ADC and Sensors

ADC, DAC, Sensor interfacing

- ADC
- DAC
- signal conditioning
- Sensors
- Glossary:
  - http://www.maxim-ic.com/app-notes/index.mvp/id/641

ADC: Analog-to-digital converter

- Input:
  - analog signal with a voltage
    e.g., pressure, light intensity,
    temperature, sound
- Output
  - digital value representing the voltage
  - 8-bit, 10-bit, 12-bit, 16-bit, 24-bit etc
    depends on the specific ADC's precision

Purposes of ADC

- Digitize a signal
  - The world is analog; computer is digital
    => bridge the real world & computer
- Benefits
  - no more <u>noise</u> due to processing
  - can be stored/retrieved like any data
  - separate timing handling from processing

Types of ADCs

- Integrating ADC (not very fast)
  - outputs pulses, freq. proportional to V
- Successive Approximation ADC (common)
  - "binary search"
- Flash ADCs aka parallel ADCs
  - parallel comparison; fast but expensive

Bit resolution and sampling rate

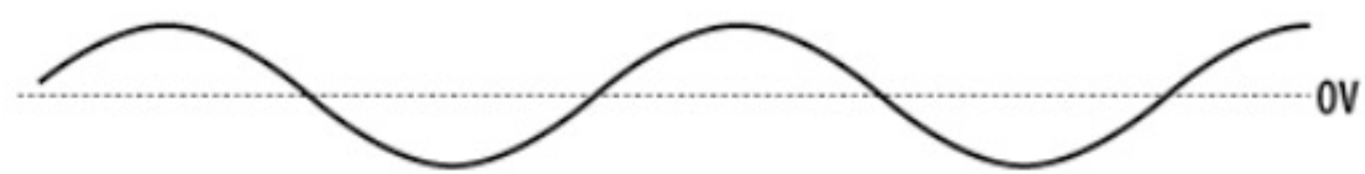
- n bits => 2^n levels
  - 8 bits: 256 gives 0.39° res. for 0-100°C => "jumping" problem if ±0.5° is needed!
- Sampling rate
  - should be ≥2x higher than signal's highest freq. component (Nyquist freq)
  - otherwise, get aliasing problem

Analog, sinusoidal signals

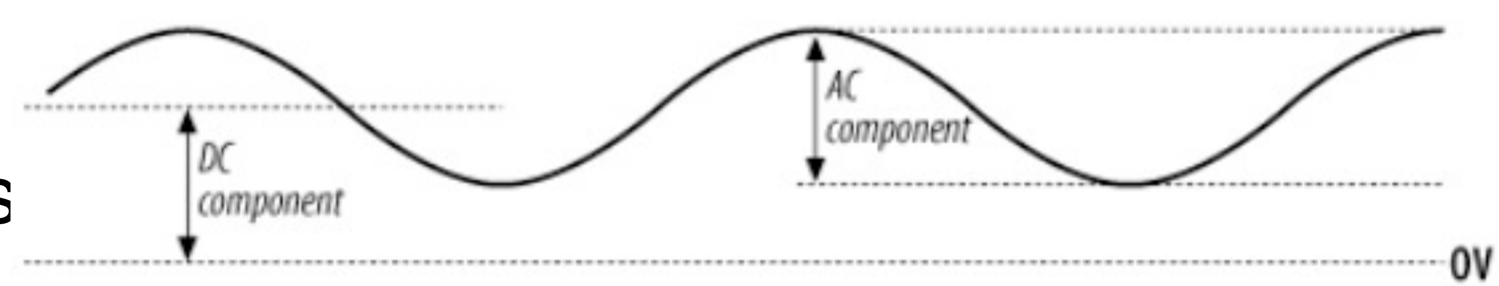
- Alternating current (AC)

- Unipolar => either positive or negative, not both

- Bipolar => both positive and negative

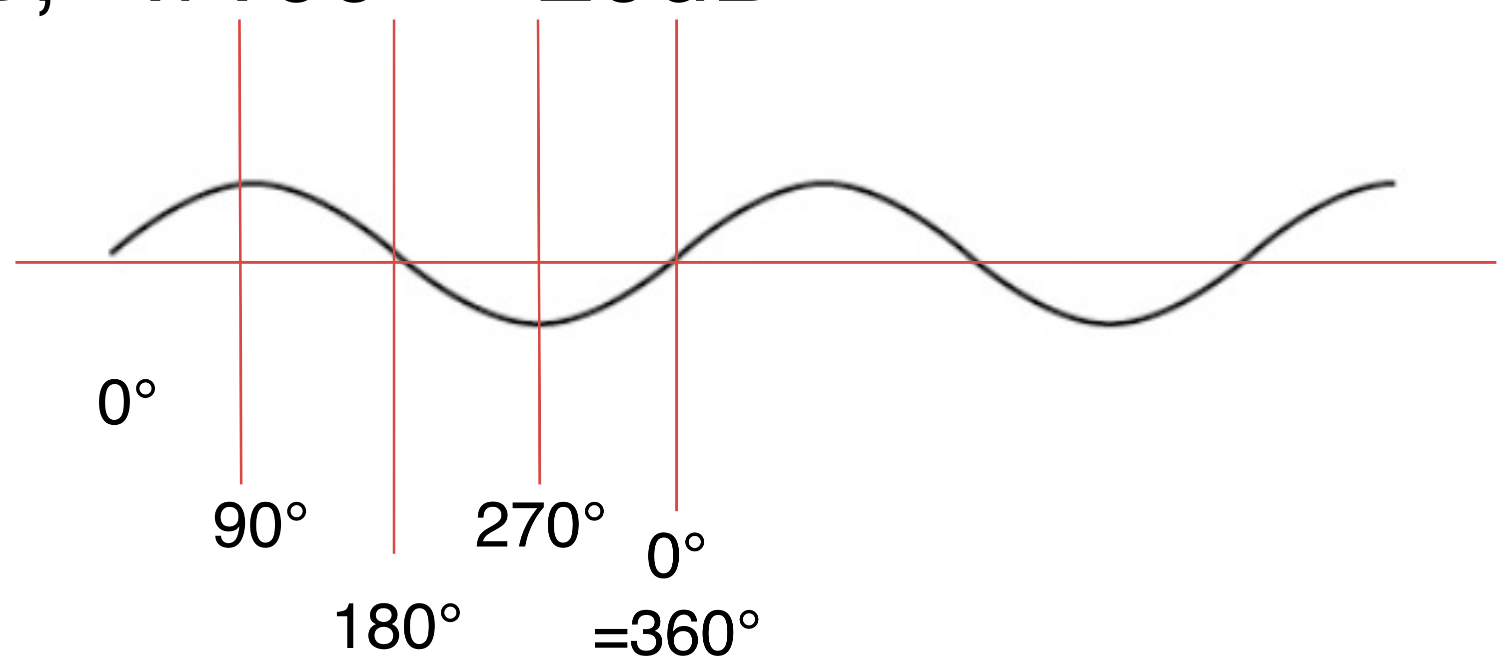


- Decompose into AC and DC components



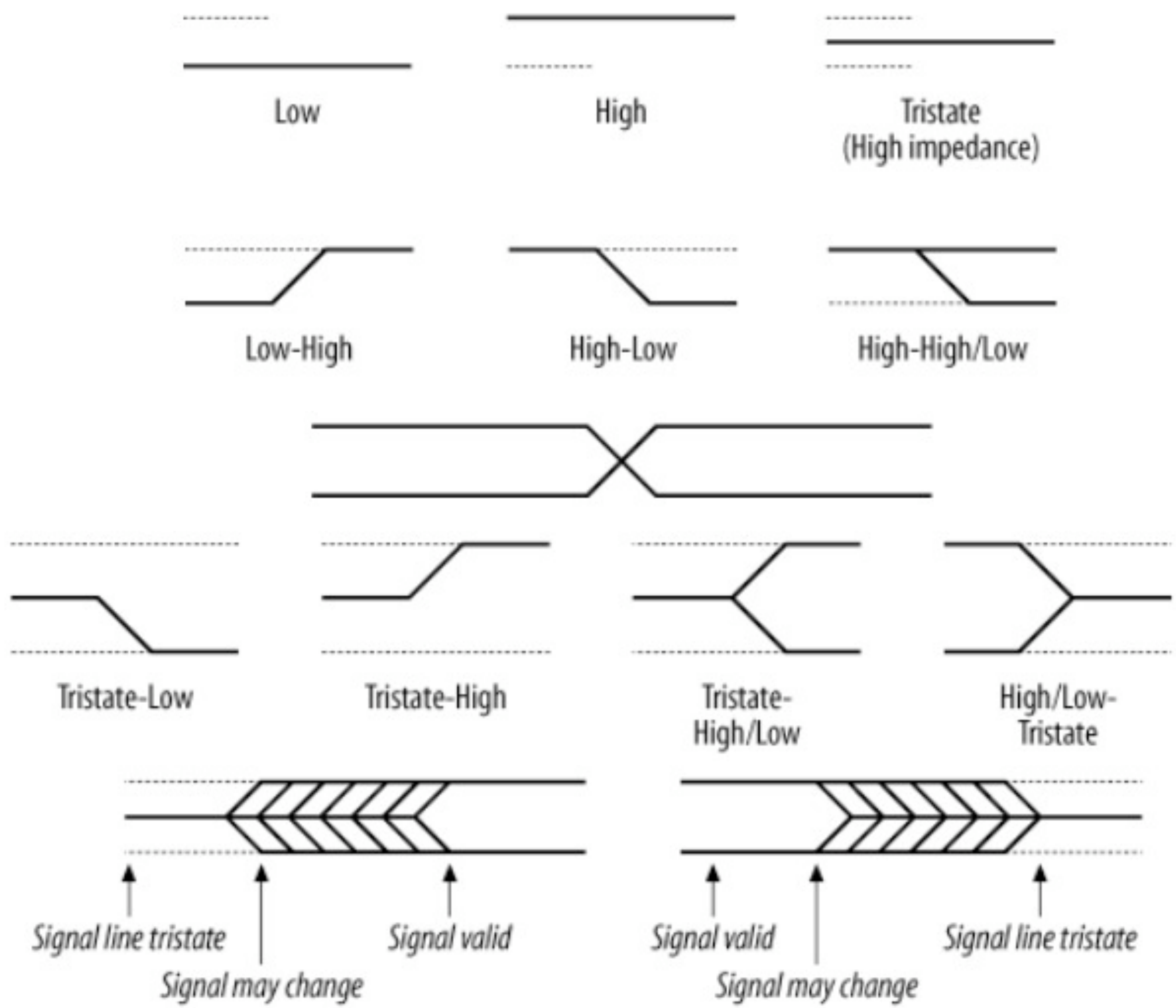
Amplitude and phase of periodic signals

- Amplitude:
  Amplify, attenuate. Unit: dB = 10 * $\log_{10}$ dif
  - 1x = 0dB, 10x = 10dB, 100x = 20dB,
    1000x = 30dB
    1/10 = -10dB, -1/100 = -20dB
- Phase
  - Degrees



Timing diagram convention

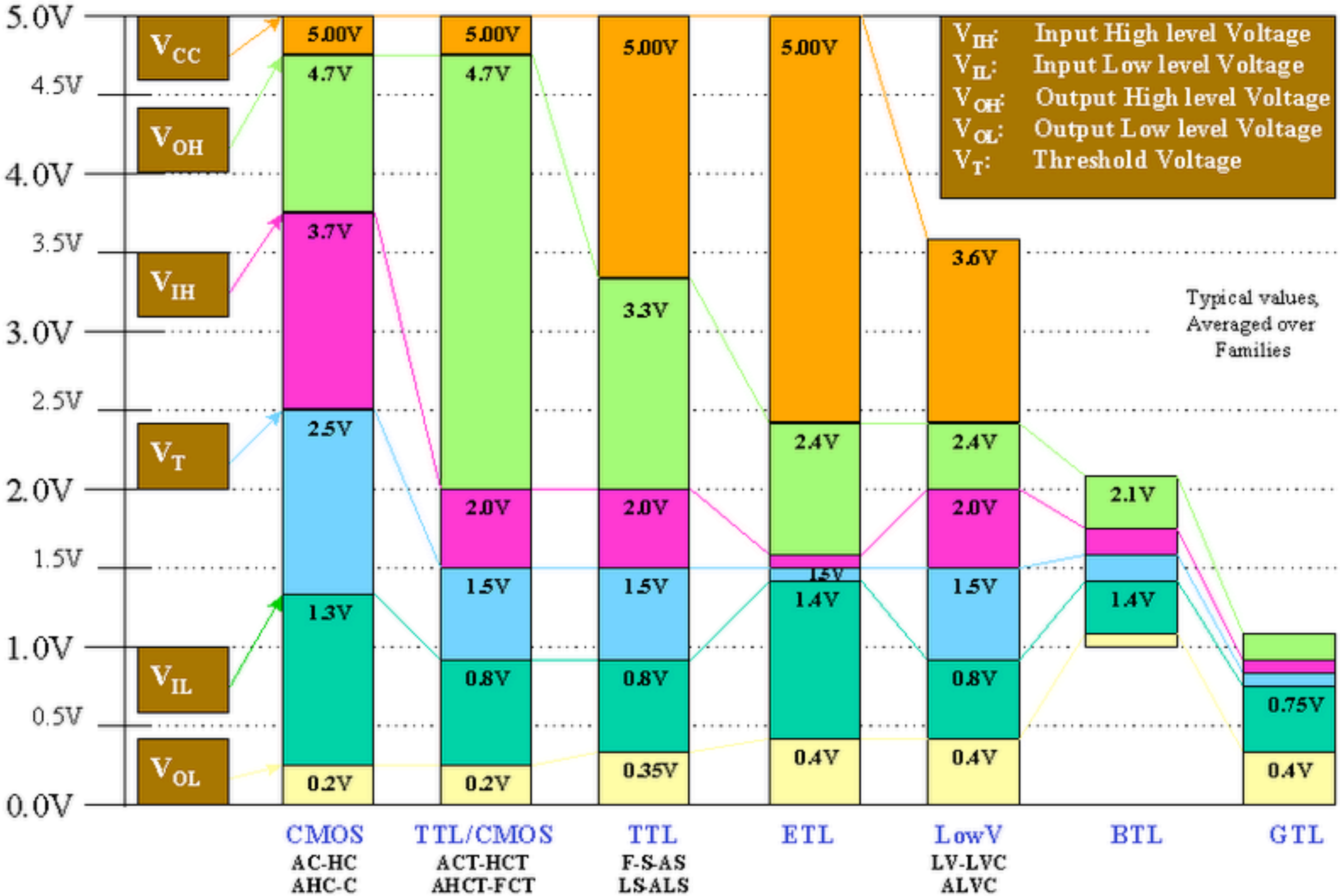
- Logic levels
- Transitions
  - known values
  - combination
- w/ Tristates
- valid period



Digital logic

- Interpret a voltage as a binary value
  - above a threshold => '1'
  - below a threshold => '0'
- Threshold is technology dependent!
  - Check data sheet to be sure
  - TTL, CMOS, ...

