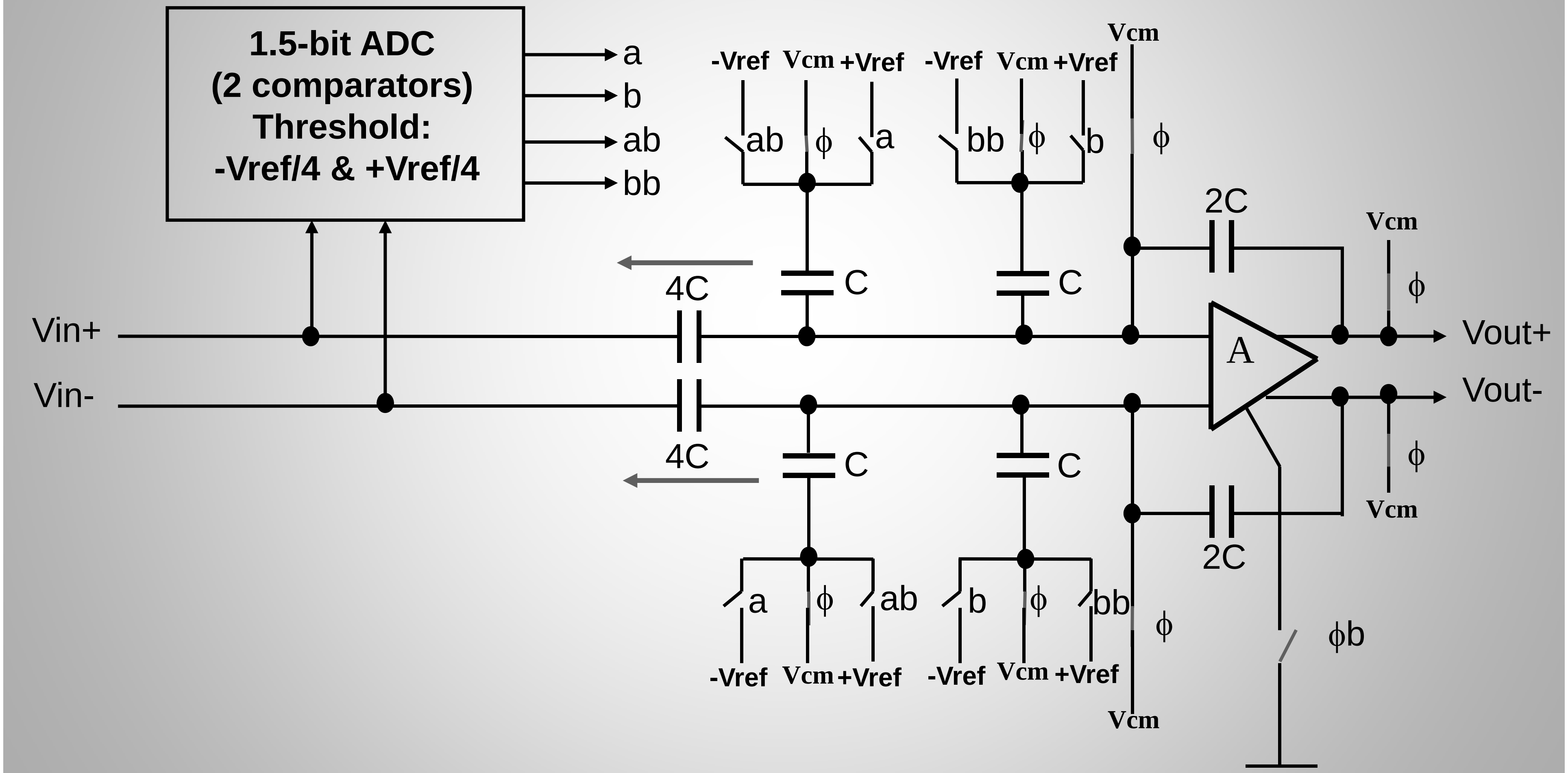
No saturation if +- Vref/4 is moving

1.5-Bit Cell Implementation



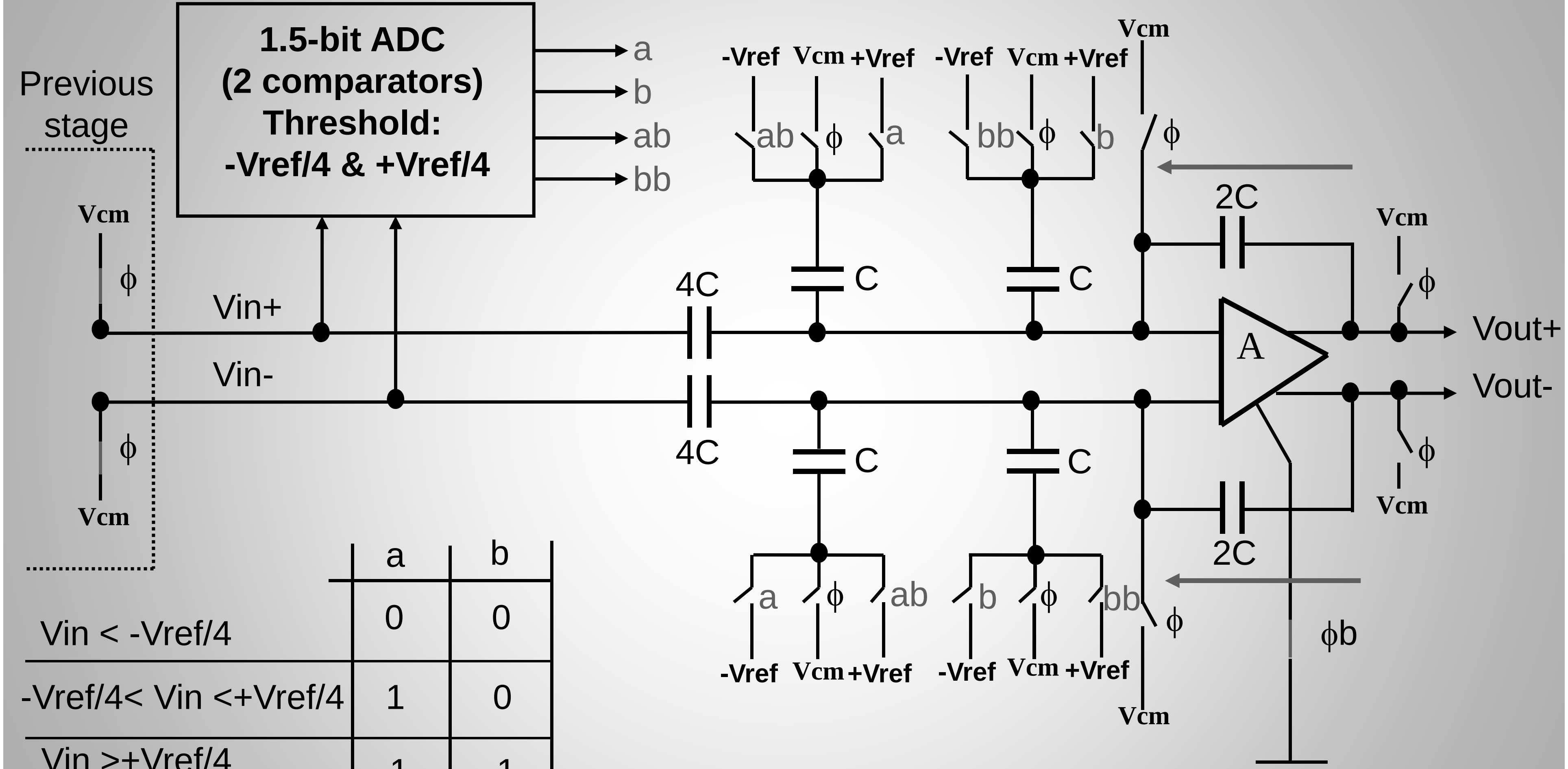
	a	b
Vin < -Vref/4	0	0
-Vref/4< Vin <+Vref/4	1	0
Vin >+Vref/4	1	1

Sampling Phase



Input signal sampled on 4C

Amplification Phase

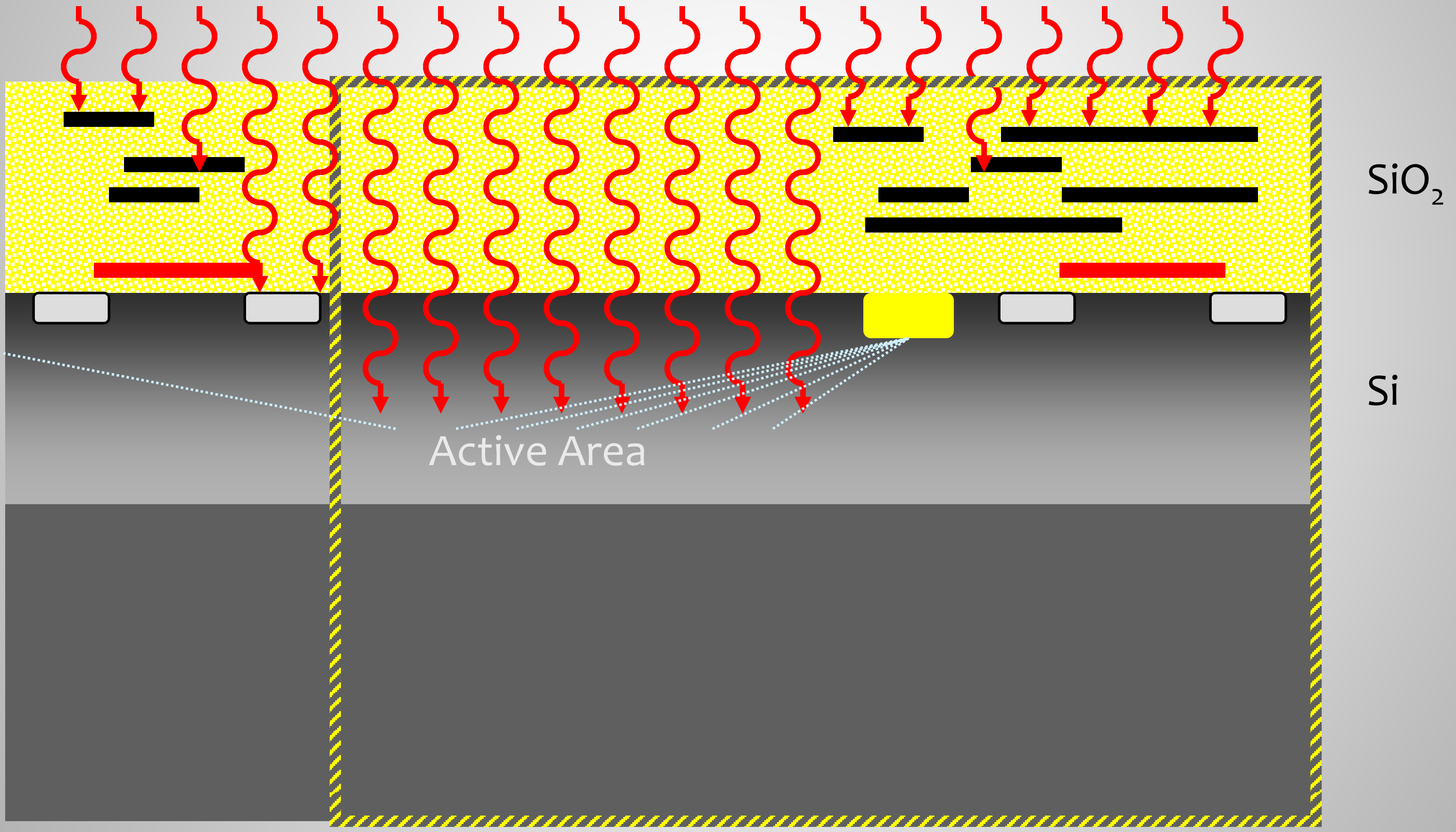


	a	b
Vin < -Vref/4	0	0
-Vref/4< Vin <+Vref/4	1	0
Vin >+Vref/4	1	1

Vout = 2xVin ±Vref/2 ±Vref/2

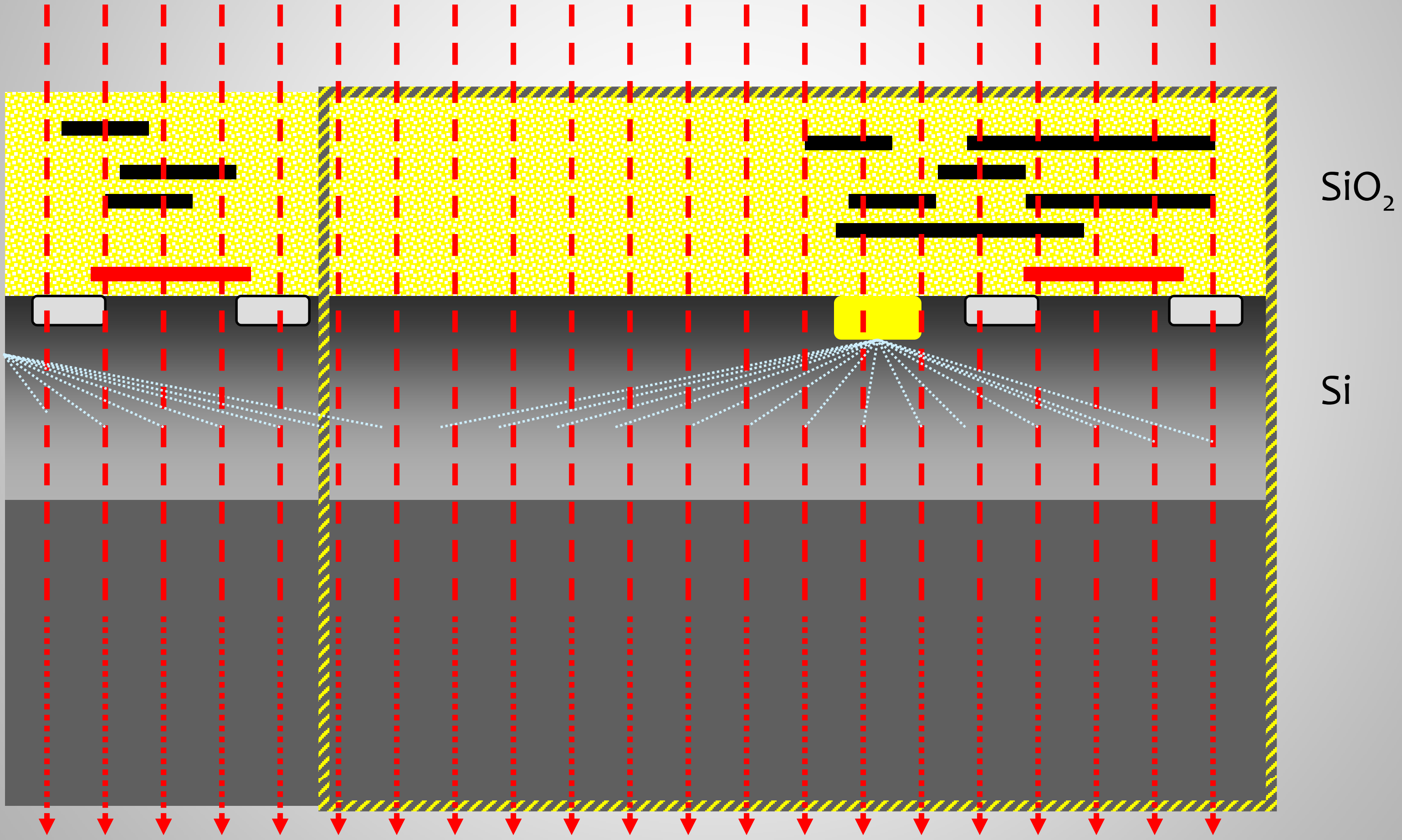
(DC gain infinite)

Optical active pixel



Fill Factor = Active / Total area

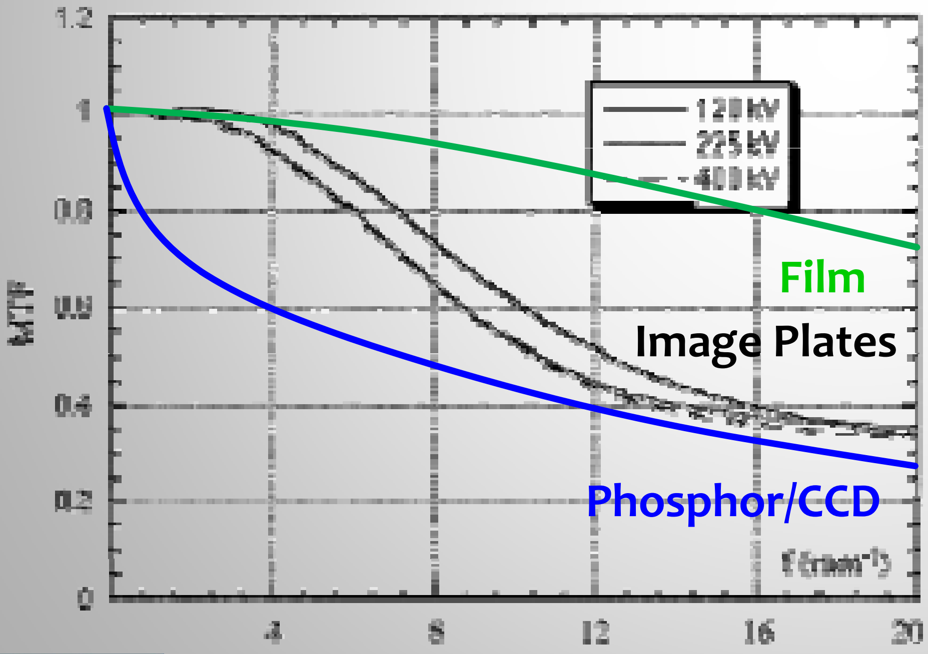
Charged particle active pixel



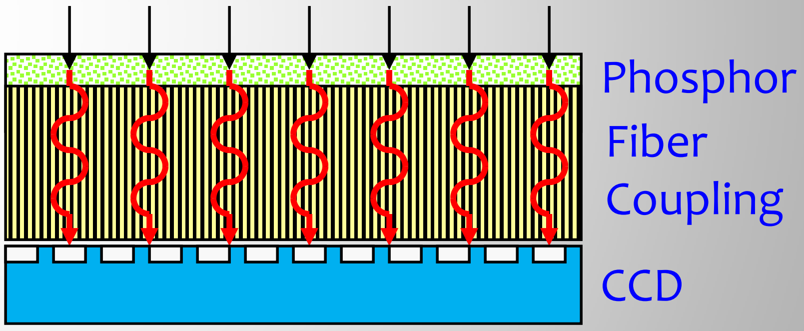
Fill Factor = 100%

Example: Transmission Electron Microscopy

- Film: Δt(exposure-to-image) – minutes-hours-days
  - Good MTF (very small grains), less aliasing (random grain sizer)
  - Non-linear, low (local) dynamic range
- Image plates: Δt(exposure-to-image) – minutes-hours-days
  - Moderate MTF
  - Wide dynamic range
- Phosphor/CCD: Δt(exposure-to-image) – seconds
  - Poorer MTF
  - Wide dynamic range



“Digital” EM (and xray) detector



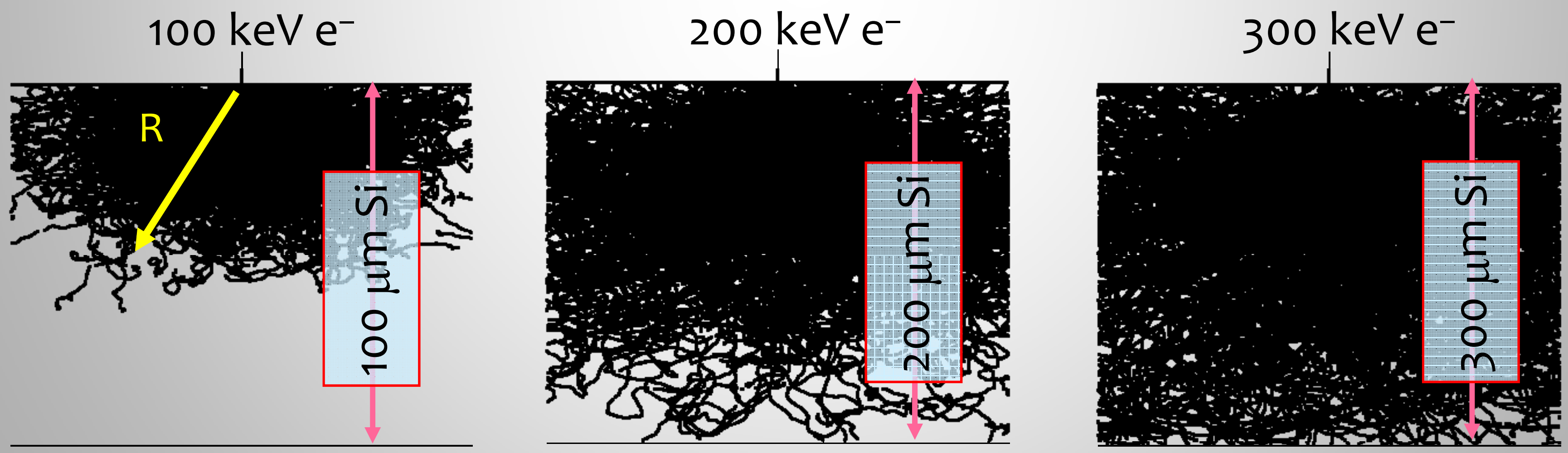
Yet, film has better MTF

Electron Detection Characteristics of a Slow-Scan CCD Camera, Imaging Plates and Film, and Electron Image Restoration -- J. M. ZUO MICROSCOPY RESEARCH AND TECHNIQUE 49:245–268 (2000)

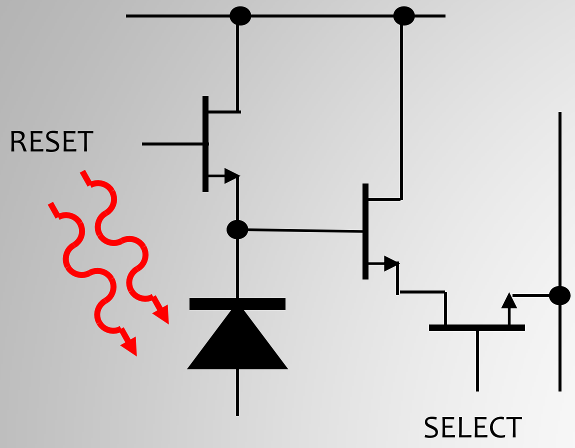
EM Detector Challenge

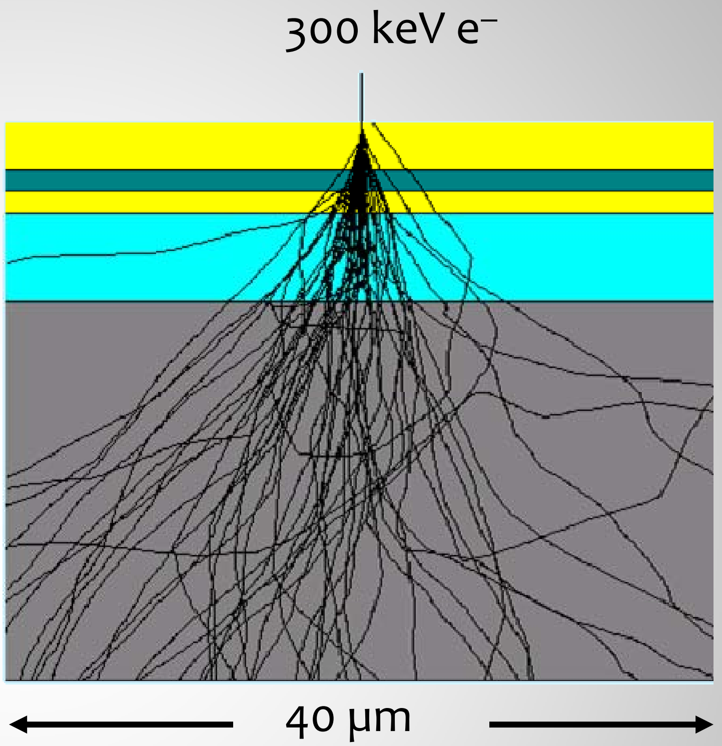
"At energies of interest for electron microscopy, electrons scatter a lot!"