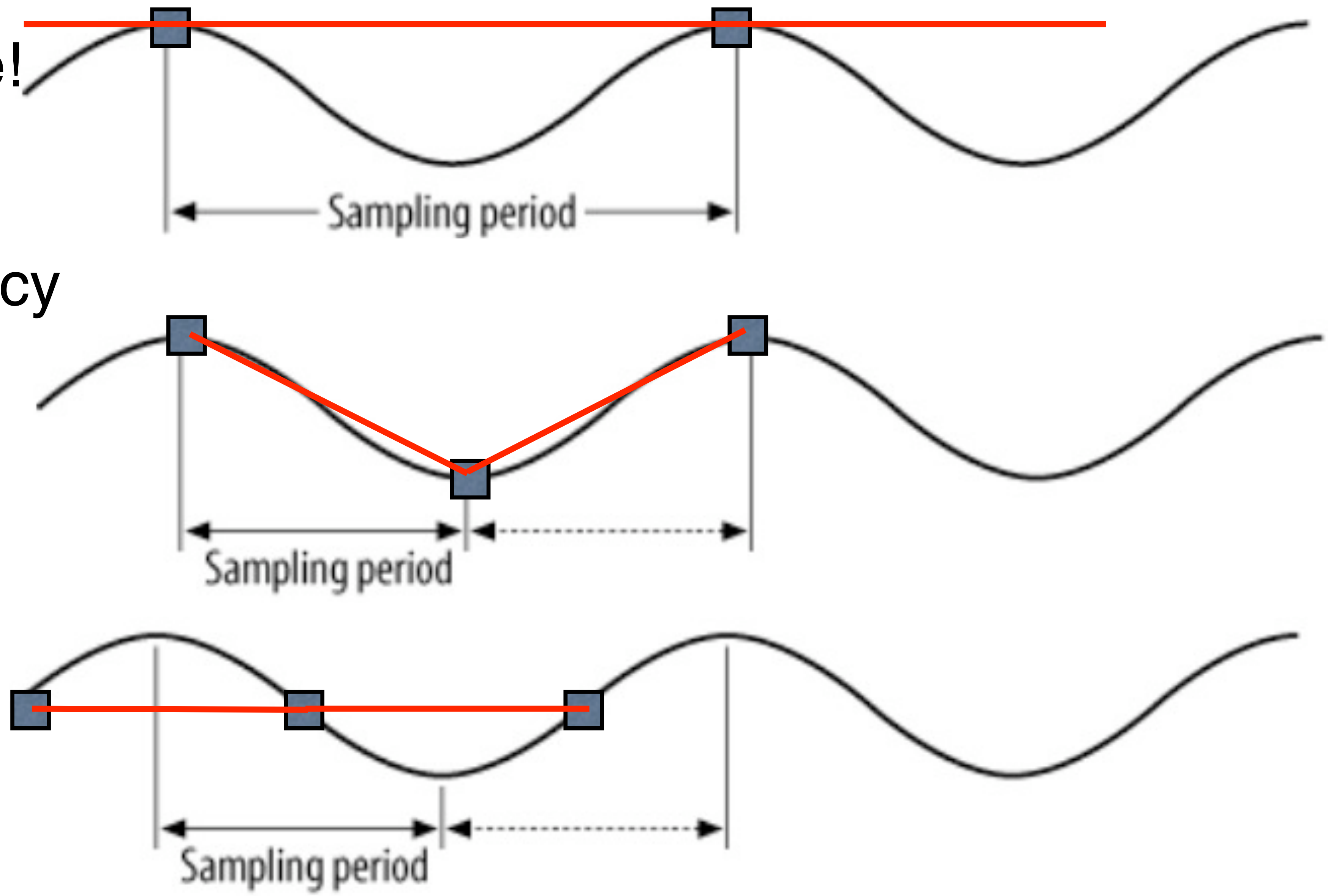
Voltage Thresholds



Credit: http://www.interfacebus.com/voltage_threshold.html

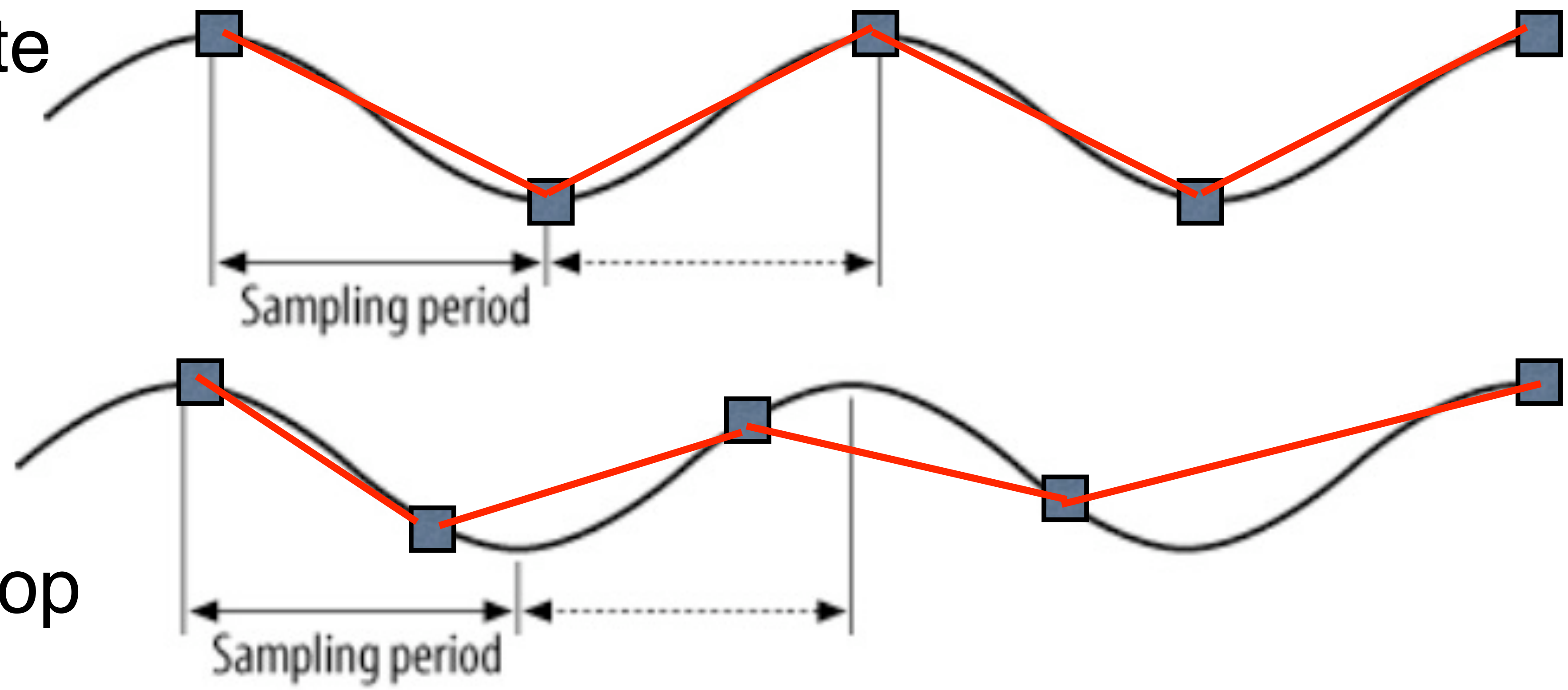
Sampling rate

- Too low:
  looks like
  a straight line!
- Minimum
  2x of frequency
- Still not sure
  if you hit the
  peak!
  still could be
  straight line