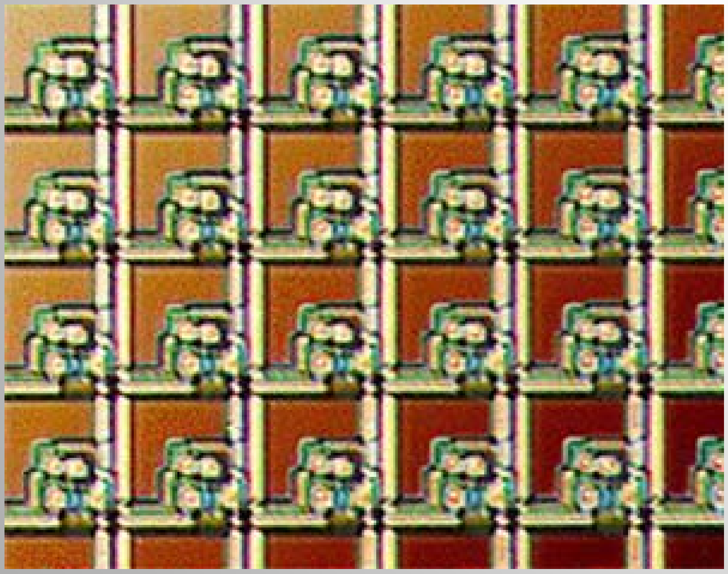
$$\left.\begin{array}{c} R\,[\mu m] \sim E\,[keV] \\ dE/dx \sim 1/E \end{array}\right\}$$ Astronomical Precision



Charged particle active pixel

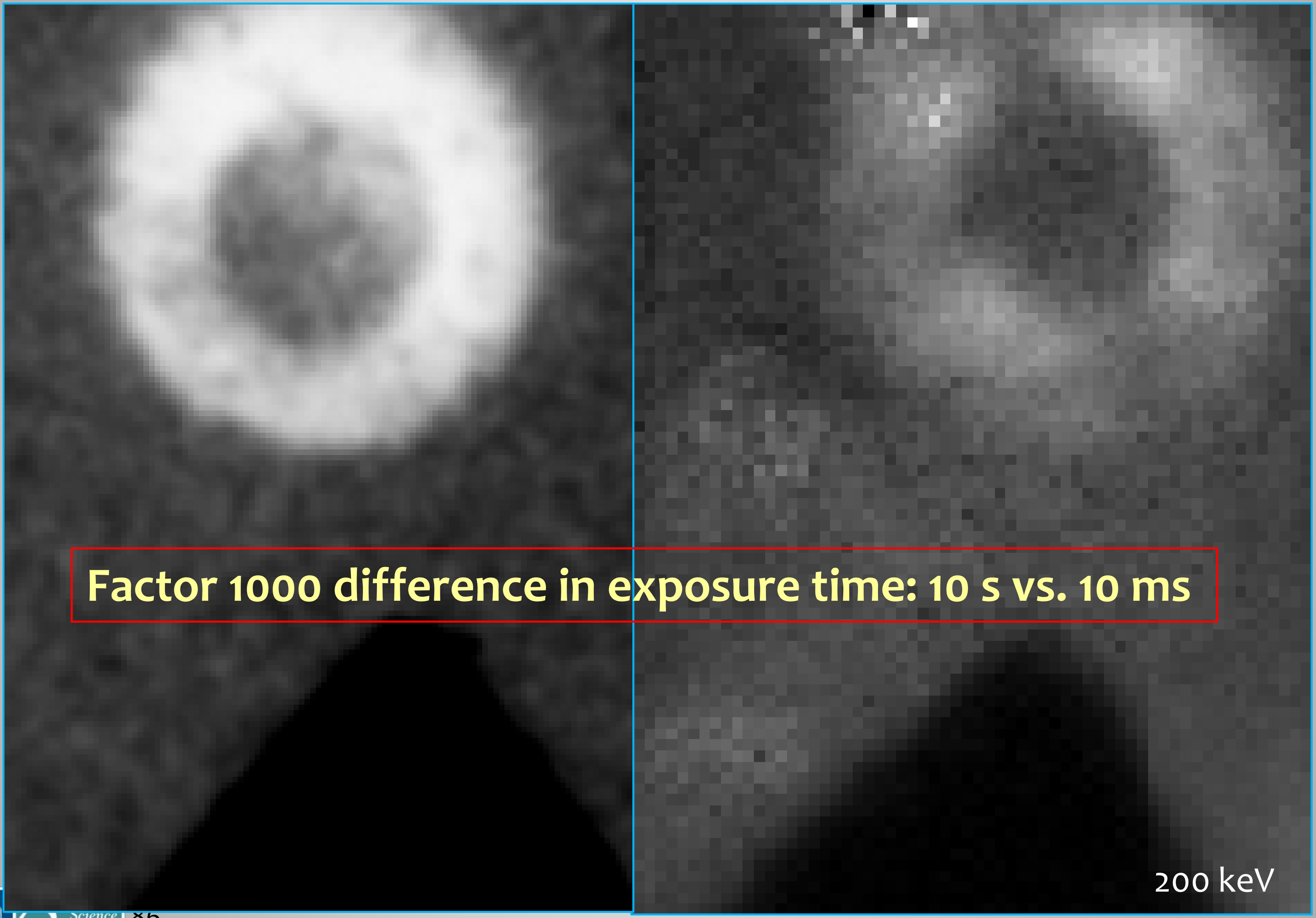






- ◆ Essentially all charge collected from thin region
- ◆ Detector can be thinned
- ◆ Higher energy → better PSF, lower S/N
- ◆ Rivals film MTF

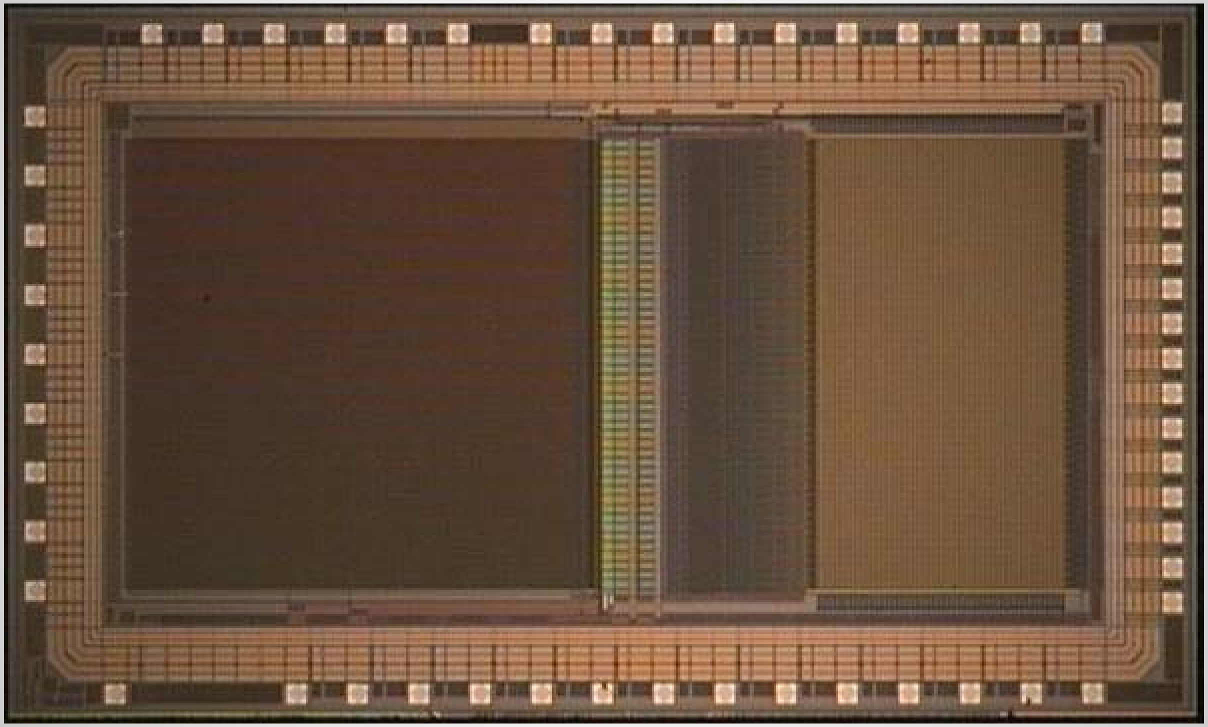
Film vs. Silicon



Factor 1000 difference in exposure time: 10 s vs. 10 ms

An example of another kind of ADC

Charged particle tracker

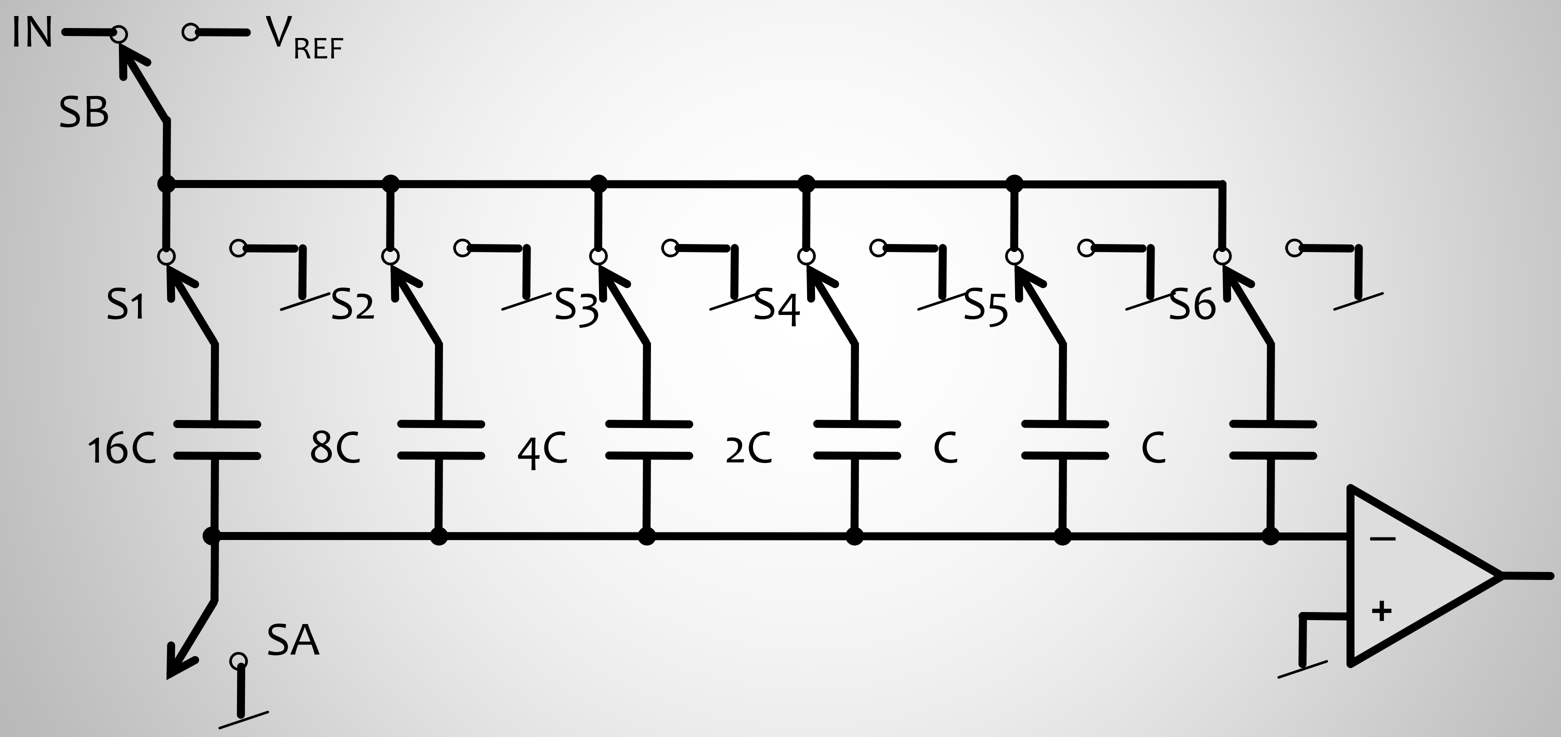


Sensor ADC Memory

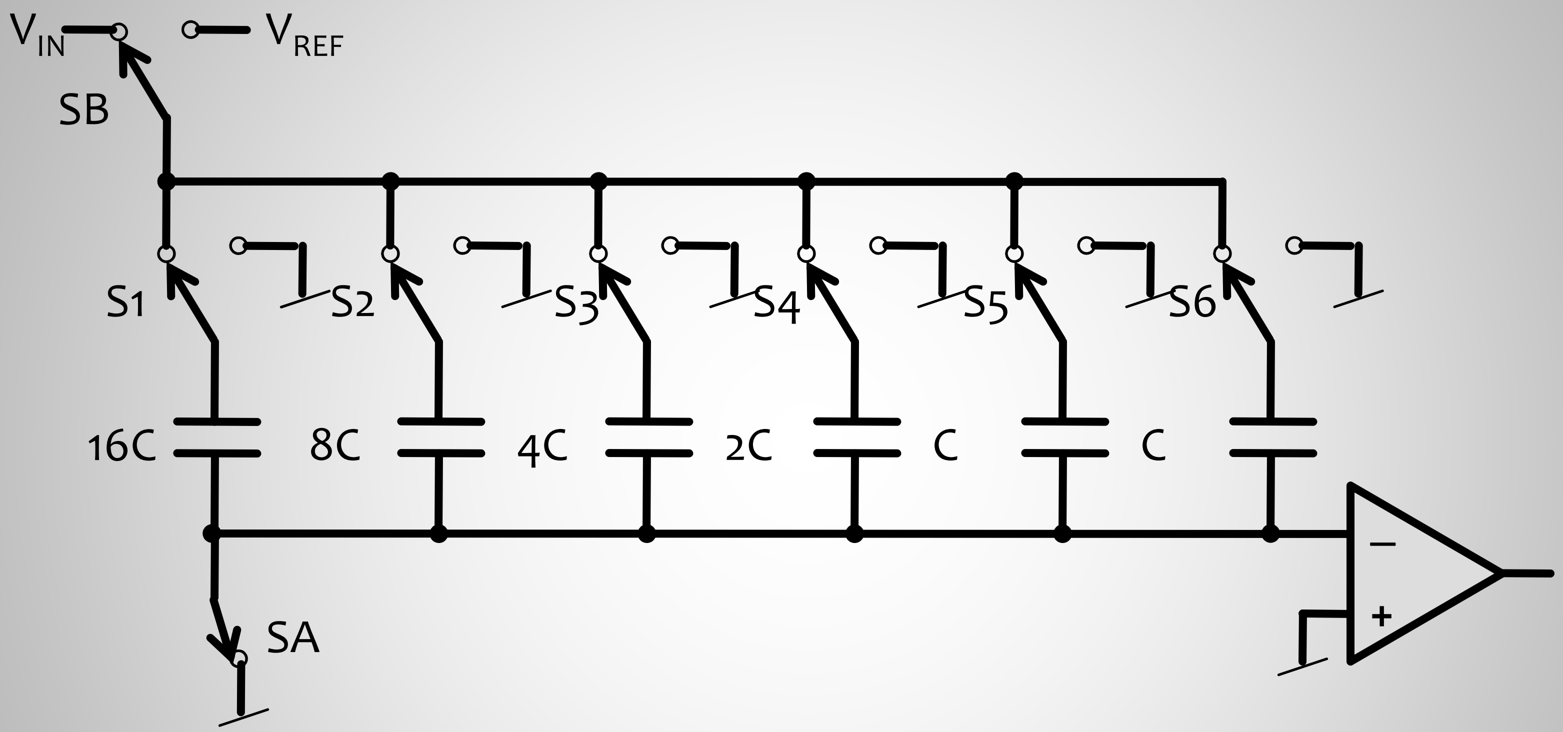
5-bit differential charge redistribution ADC

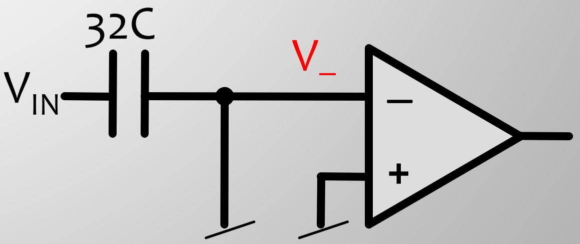
Capacitive charge redistribution ADC

A form of successive approximation ADC



Sample input

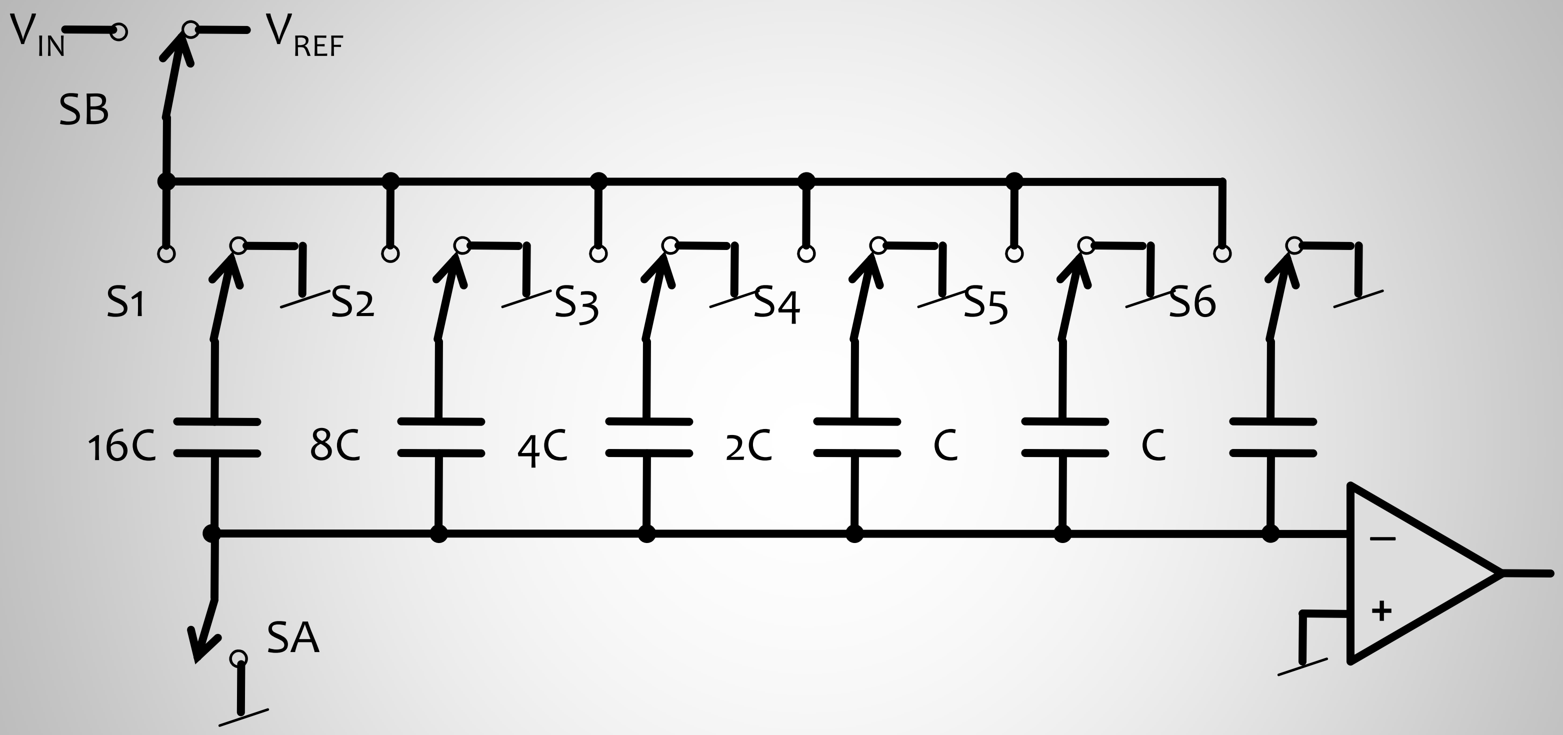




Charge stored on capacitors: $Q = 32C \times V_{IN}$

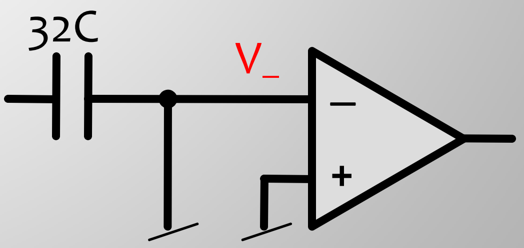
$V_- = 0$

Hold – do nothing

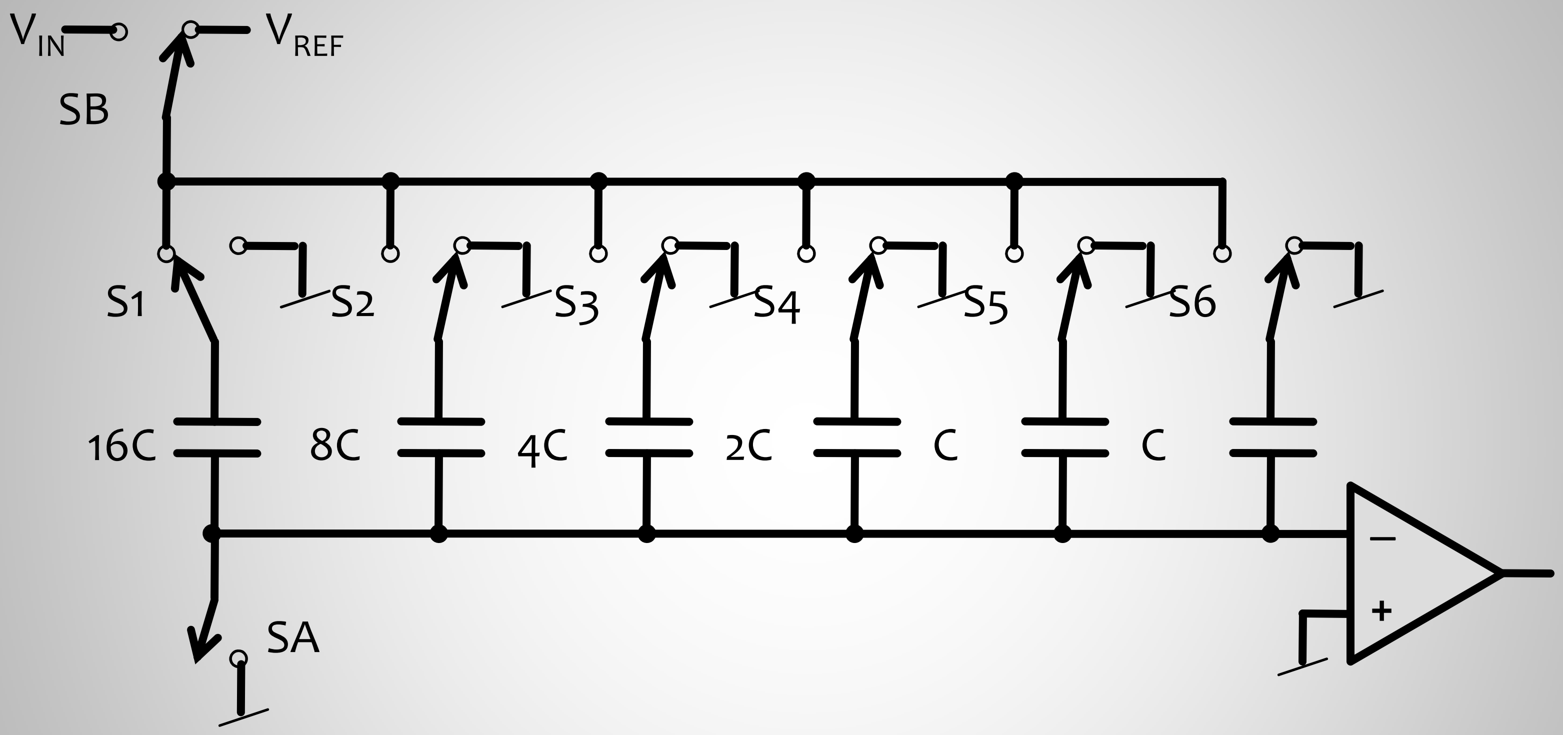


Charge stored on capacitors: $Q = 32C \times V_{IN}$

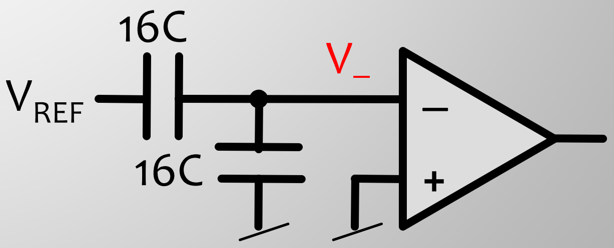
$V_{\_} = -V_{IN}$



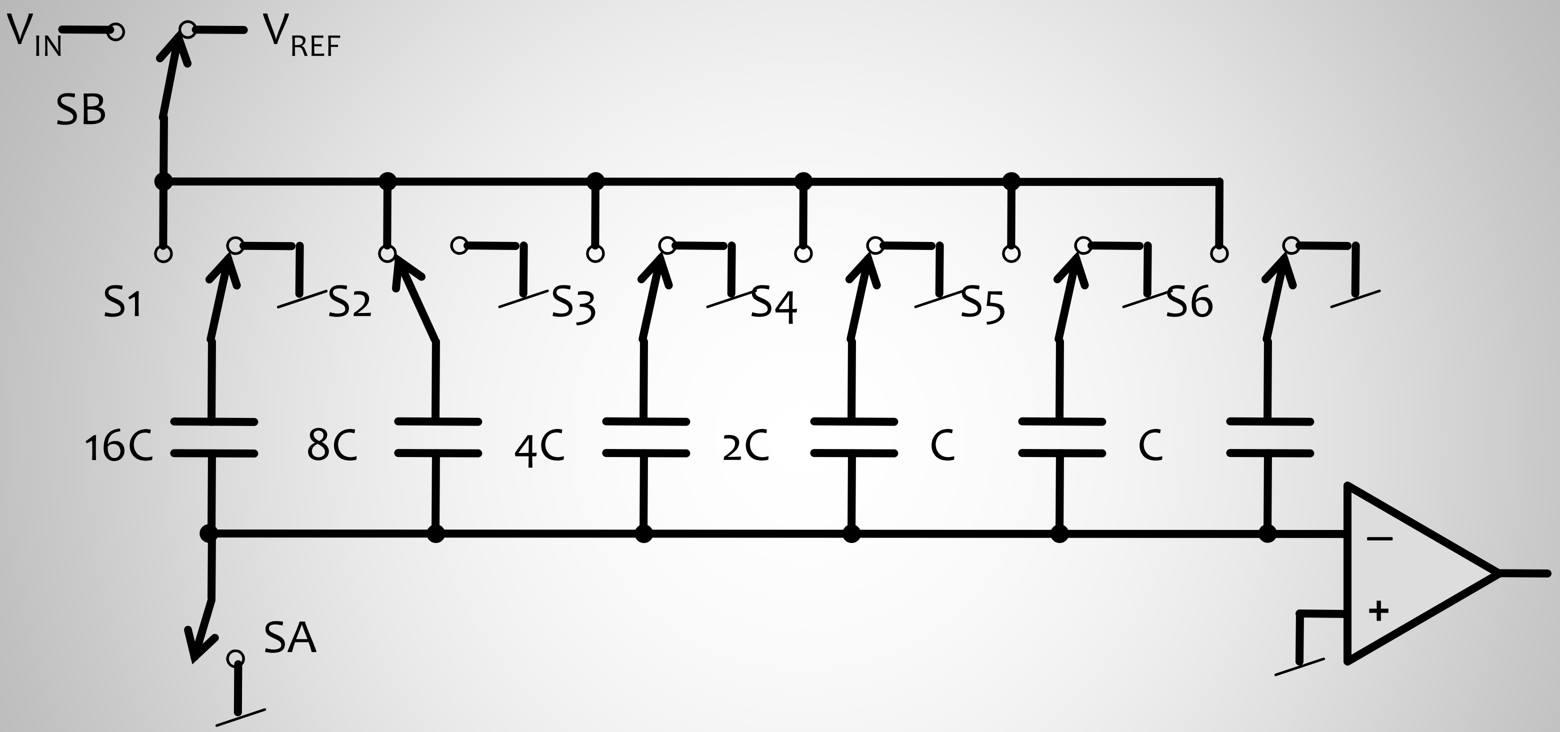
Start digitization – determine MSB



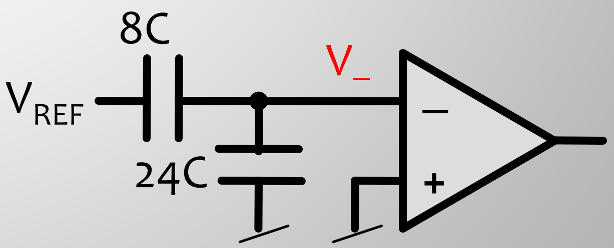
$V_- = V_{REF}/2 - V_{IN}$



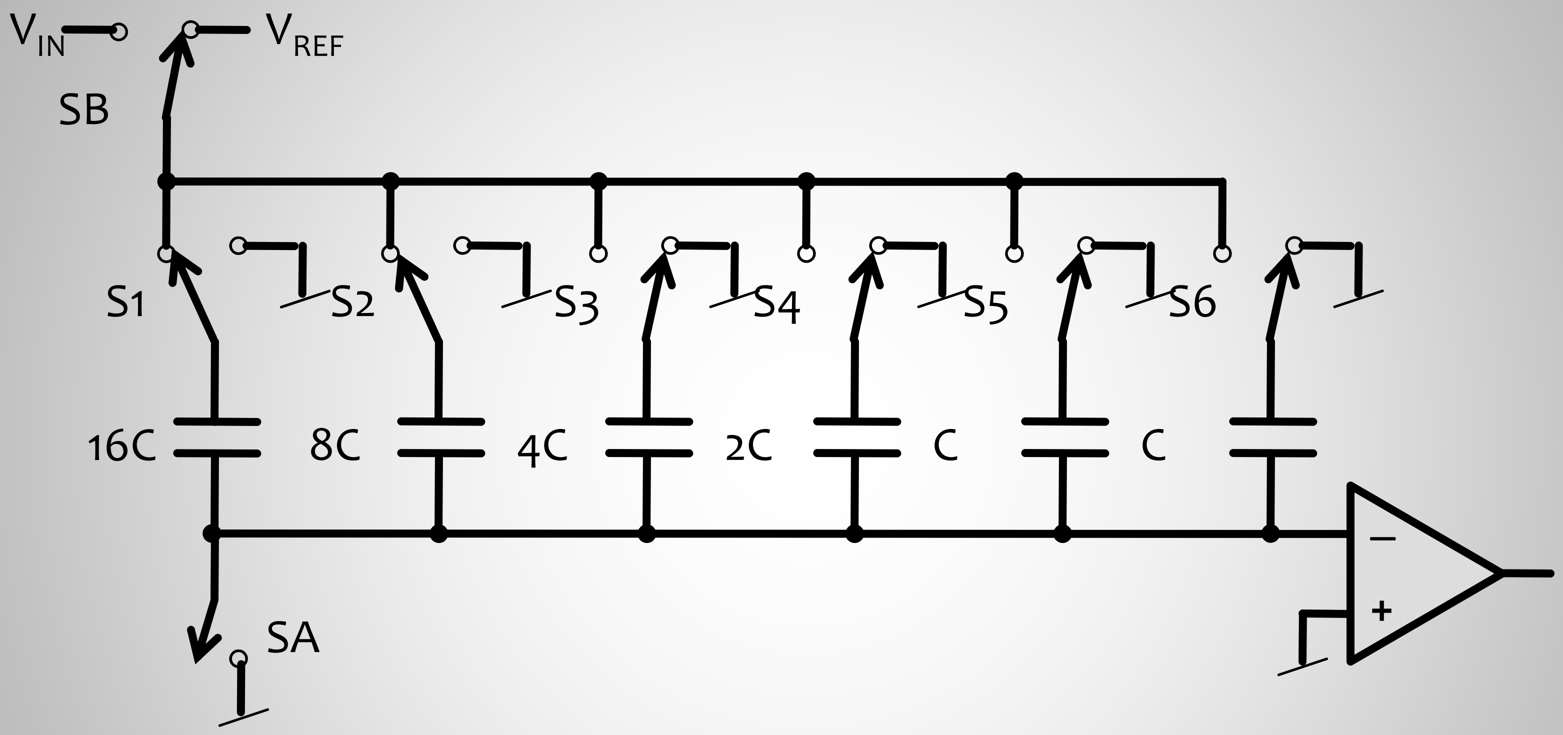
If comparator fired (MSB = 1) $V_{IN} < V_{REF}/2$



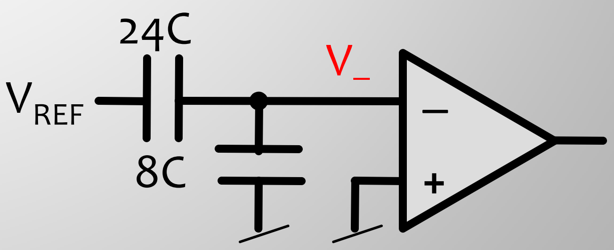
$V_- = V_{REF}/4 - V_{IN}$



If comparator did not fire (MSB = 0) $V_{IN} > V_{REF}/2$



$V_{\_} = 3xV_{REF}/4 - V_{IN}$



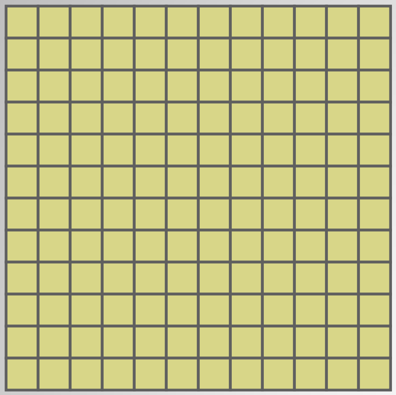
CCD vs. APS

- Consumer market
  - APS – “system on a chip” (cell phone cameras)
  - CCD – high end digital camera, but overtaken by APS (again, system on a chip)
- Scientific market
  - Still CCD (more sensitive, bigger – easier to make “wafer scale”)