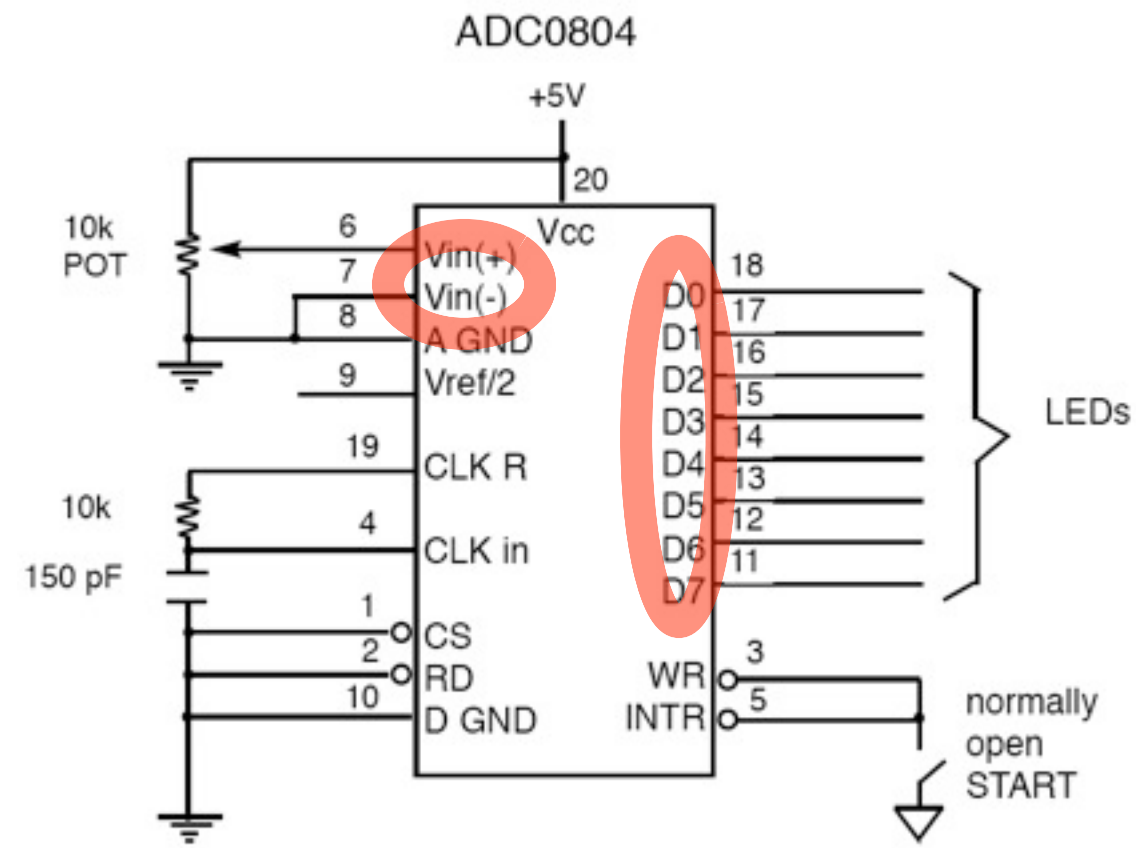
Jitter

- Unstable rate
- wrong reading
- Solution: hardware loop



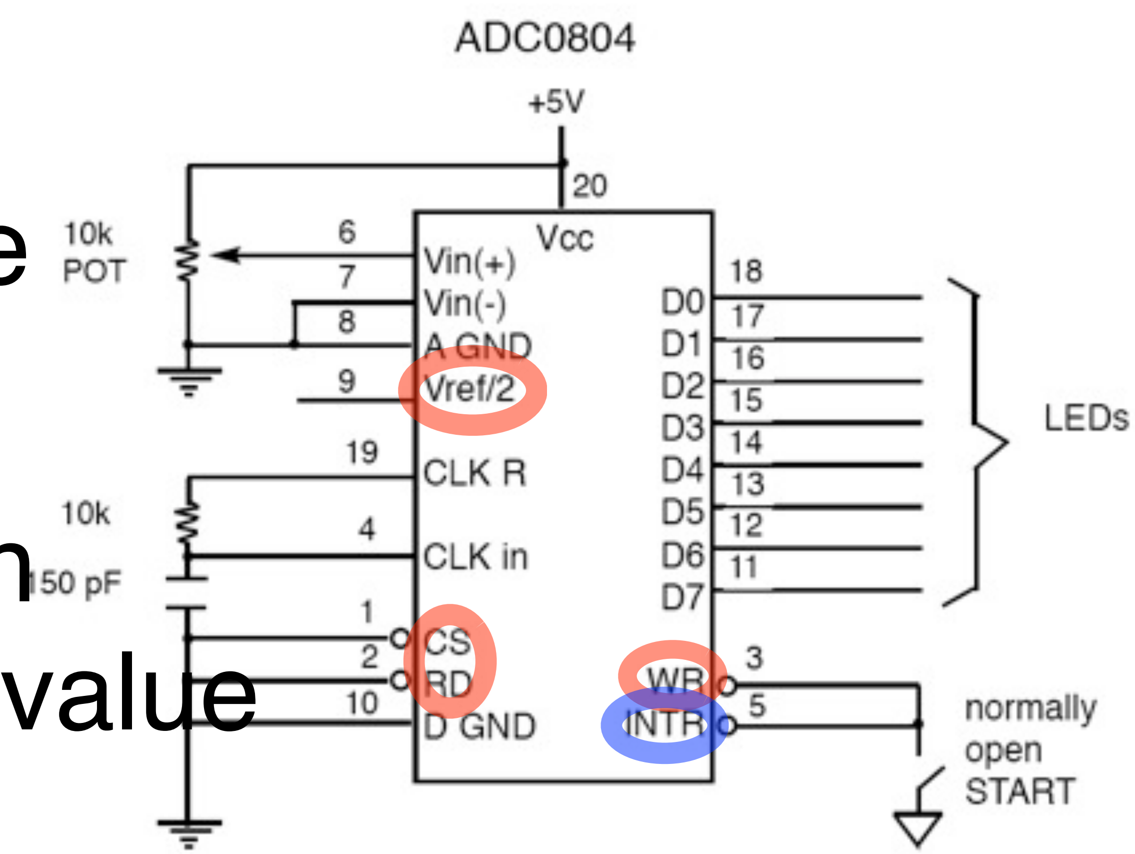
Example: ADC0804 (National Semicond.)

- input signals
  - single ended Vin(+) vs. differential pair Vin(+)(-)
- output signal
  - 8-bit value representing voltage

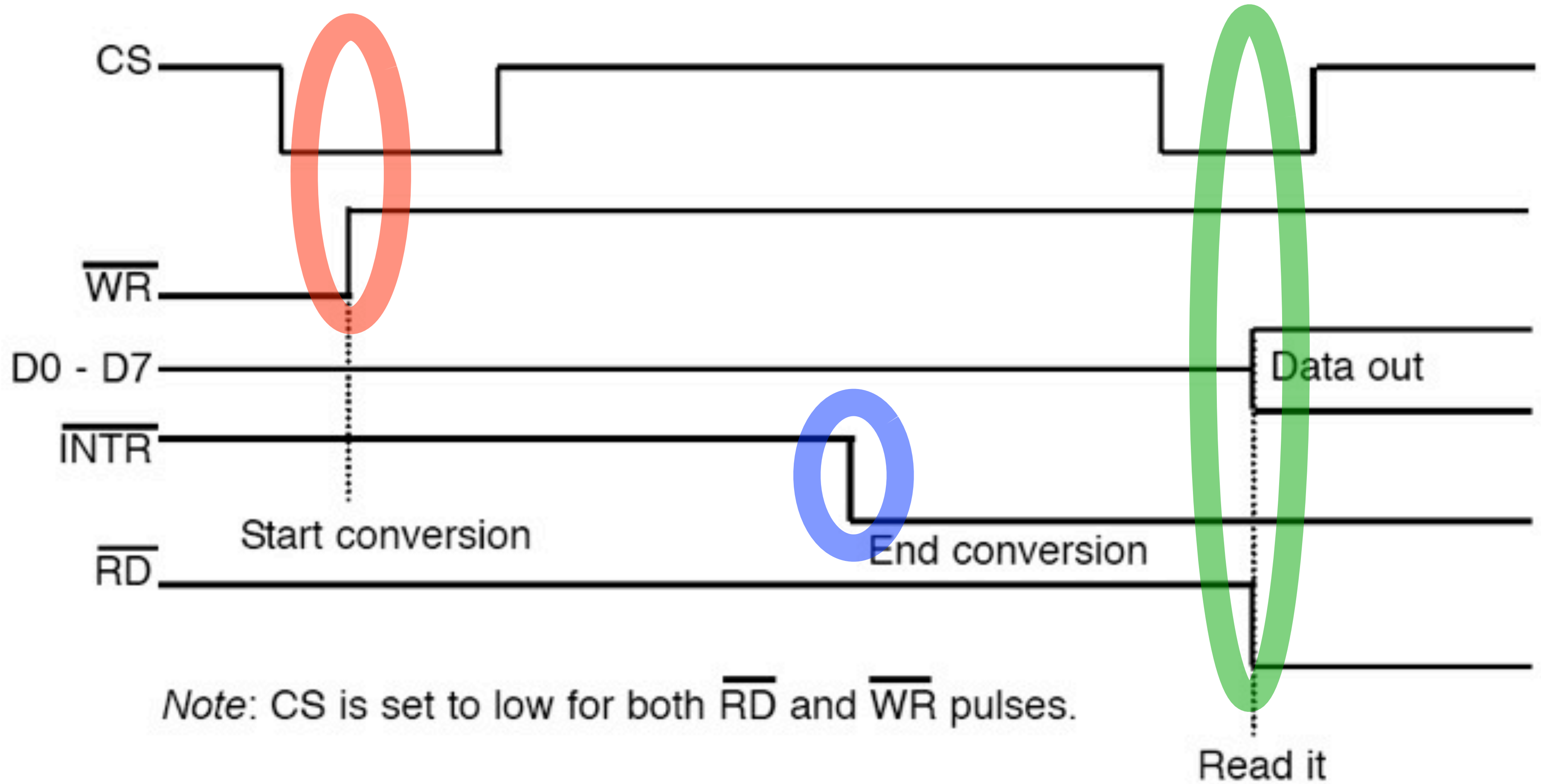


Example: ADC0804 (National Semicond.)

- Input control:
  - $V_{ref}/2$ to set the range
  - /CS: chip select
/WR: start conversion
/RD: read converted value
- Output control:
  - /INTR: interrupt line
indicating end-of-conversion



Timing Diagram for ADC transaction



1. rising /WR during /CS

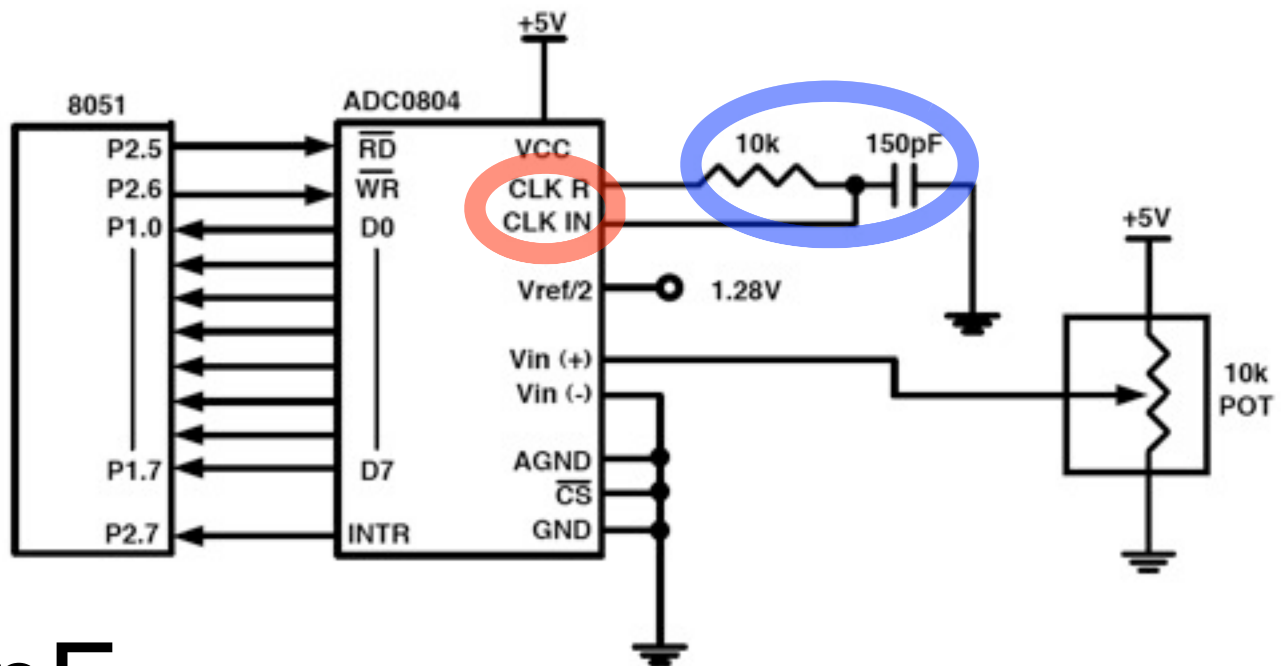
2. ADC finishes conversion

3. assert /RD during /CS

Could also assert /CS the whole time w/out pulsing!

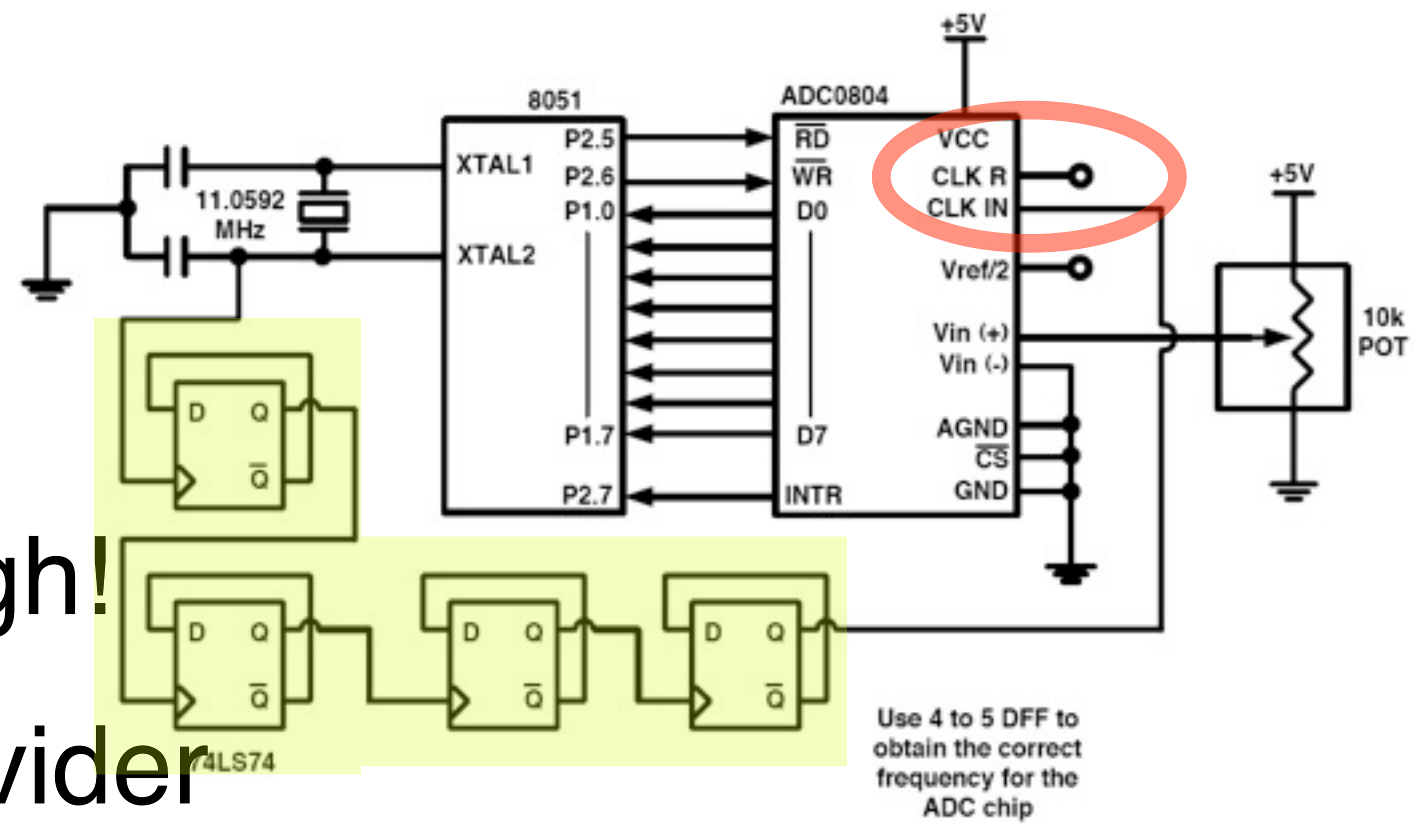
CLK IN and CLK R

- Opt. 1: internal clock
  - Set the R, C value
    $f = 1/(1.1\ RC)$
  - R = 10KΩ, C = 150pF
    $f = 1/(1.1 * 10^4 * 150 * 10^{-12})$
    = 606060.6 => 606KHz,
    or 1.65μs cycle time
- Option 2: external clock

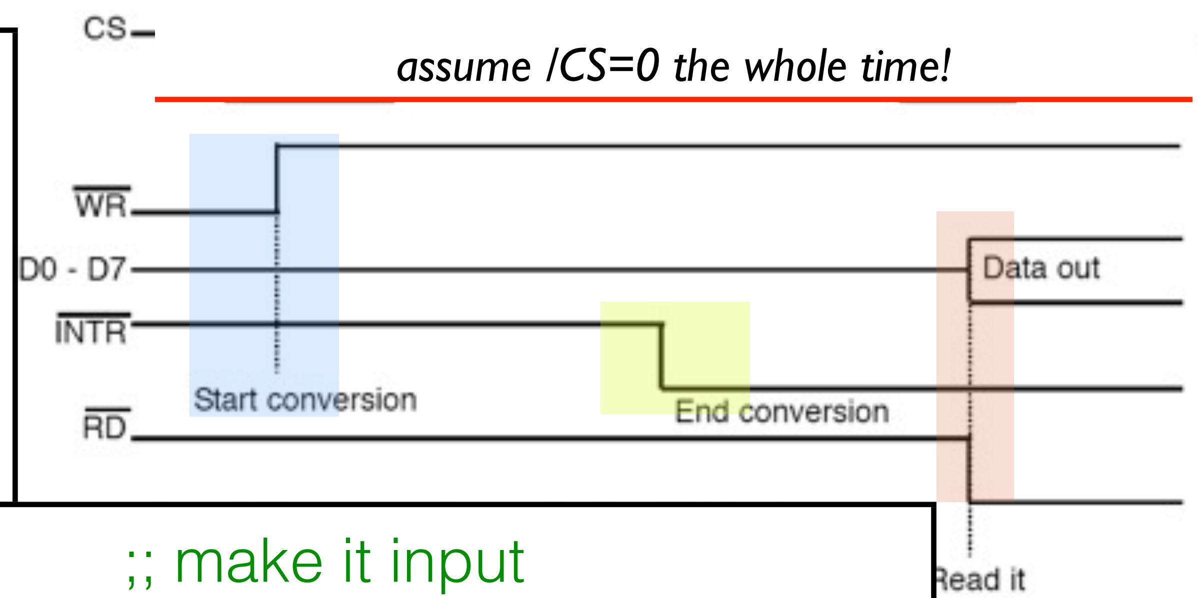


External clocking scheme for ADC0804

- Could use the same crystal as for 8051
- Issue: freq too high!
- Solution: clock divider
  - cascaded D-flipflops:
    next one is clocked by the prev's Q,
    each feeds /Q to its own D



Assembly for ADC0804



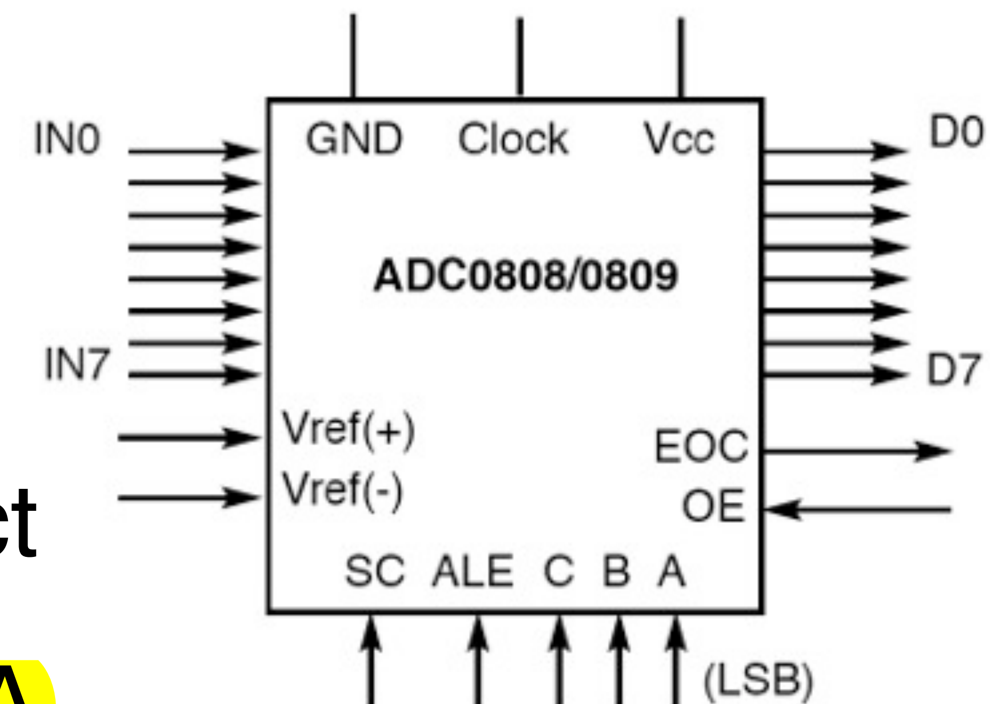

```
RD      BIT     P2.5
WR      BIT     P2.6
INTR    BIT     P2.7
MYDATA  EQU     P1

        SETB    INTR            ;; make it input
BACK:   CLR     WR              ;; pulse WR by lowering first
        SETB    WR              ;; conv starts on rising edge
HERE:   JB      INTR, HERE      ;; poll for /INTR to go low
        CLR     RD              ;; assert output enable
        MOV     A, MYDATA       ;; read conv value from port
        ACALL   CONVERSION      ;; Chap.6 routine to ASCII
        ACALL   DATA_DISPLAY    ;; Chap. 12 routine to display
        SETB    RD              ;; de-assert output enable
        SJMP    BACK            ;; do it again
```

ADC0808/0809: multi-(analog)-channel

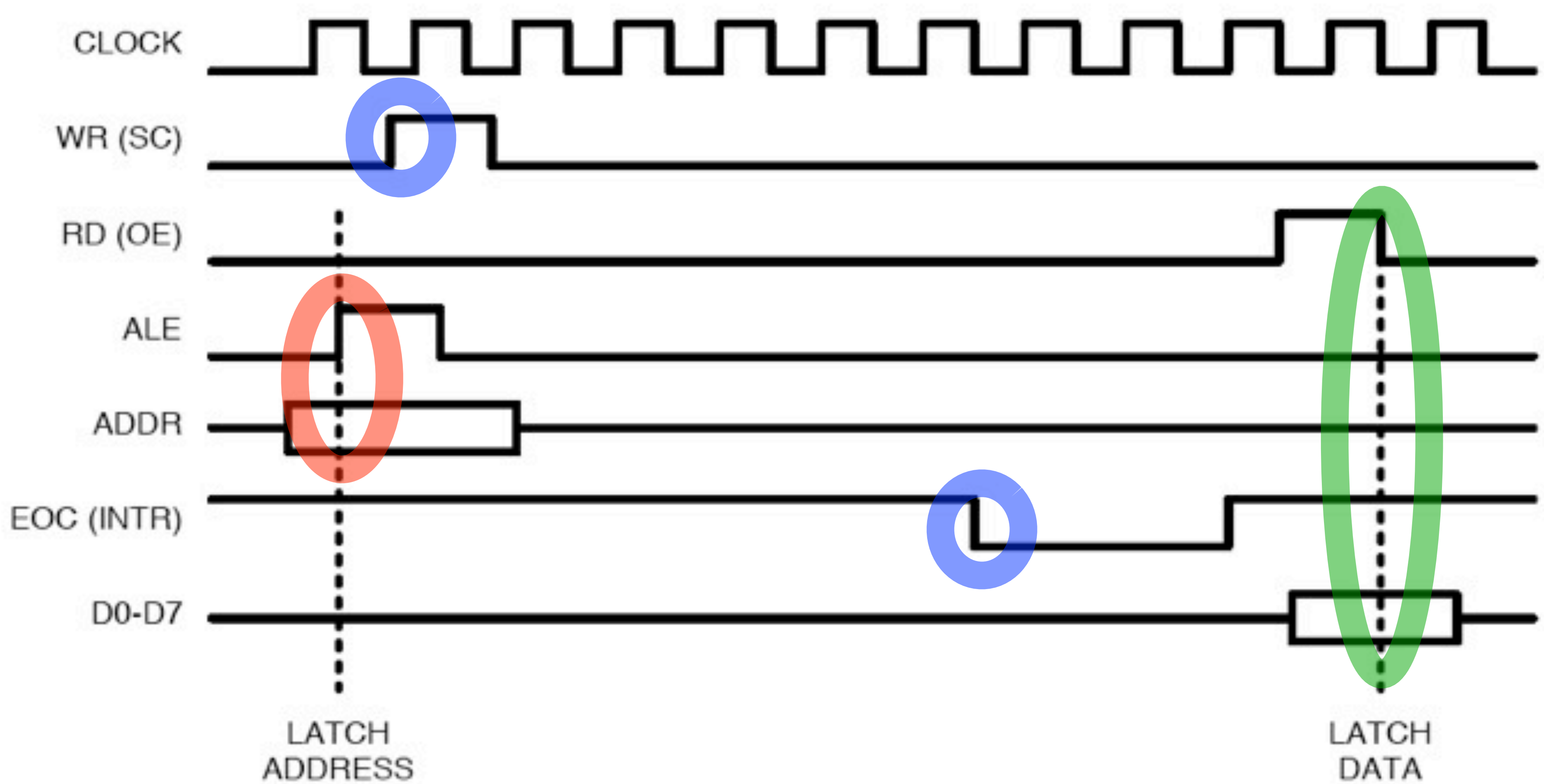
- 8 analog input lines
  - Selected by 3-bit, internally share 1 ADC
  - Conceptually, analog multiplexor on input
  - ALE latches the address
- 8-bit output port
  - similar to the single-channel ADC

Pin interface on ADC0808/0809

- IN0..IN7: analog input channels
- SC, EOC: (=WR, INTR)
  start conv, end-of-conv
- OE: (=RD) output enable
- C B A : 3-bit channel select
- ALE: clock for latching CBA
- $V_{ref}(+)$, $V_{ref}(-)$: max and "gnd"