    - Ubiquitous x-ray and electron detector is a phosphor fiber-coupled to a CCD
  - APS a growing interest for charged particles
  - CCD lends itself naturally to CDS
    - But modern optical APS do too
  - Back-illuminated CCDs have 100% optical fill factor

Who Wins?

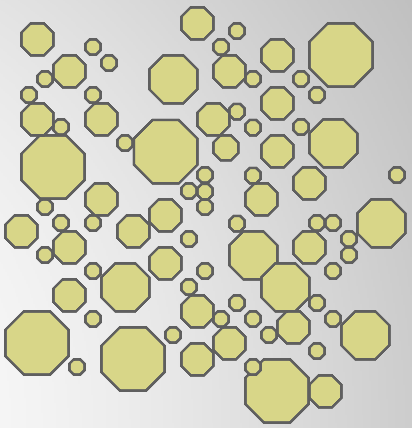
Silicon

Film

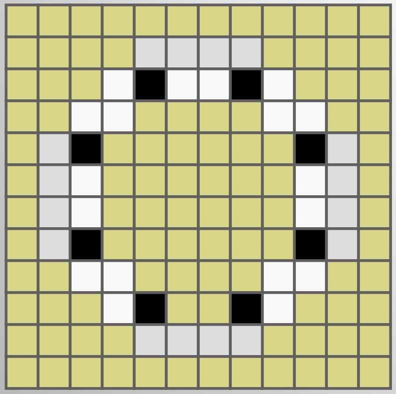


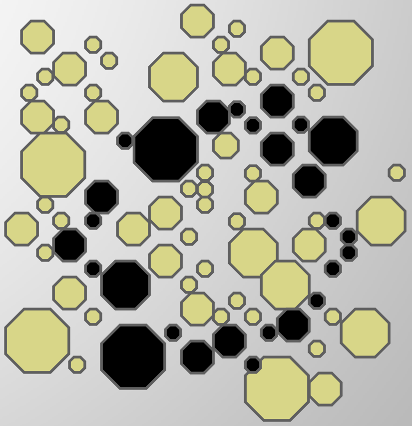
Regular array of pixels
pitch p

Random collection of
different grain sizes



For now film grains smaller than silicon pixels





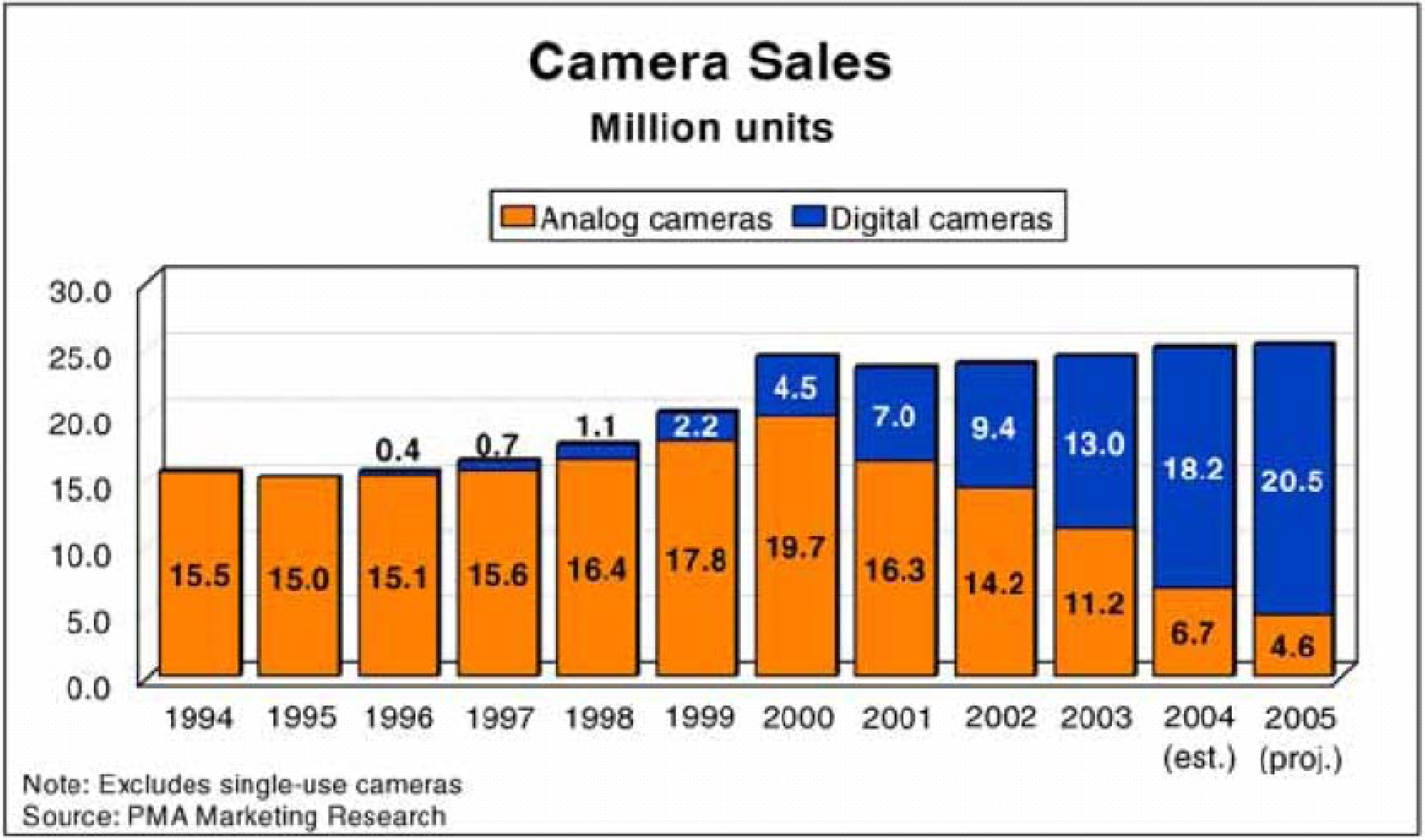
Analog

Digital

Pros and Cons

	Silicon	Film
Processing	Electronic	Chemical
Linearity	“ideal” $n(e^{-}) = QE \times n(\gamma)$	non-linear – $n\ \gamma$ required to flip a grain; thermal fluctuations vs grain size
Resolution	Larger pixels	Smaller grains
Dynamic range	CCDs – 16 bits	Locally, ~4 bits
Integration time	Ultra-high quality process – minutes; opto process – seconds; normal process – ms	“long” (also thermally limited)
MTF	Regular pattern – aliasing	Given by smallest grains, no aliasing
MTF x S/N	Better	Worse