Timing Diagram for the ADC0809



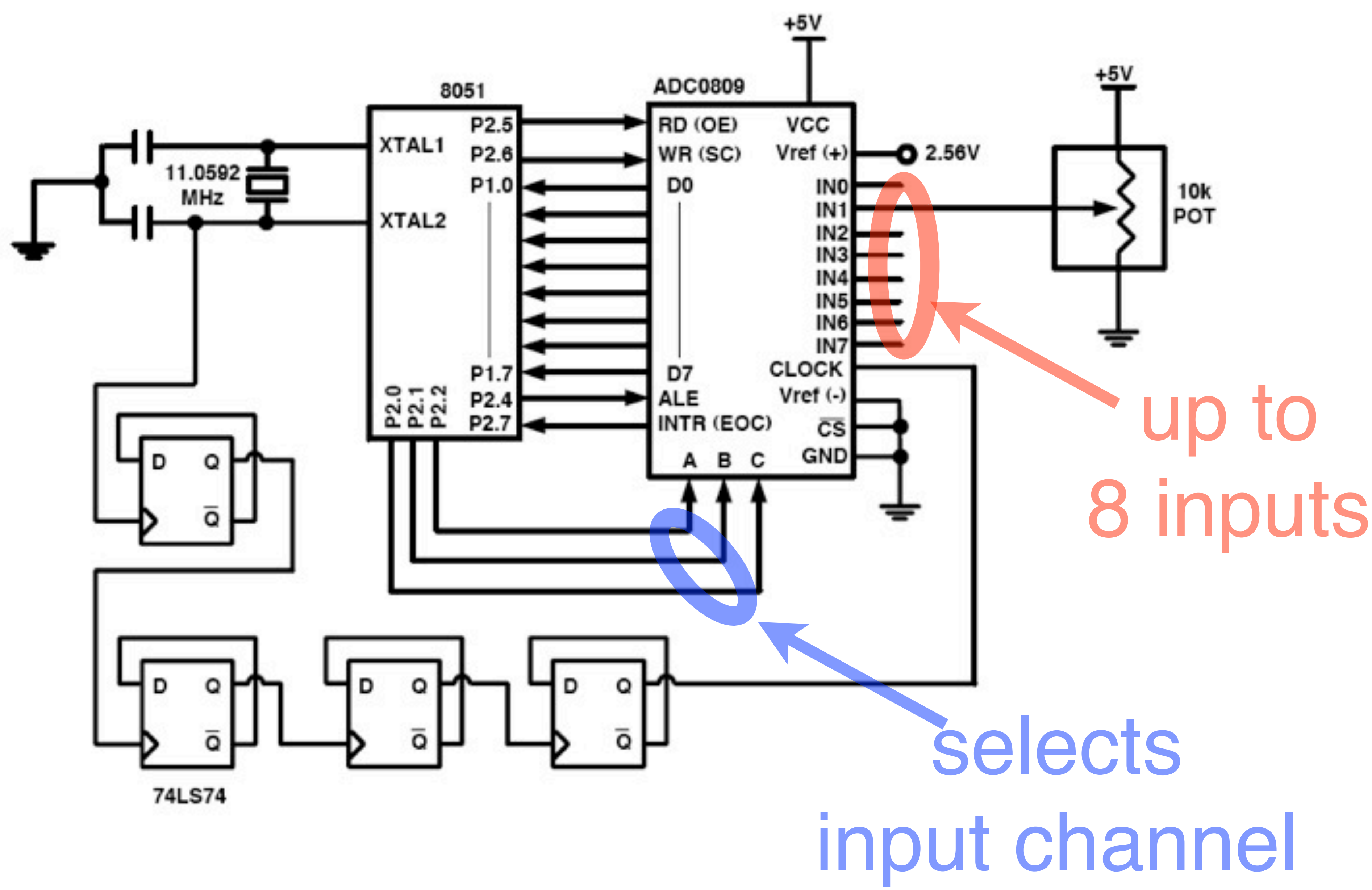
1. set ADDR, pulse ALE

2. pulse SC, wait for EOC

3. read data during OE

ADDR is formed by C B A

Schematic for 8051 connected to ADC0809



Reference voltages

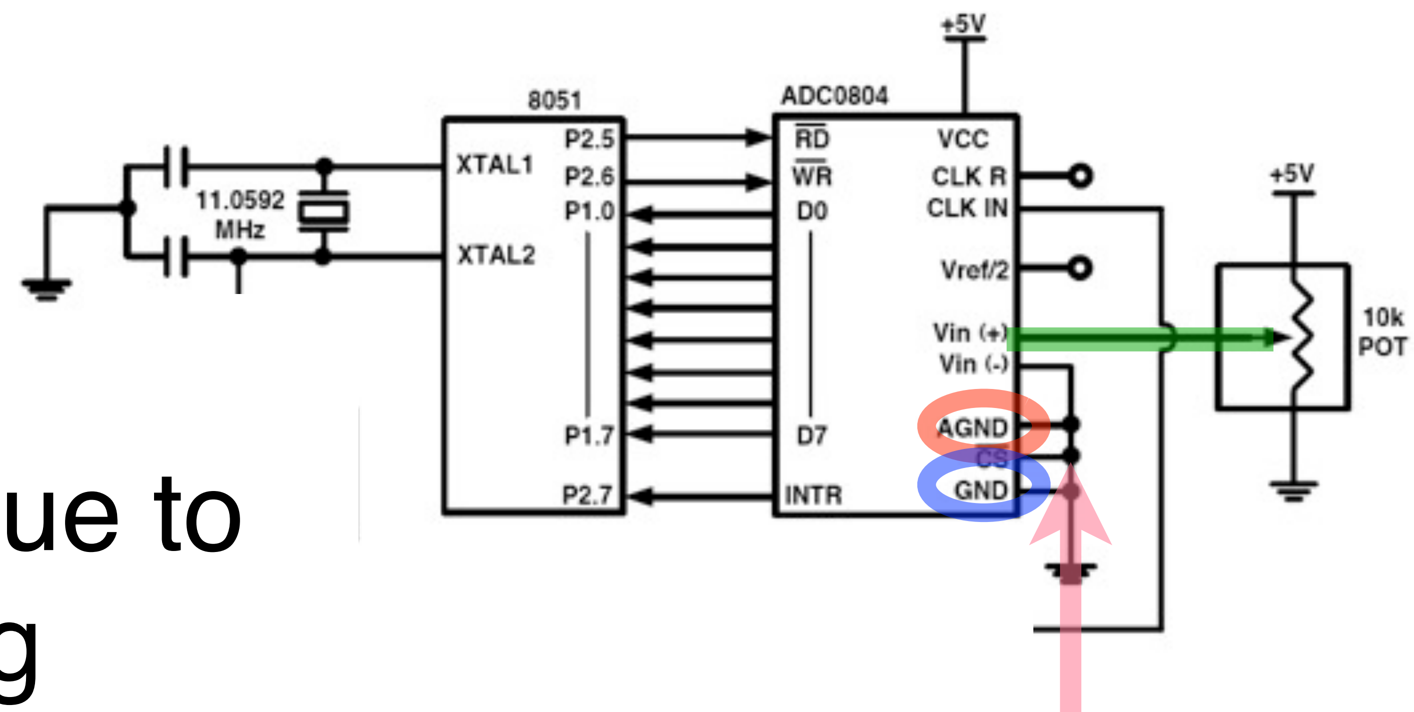
- $V_{ref}/2$ (*e.g., ADC0804*): half the max voltage
  e.g., $V_{ref}/2=2.5V$ => max voltage = 5.0V
  => each step is $5.0V / 2^8 = 19.53mV$
    - Assumes same GND as signal source
- $V_{ref}(+)$, $V_{ref}(-)$ differential pair (*e.g., ADC0808/9*)
    - $V_{ref}(-)$ serves as GND for signal source
      possible to tie $V_{ref}(-)$ to same GND
    - voltage step = $(V_{ref}(+)-V_{ref}(-)) / 2^8$

Single-ended vs Differential Pair input

- Single ended: relative to (common) GND
  - Problem: ground noise, ~10mV
- Differential pair: $V_{in}(+)$, $V_{in}(-)$
  - Advantages: no ground noise, also "common mode noise rejection"
- More info: http://www.eettaiwan.com/ARTICLES/2002MAR/PDF/2002MAR01_AMD_DSP_AN53.PDF

Digital vs Analog Ground

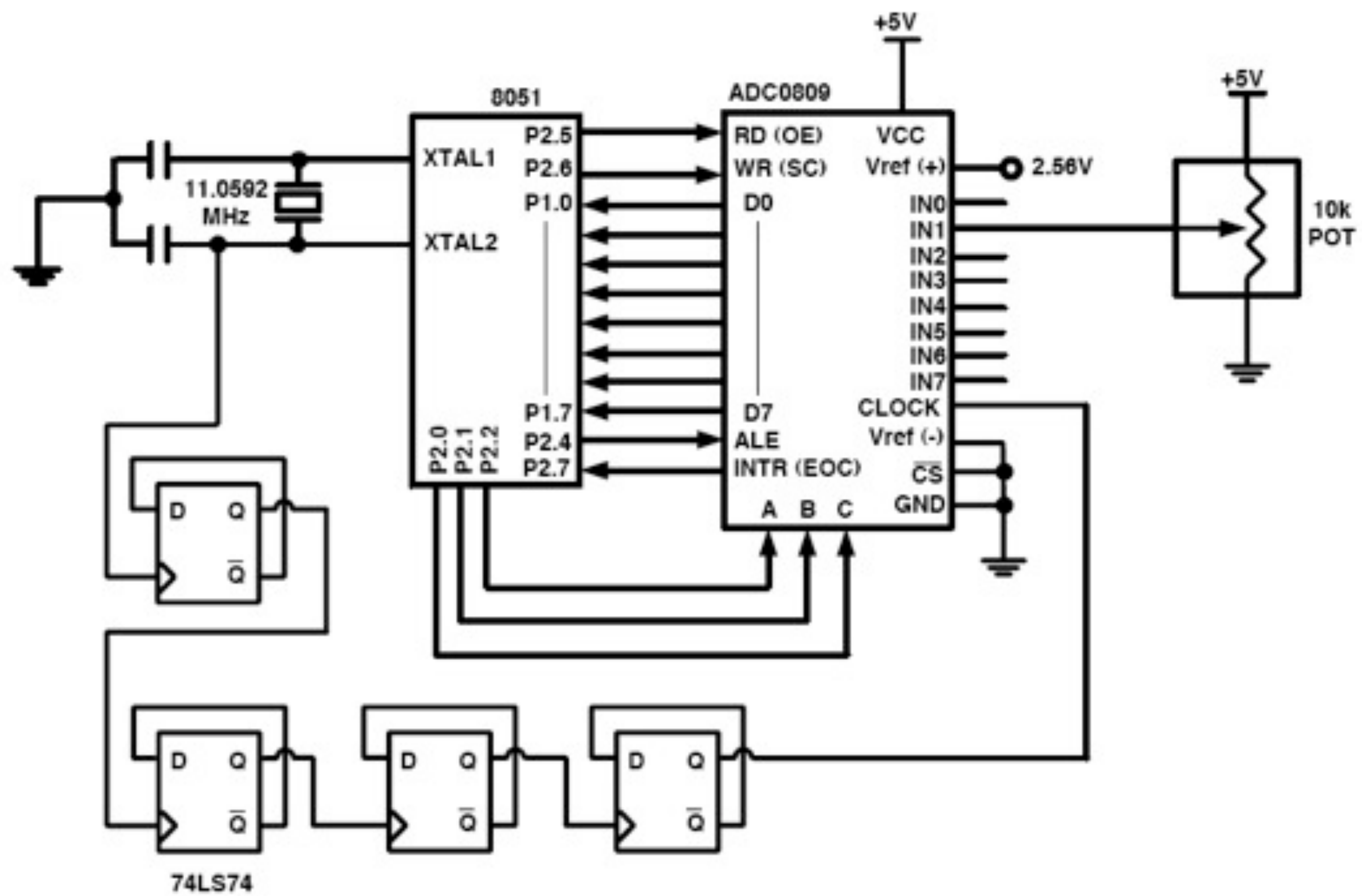
- AGND: analog
- GND: digital
- Digital => noisy due to frequent switching
- Analog: sensitive to noise
- Solution: separate AGND & GND
- Keep analog signal lines short



bad idea to tie them together!

Assembly for ADC0809

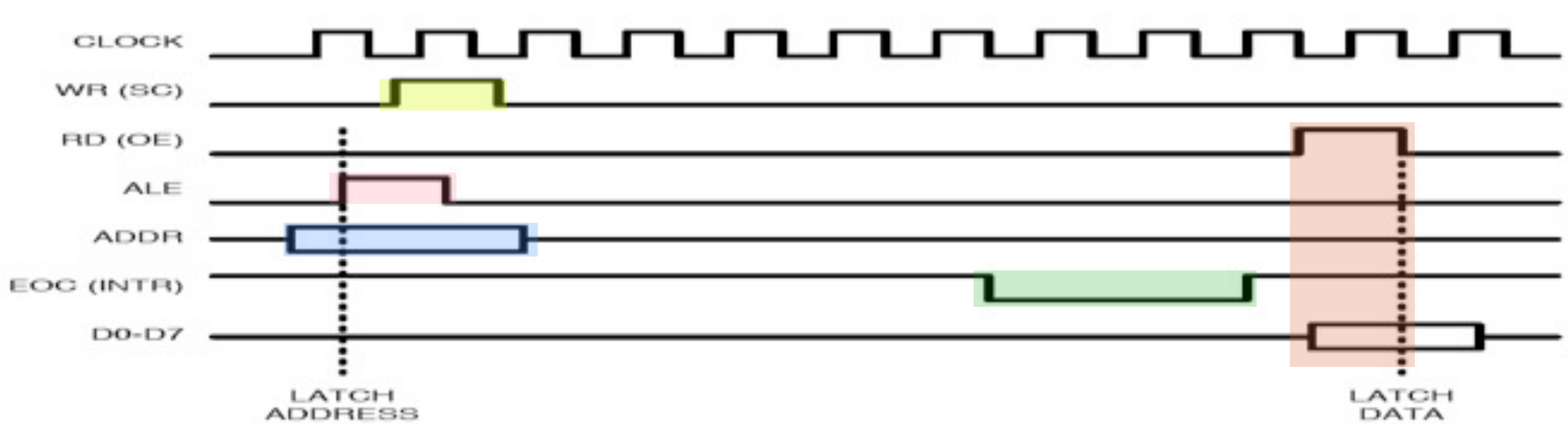
```
ALE     BIT  P2.4
OE      BIT  P2.5
SC      BIT  P2.6
EOC     BIT  P2.7
ADDR_A  BIT  P2.0
ADDR_B  BIT  P2.1
ADDR_C  BIT  P2.2
MYDATA  EQU  P1


        ORG  0H
        SETB EOC    ;; input
        CLR  ALE
        CLR  SC
        CLR  OE
```



Assembly for ADC0809

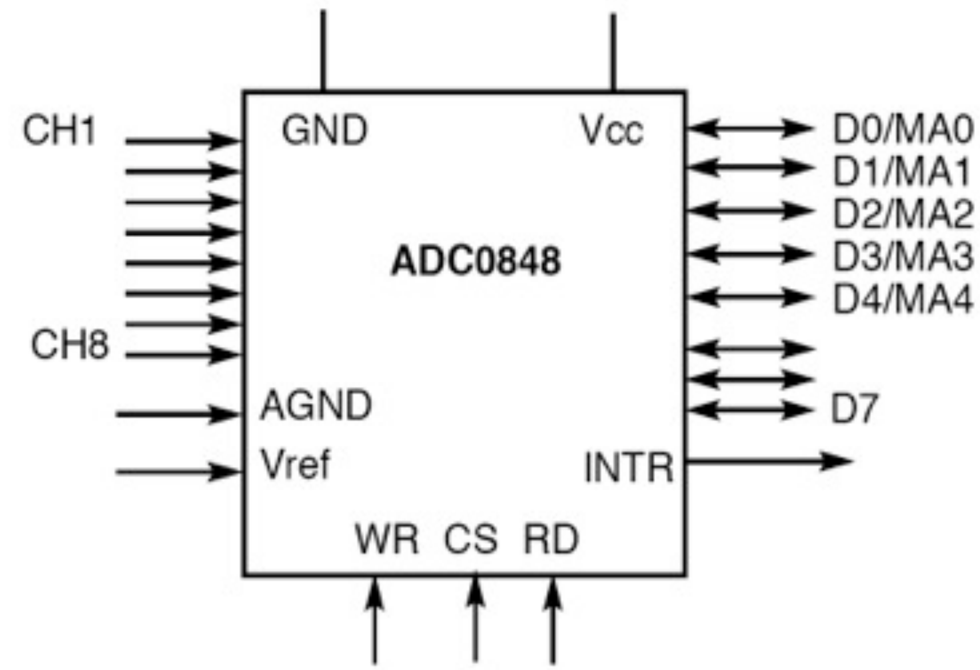
```
BACK:   CLR     ADDR_C
        CLR     ADDR_B          ;; sel ch=1
        SETB    ADDR_A
        ACALL   DELAY
        SETB    ALE             ;; latch addr
        ACALL   DELAY
        SETB    SC              ;; start
        ACALL   DELAY
        CLR     ALE
        CLR     SC
```