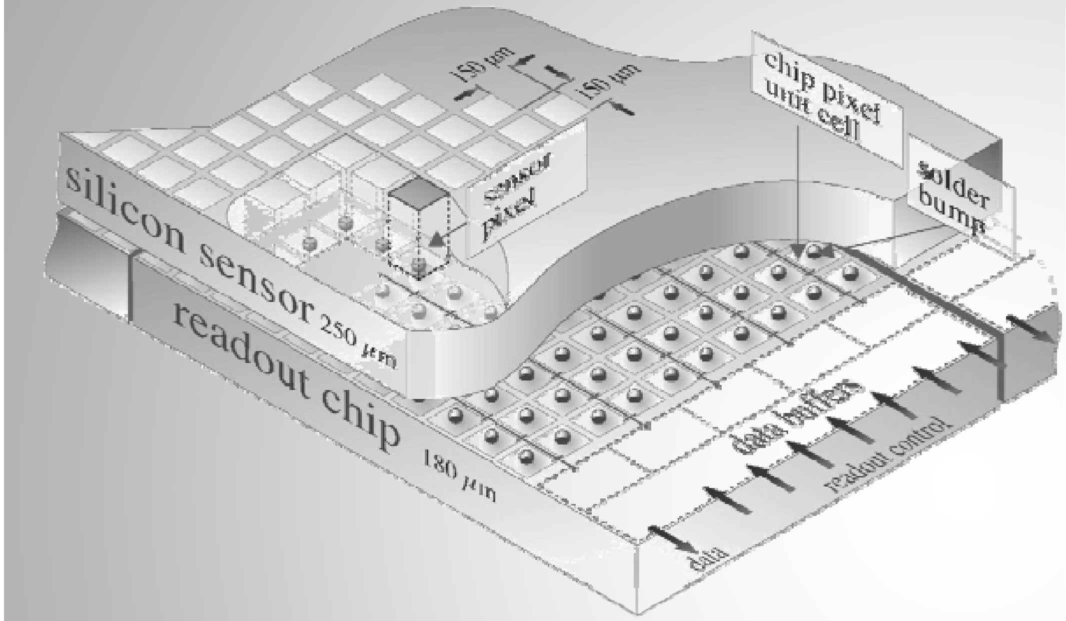
Marketplace has decided



Note: Excludes single-use cameras
Source: PMA Marketing Research

Photo Marketing Association International 2005 Outlook

Hybrid Pixels

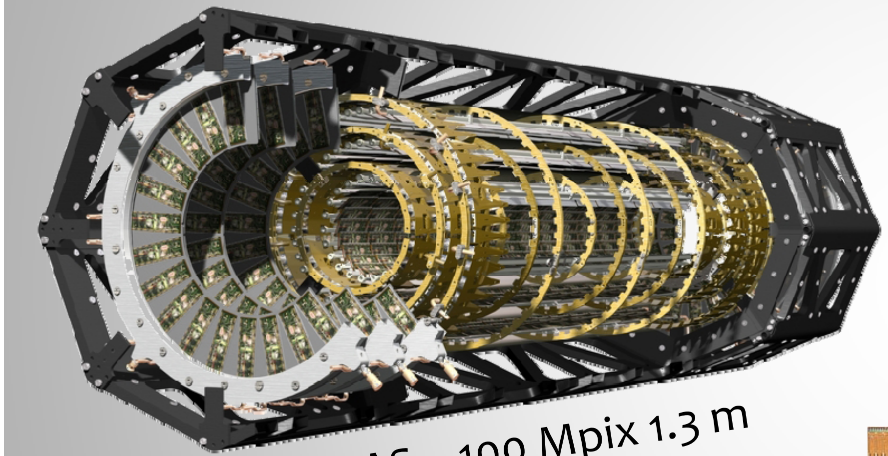


- Thick sensor
- Large pixels (due to bump bonding)
- Bump bonding
- Size limitations (due to IC)
- Lots of electronics in a pixel (large pixel)

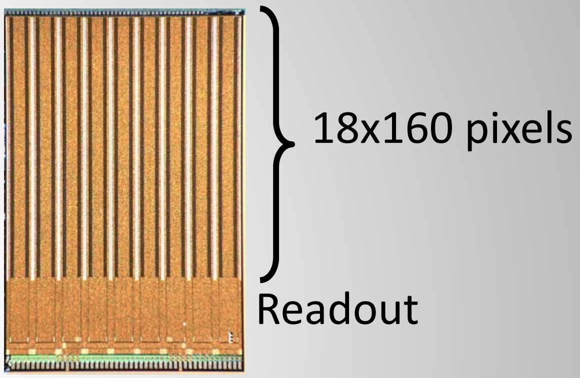
- Pixilated sensor on high-resistivity silicon
  - Fully depleted
    - Fully depleted devices collect charge by drift (little diffusion)
    - Partially depleted devices (APS, many CCDs) collect charge by diffusion
- Bonded to readout IC

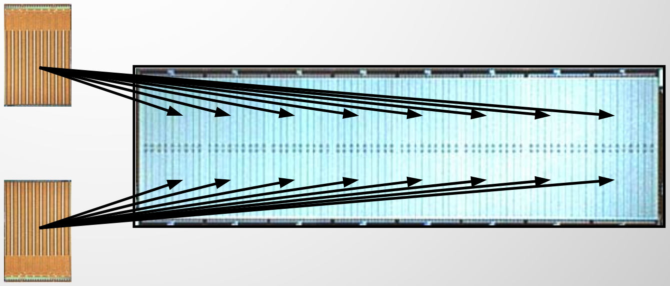
ATLAS pixel

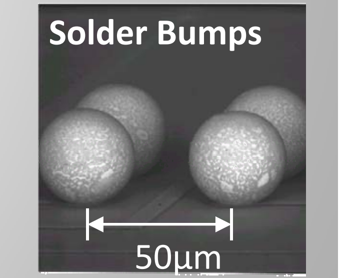
Massive (~$200M) development for Large Hadron Collider at CERN
ATLAS (LBNL and others), CMS (PSI and others)
CERN spinoff → “Medipix”

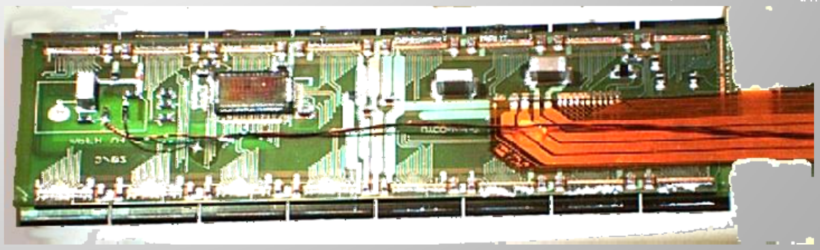


ATLAS – 100 Mpix 1.3 m



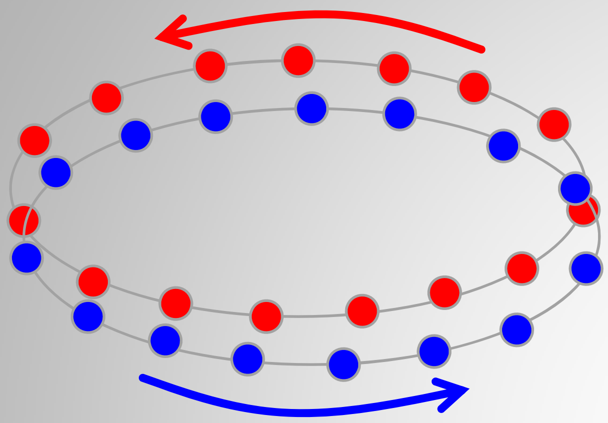






A “module” is 1 sensor with
2x8 bump-bonded chips

Requirements

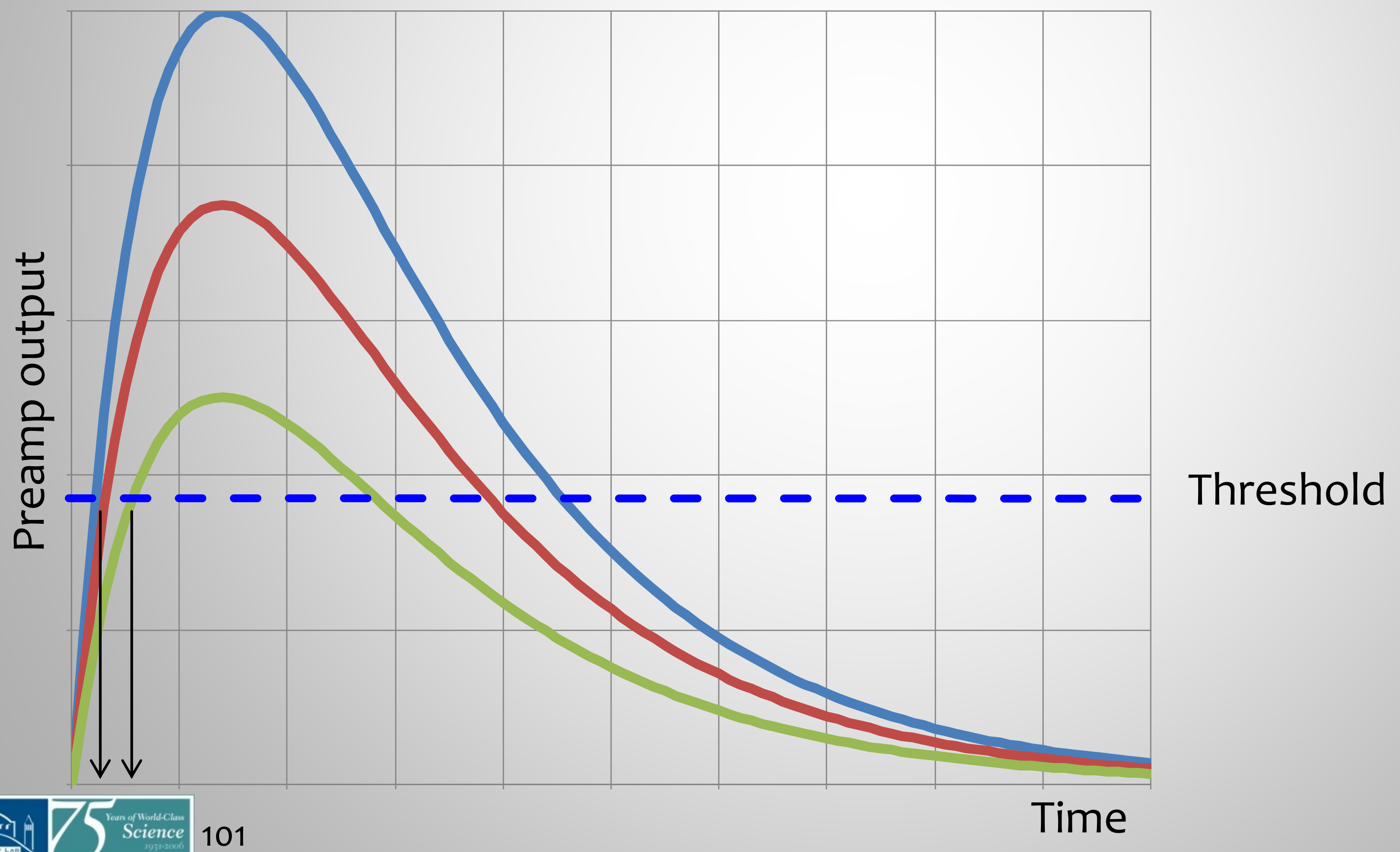


- LHC – counter-rotating proton beams
- Bunch crossings every 25 ns
- Much longer to decide if event from BC_i is interesting

- Detect hits in the pixel
- Tag them to the specific bunch crossing they came from
- Trigger (request to provide data corresponding to BC_i) will come later
  - Provide data for BC_i
  - Flush out other data
- Radiation hardness