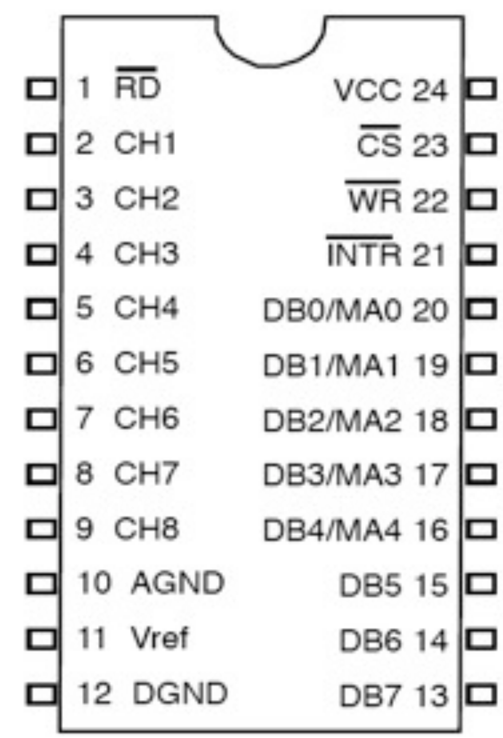
```
HERE:   JB      EOC, HERE
HERE1:  JNB     EOC, HERE1
        SETB    OE
        ACALL   DELAY
        MOV     A, MYDATA
        CLR     OE
        ACALL   CONVERSION
        ACALL   DATA_DISPLAY
        SJMP    BACK
```



ADC0848: 8-channel ADC

- /CS: Chip select
- /RD: Read /WR: Write
- Vref: reference voltage
- DB0-DB7
- MA0 - MA4: multiplexed address
- CH1 - CH8: analog inputs
- /INTR: end-of-conversion

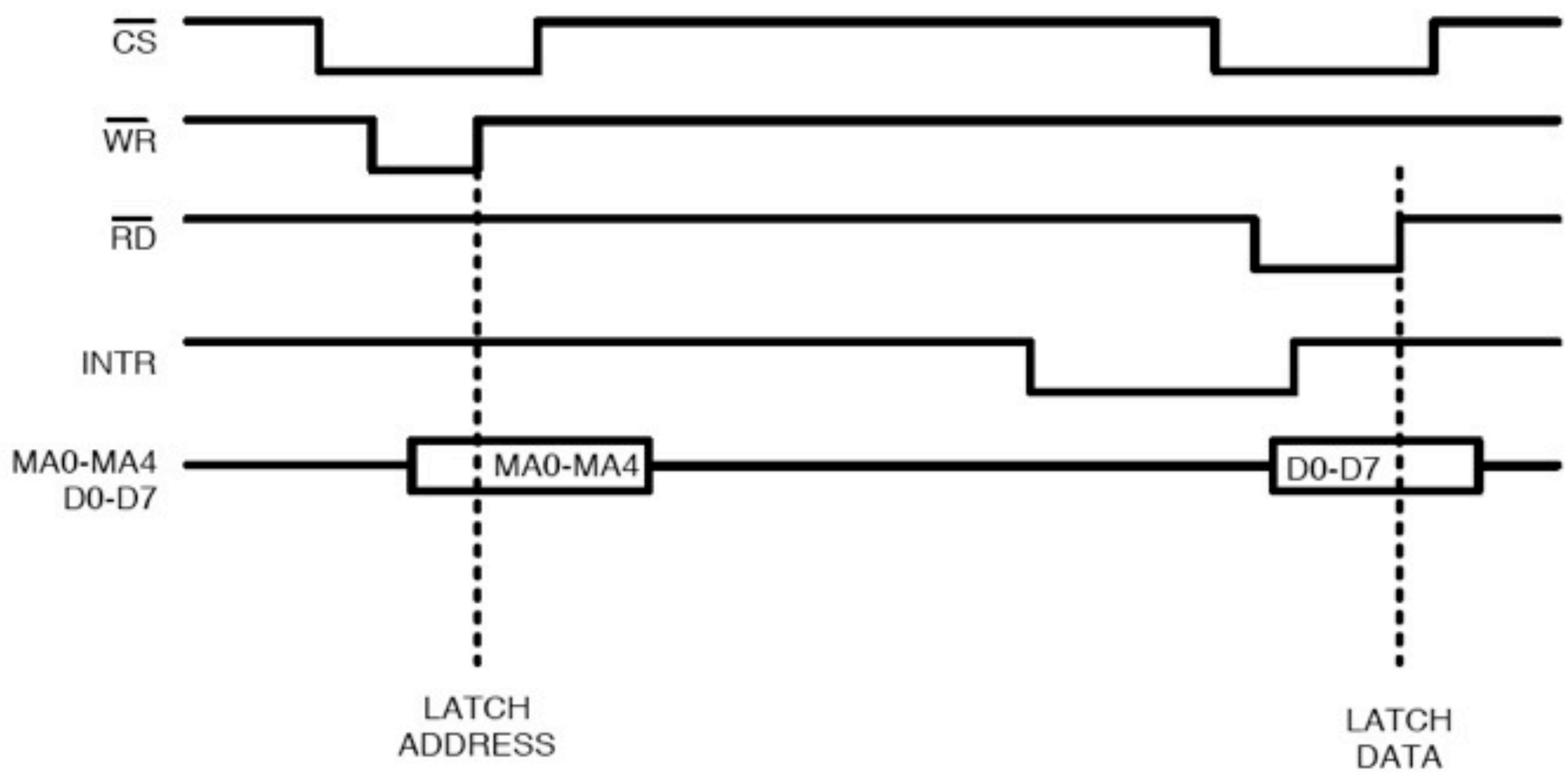




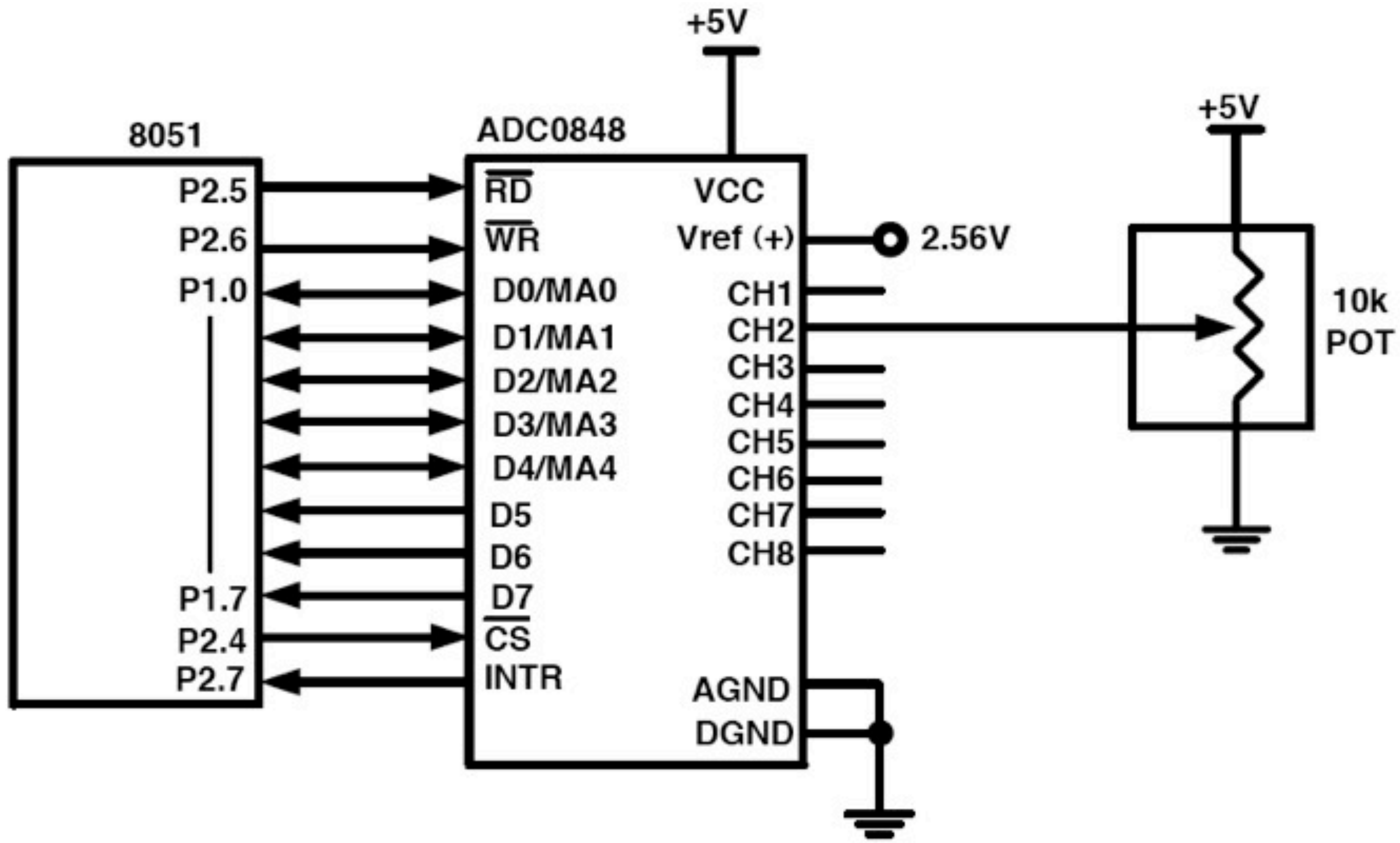
Channel selection

Mode	Chan	MA4	MA3	MA2..0
single ended	1	0	1	0
	...			...
	8			111
differ- ential	CH1(+),CH2(-)	don't care	0	?
	...			...
	CH7(+), CH8(-)			?

Timing Diagram for ADC0848

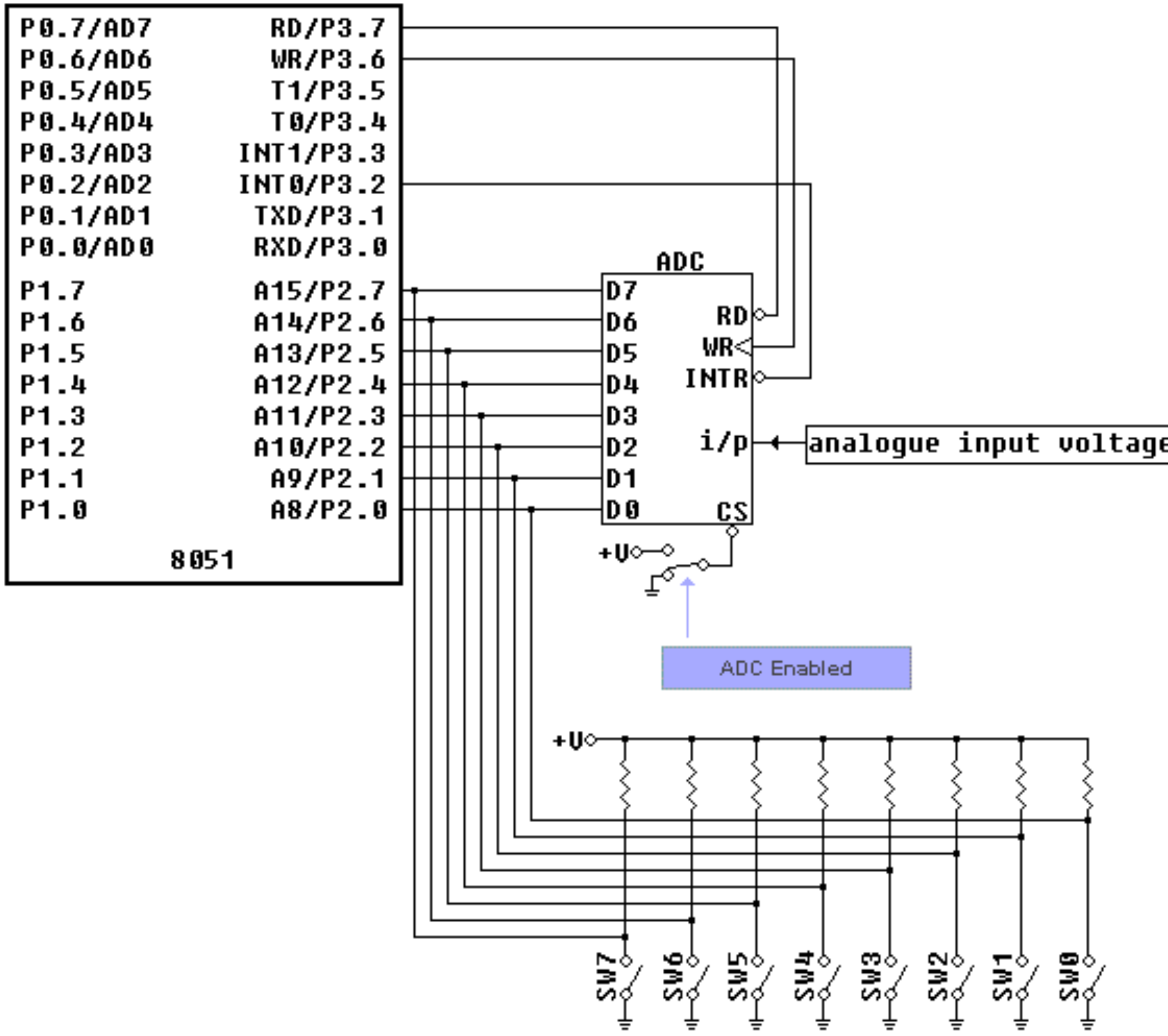


Connection of ADC8048 to 8051



8-bit ADC on EdSim

- /CS always asserted
- /INTR interrupts MCU upon finishing conversion
- WR to start conversion
- /RD to output
- D7-D0: digital data

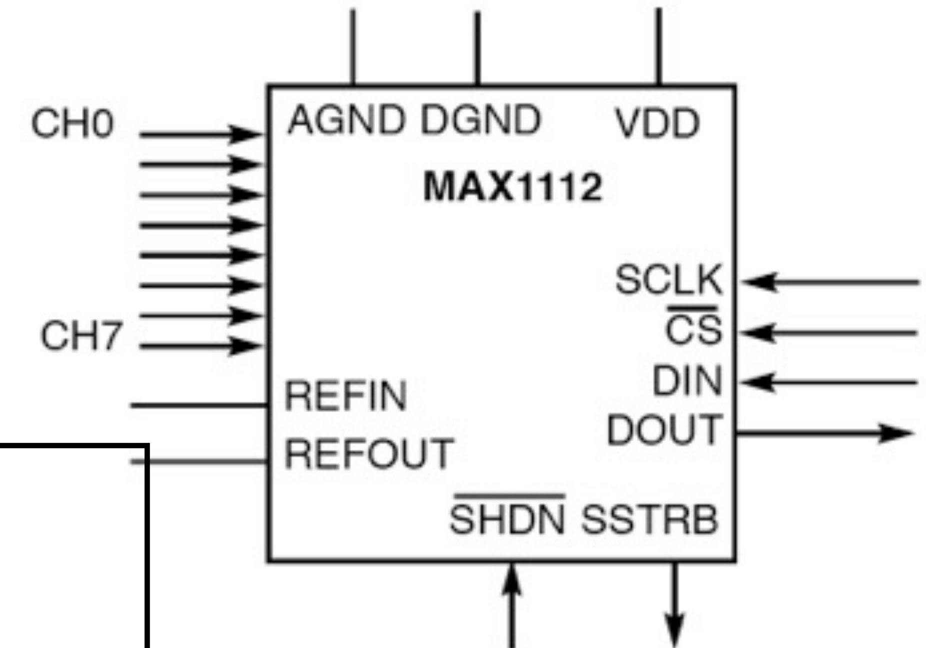


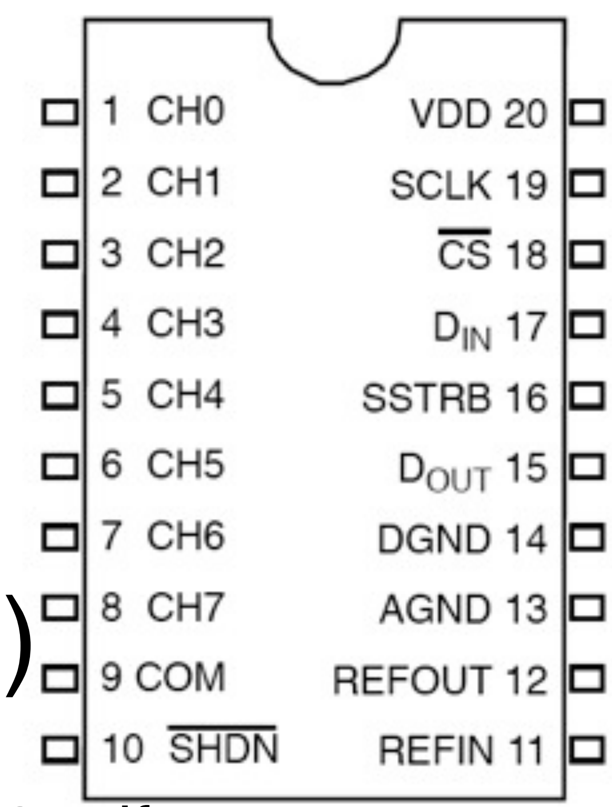
MAX 1112: Serial ADC

- COM: analog GND for single-ended

Looks familiar?

- /CS: chip select
- SCLK: serial clock (input)
- Dout: serial data out
- Din: serial data in
- SSTRB: serial strobe out (EOC)





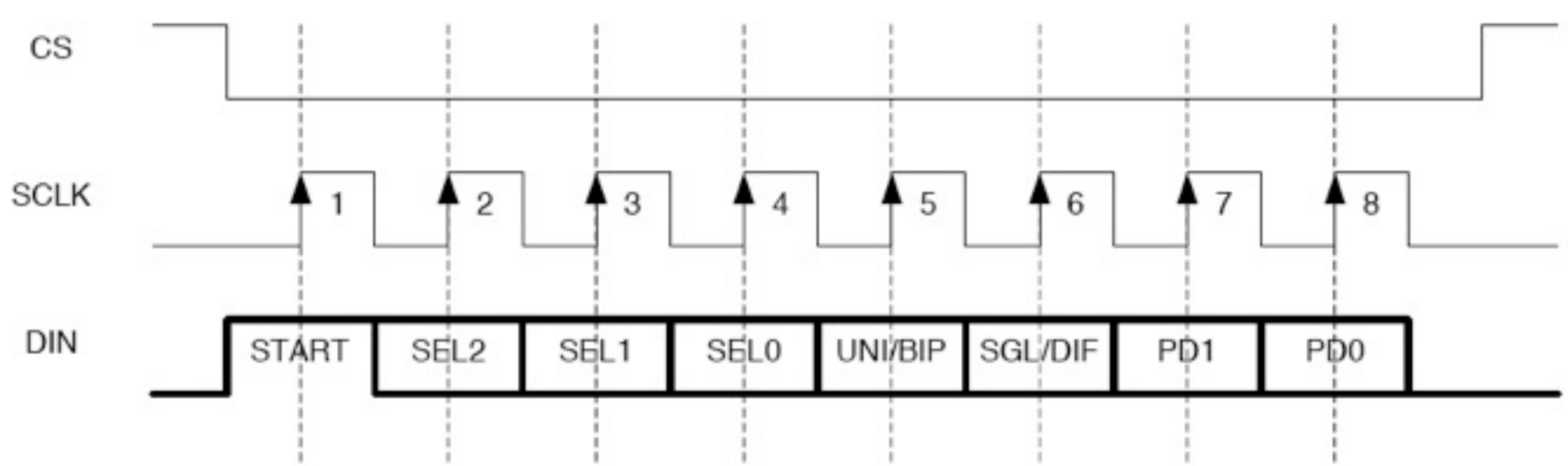
http://datasheets.maximintegrated.com/en/ds/MAX1112-MAX1113.pdf

More pins of MAX 1112

- /SHDN: shutdown
- REFIN: reference voltage input
- REFOUT: internal reference voltage output
- VCOM: 0V for unipolar, Vref/2 for bipolar
- AGND, DGND: analog/digital ground
  - Note: AGND is for MAX112, whereas COM is for signal's GND (unrelated to AGND)

Configure MAX 1112: send Control Byte

- unipolar or bipolar
- Single-ended or Differential
- power-down or operational
- external clock or internal clock



Format of Control Byte

Start	SEL2	SLE1	SEL0	UN/BIP	SGL/DF	PD1	PD0

Start The MSB (D7) must be high to define the beginning of the control byte. It must be sent in first.

SEL2	**SEL1**	**SEL0**	**CHANNEL SELECTION** (SINGLE-ENDED MODE)
0	0	0	CHAN0
0	0	1	CHAN1
0	1	0	CHAN2
0	1	1	CHAN3
1	0	0	CHAN4
1	0	1	CHAN5
1	1	0	CHAN6
1	1	1	CHAN7

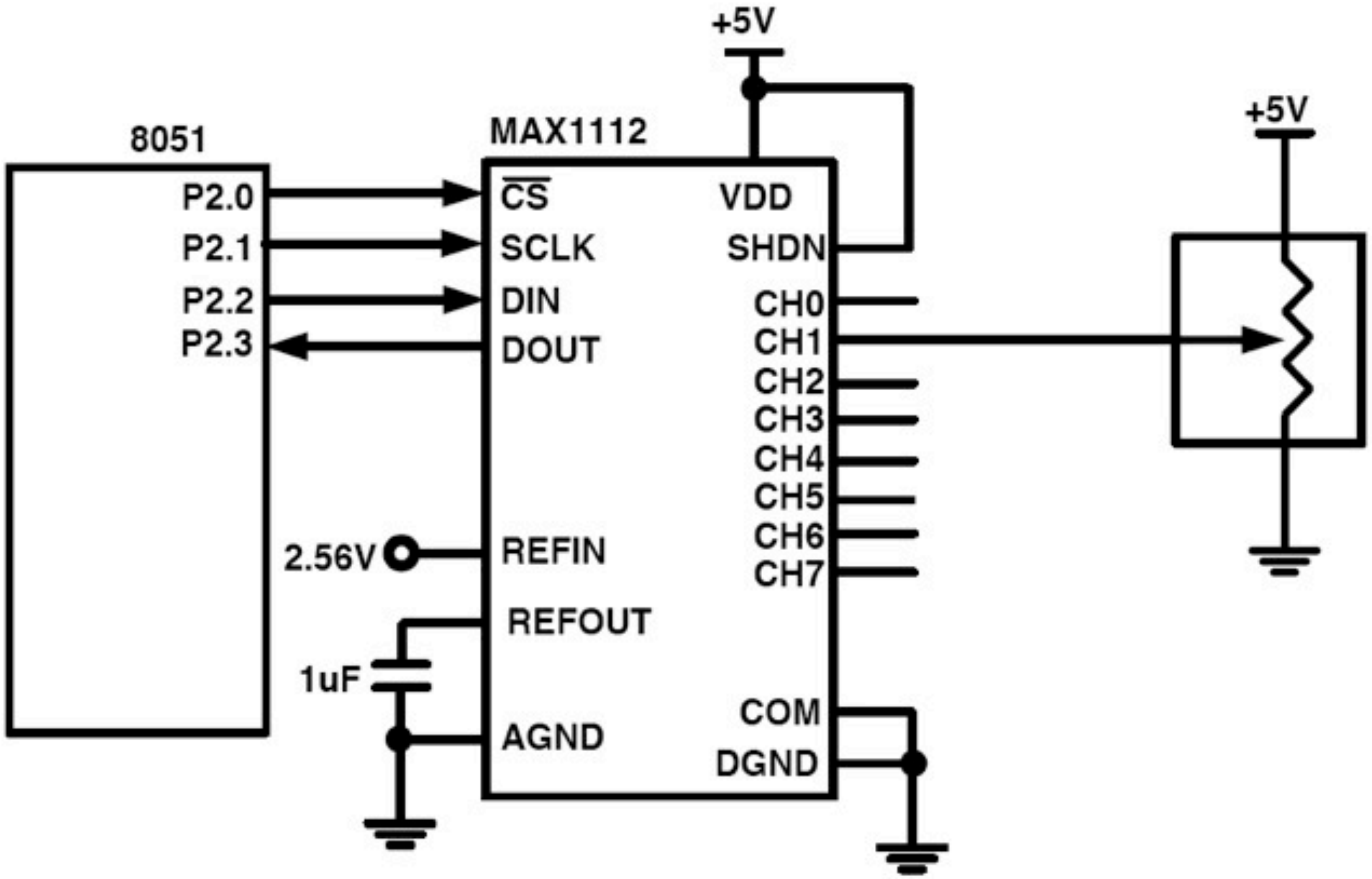
UNI/BIP 1 = unipolar: Digital data output is binary 00 - FFH.
0 = bipolar: Digital data output is in 2's complement.

SGL/DIF 1 = single-ended: 8 channels of single-ended with COM as reference
0 = differential: Two channels (eg., CH0 - CH1) are differential.

PD1 1 = fully operational
0 = power-down: Power down to save power using software.