Solution

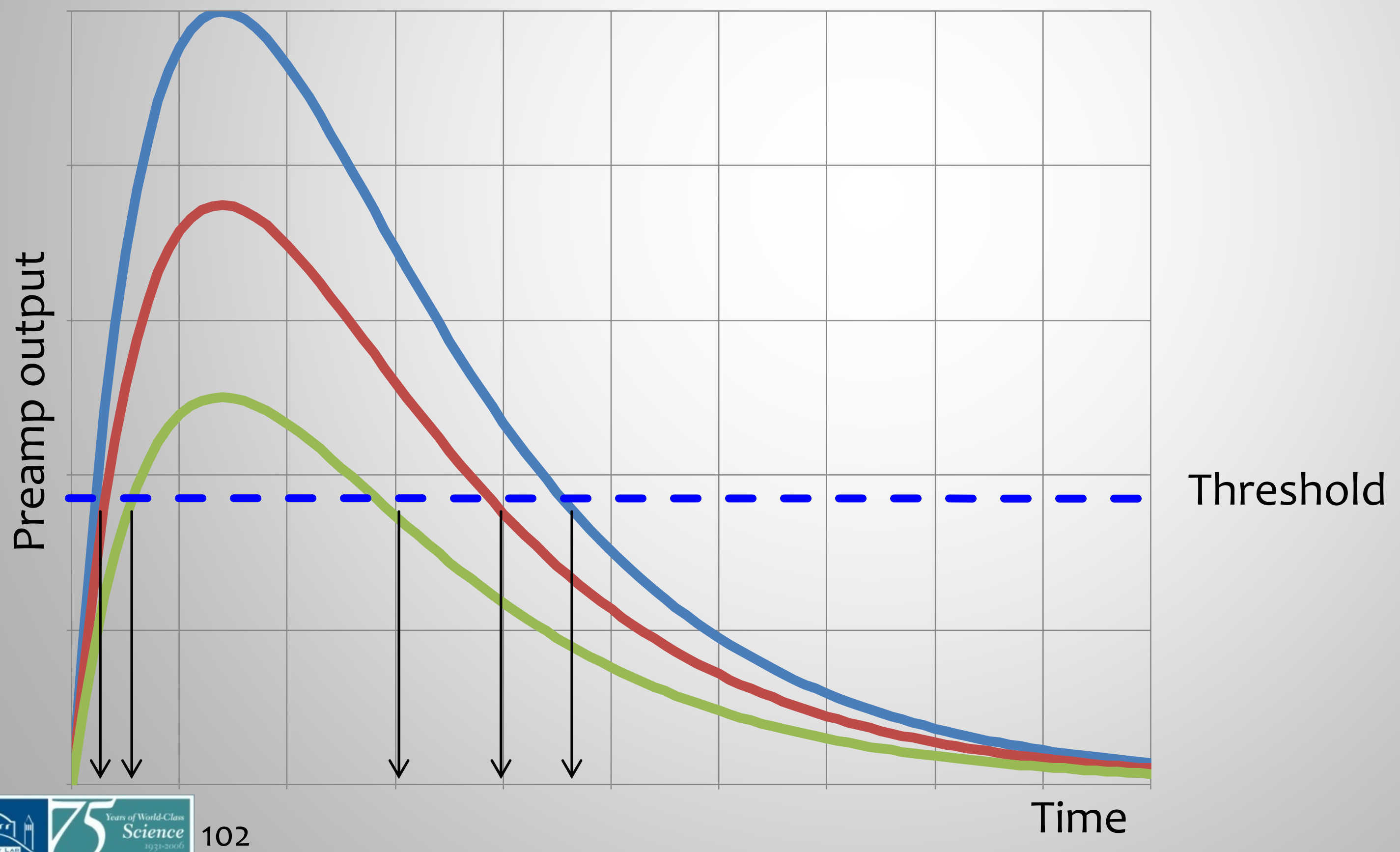
- Folded cascode preamp + comparator
- Linear discharge feedback
  - Noise ~ $BW^{1/2}$ - reduce noise by making preamp slower
  - Introduces "timewalk" problem



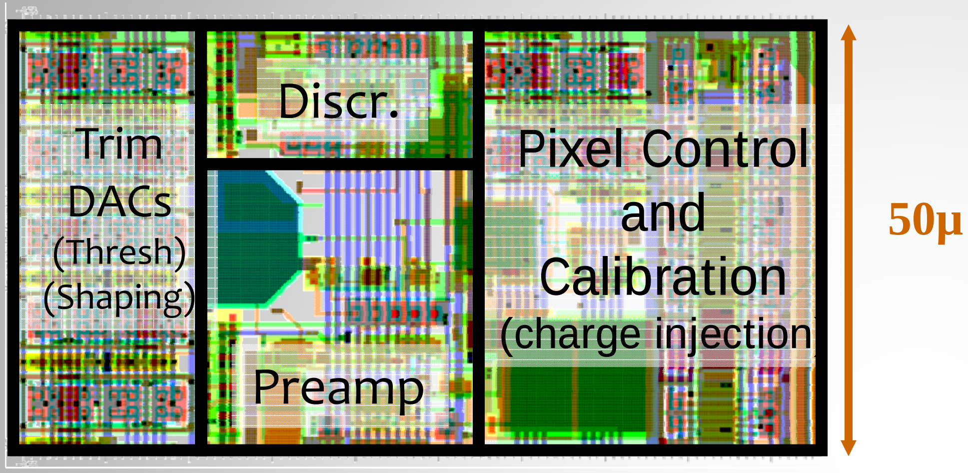
TOT

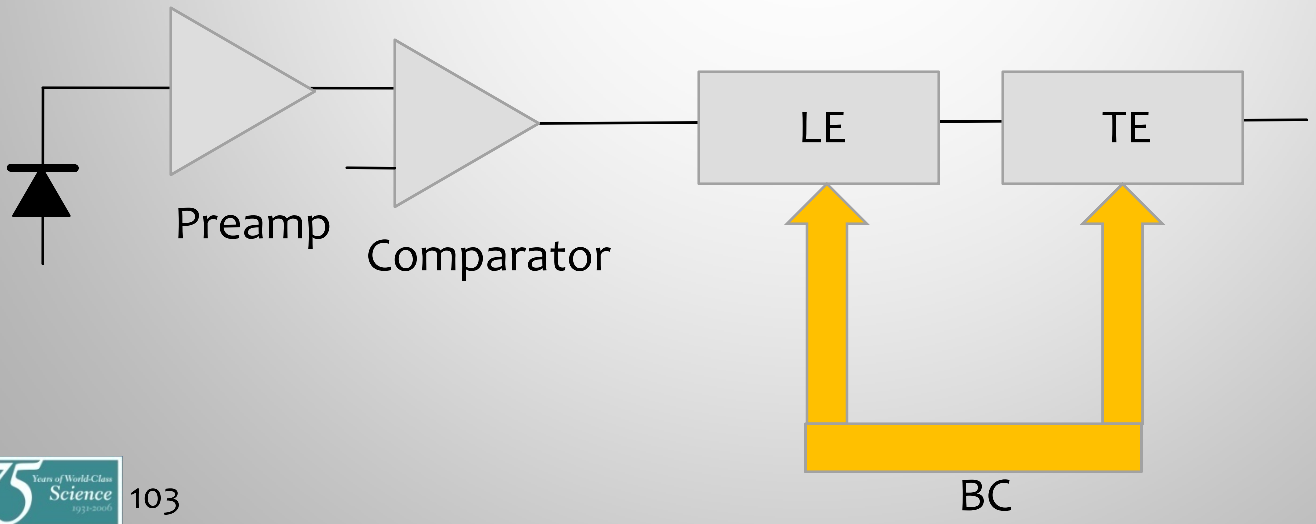
◆ Measuring "time over threshold" measures charge, and can be used to correct timewalk

◆ Variant of Wilkinson ADC

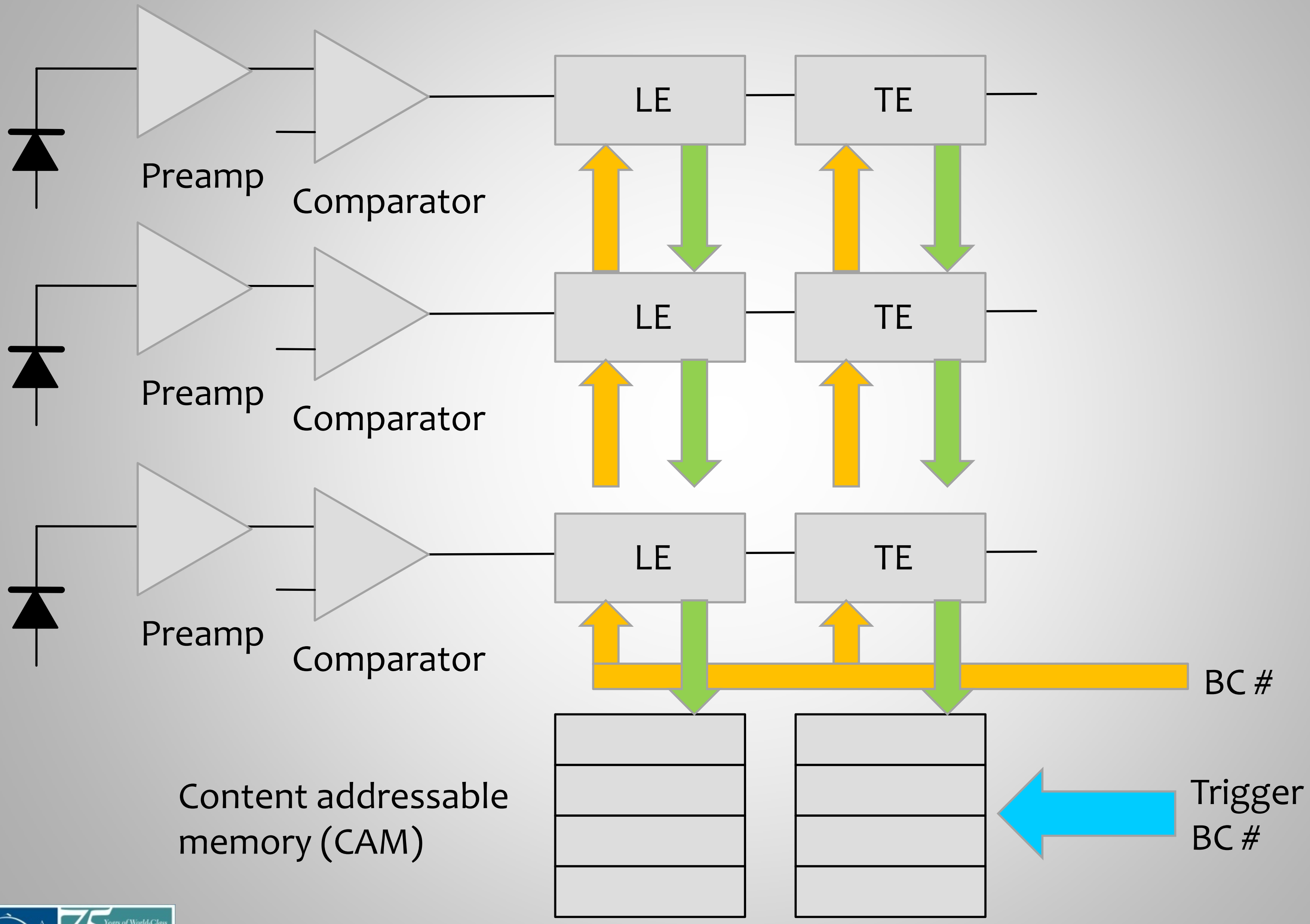


In a pixel

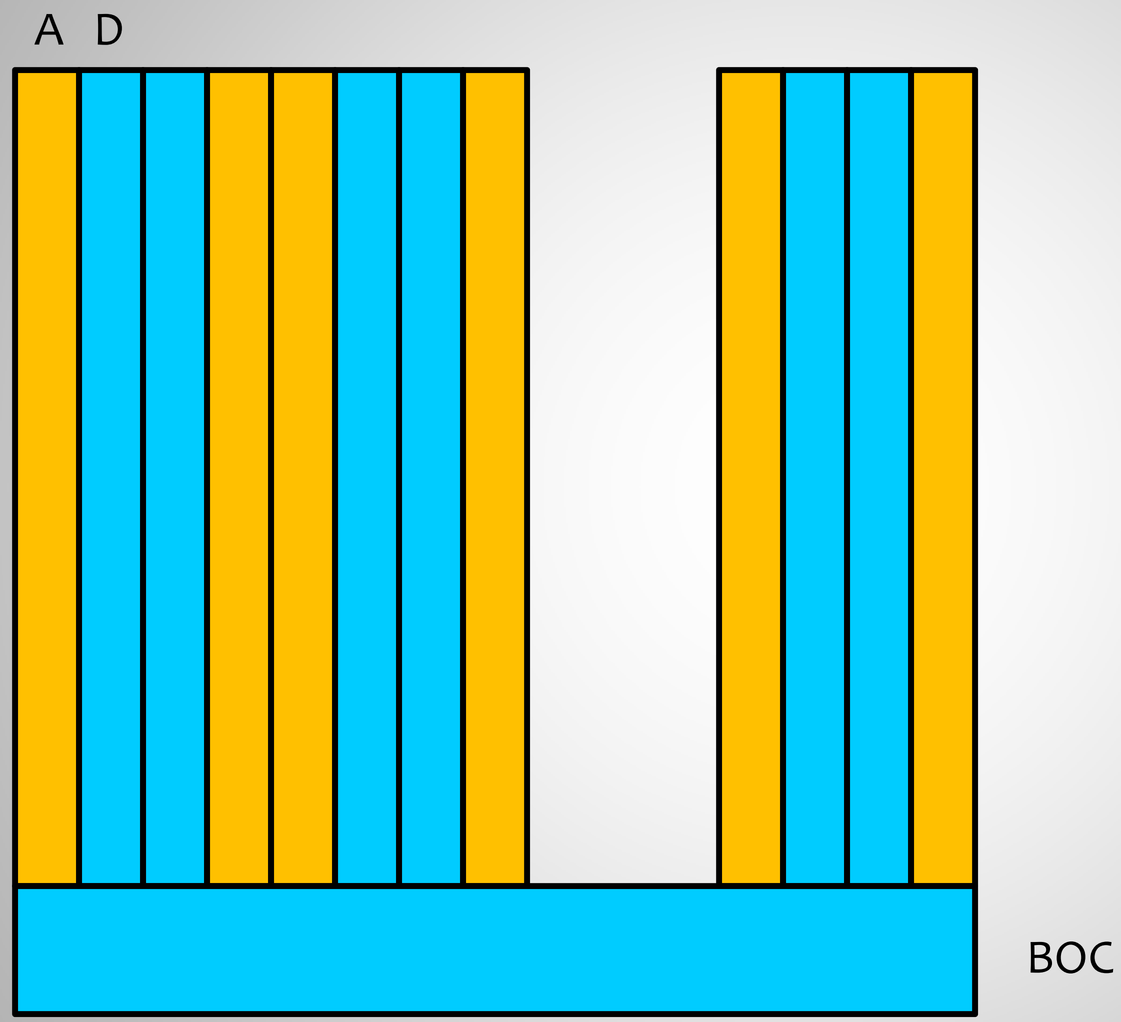

Trim
DACs
(Thresh)
(Shaping)
Discr.
Preamp
Pixel Control
and
Calibration
(charge injection)
50µ


Preamp
Comparator
LE
TE
BC

In a column


Preamp
Comparator
LE
TE
Preamp
Comparator
LE
TE
Preamp
Comparator
LE
TE
BC #
Content addressable memory (CAM)
Trigger BC #

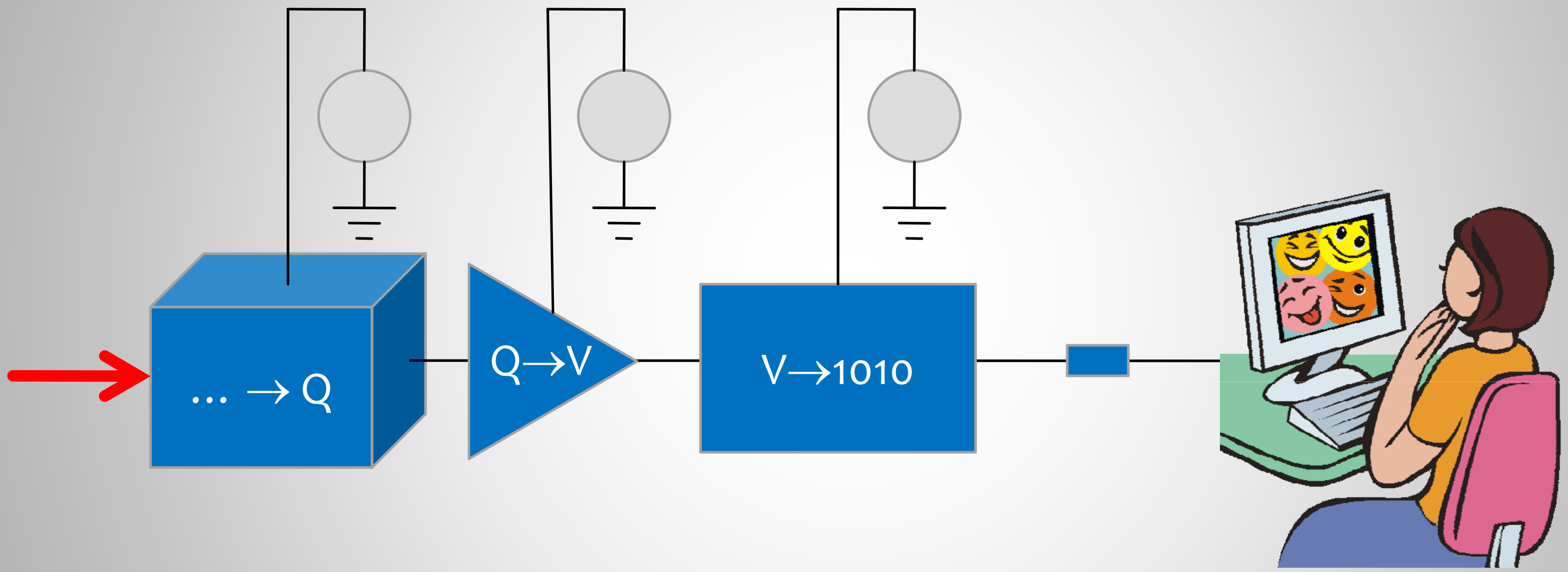
In a chip



"Column pairs"

Caveat Emptor

Helmuth will warn you about the pitfalls



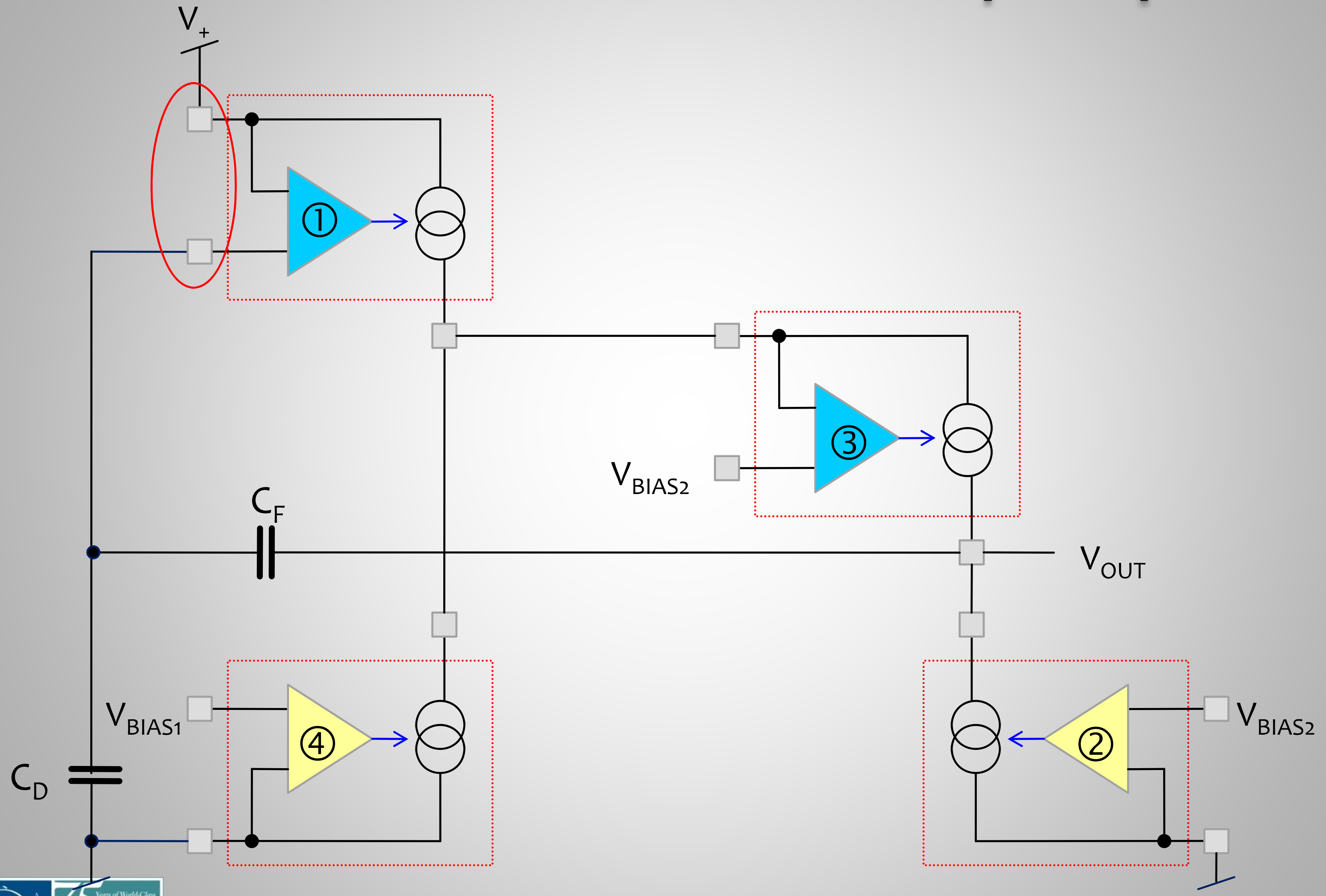
- Analog and Digital blocks
- Analog and digital power (and detector bias)
- Digital communications interface

Not discussed, but significant!

Rule #1 – Follow the current

- 99% of "unexpected problems" are due to
  - V = IR (parasitic resistance, improper grounding, …)
  - dV/dt = I/C (parasitic capacitance)
  - V = L dI/dt (parasitic inductance)
- Mixed-mode systems have digital "spikes" and quiet analog inputs
- Grounding is not "magic"
- Power is ground

PMOS version of folded cascode preamp



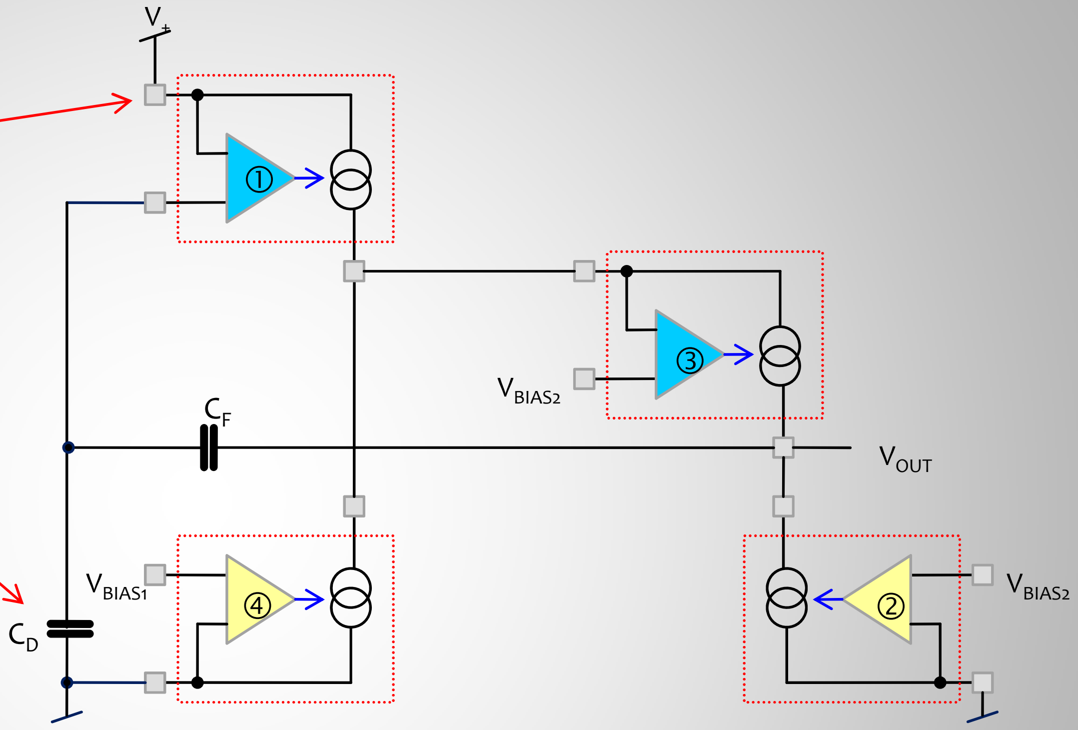
P. Denes IEEE Nuclear Science Symposium 2008 – Front-End Electronics Systems for Particle Detection and Imaging

Follow the current

Two inputs

The power supply

The detector



Power Supply Rejection Ratio $\frac{\partial V_{OUT}}{\partial V_+}$

Front-End Electronics Systems for Particle Detection and Imaging

- Quantize charge
- Electronic detectors *approach* film (but have obvious advantages – particularly speed)
- Practically, each solution is determined by the dE/dx of the particle being looked at
- Electronically, the challenges are noise (e^- from single photons) and dynamic range
  - Ultimately, radiation hardness