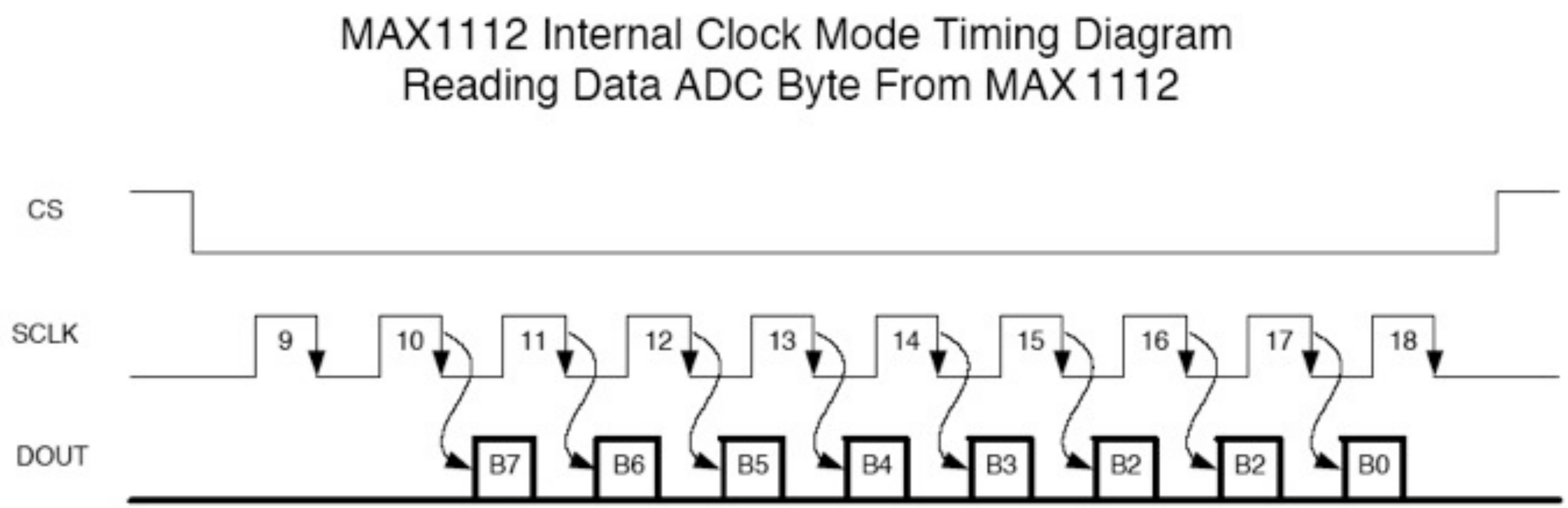
PD0 1 = external clock mode: The conversion speed is dictated by SCLK.
0 = internal clock mode: The conversion speed is dictated internally, and the SSTRB pin goes high to indicate end-of-conversion (EOC).

Connecting MAX 1112 to 8051



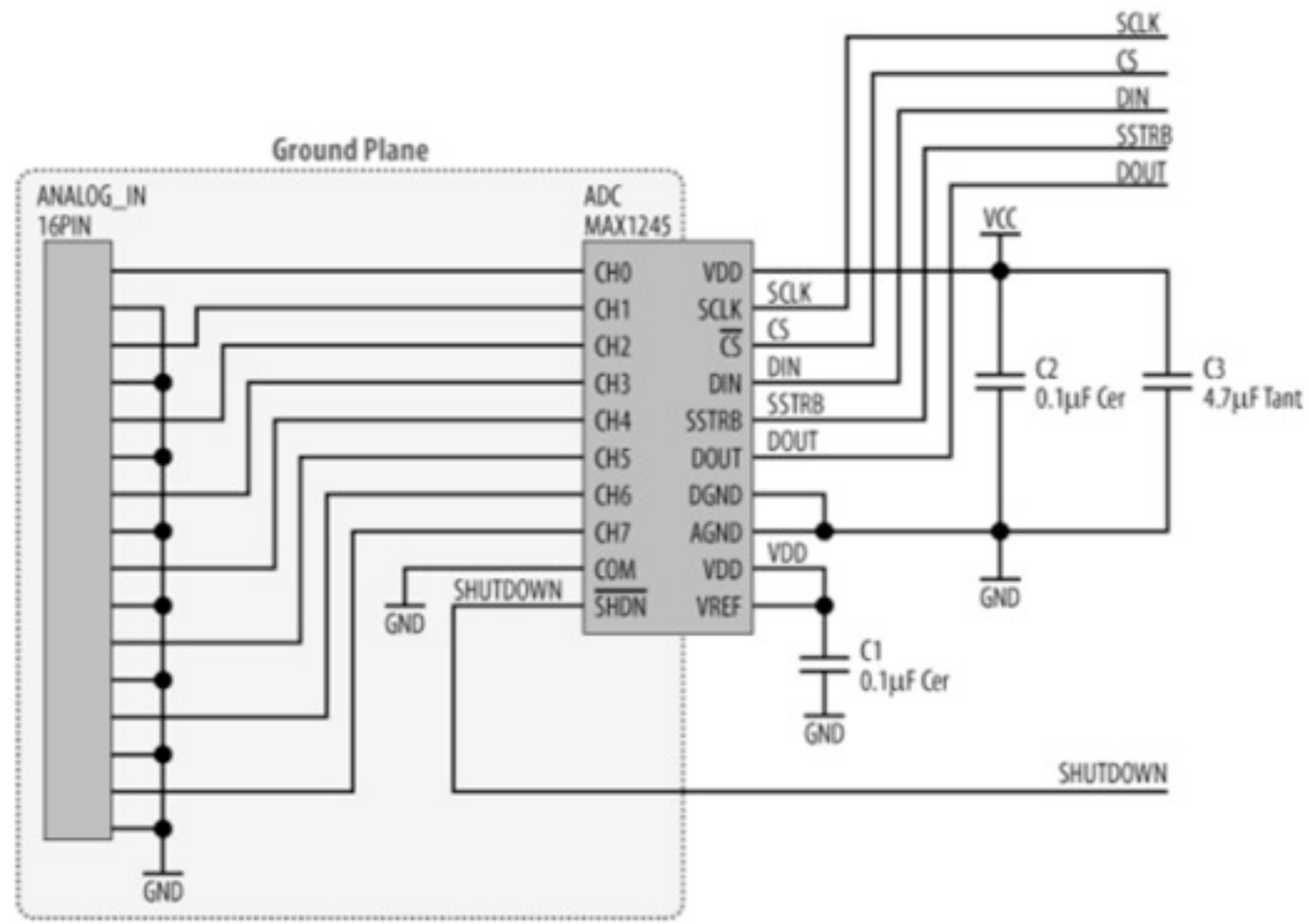
essentially SPI port!
emulated using GPIO if hardware SPI not available

Read cycle: extra SCLK pulse



Ex: Max1245 ADC

- SPI, 8 channels
- 12 bits, up to 100k sps ($7.5\mu s$ conv time)
- track-and-hold type (aka sample & hold) unipolar or bipolar input

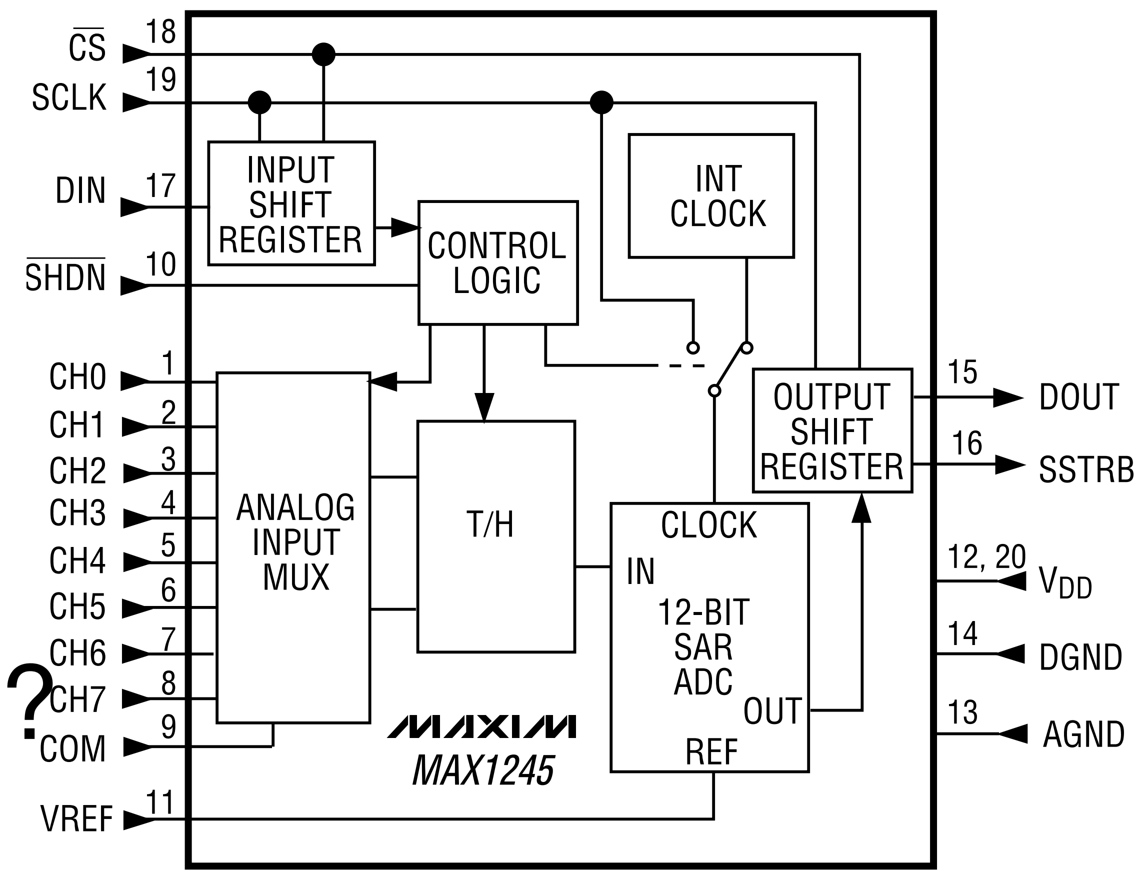


- Ground sep. betw. input lines

http://datasheets.maxim-ic.com/en/ds/MAX1245.pdf

Detailed Description

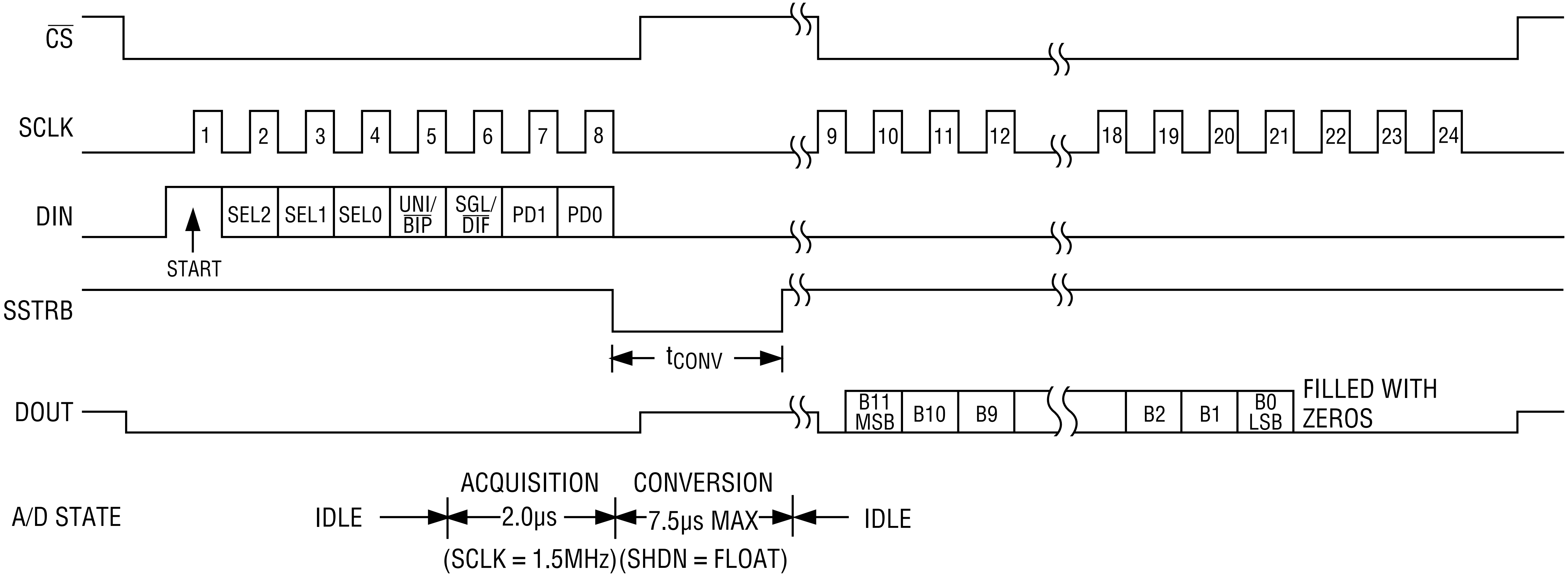
- Single-ended: 0 to Vref
- pseudo-differential:
  -Vref/2 to +Vref/2
- What's pseudo-differential?
  - only IN+ is sampled
  - IN- must remain stable w.r.t. AGND during conv.



- Control byte:
  bit7 = start,
  bits6..4 = channel,
  bit3=unipolar or bipolar
  bit2=single ended or dif
  bit 1..0=mode

Basic Transaction

- Send control byte, ignore received byte
- Clock in all 0s byte, get higher-order byte
- Clock in all 0s byte, get lower-order byte

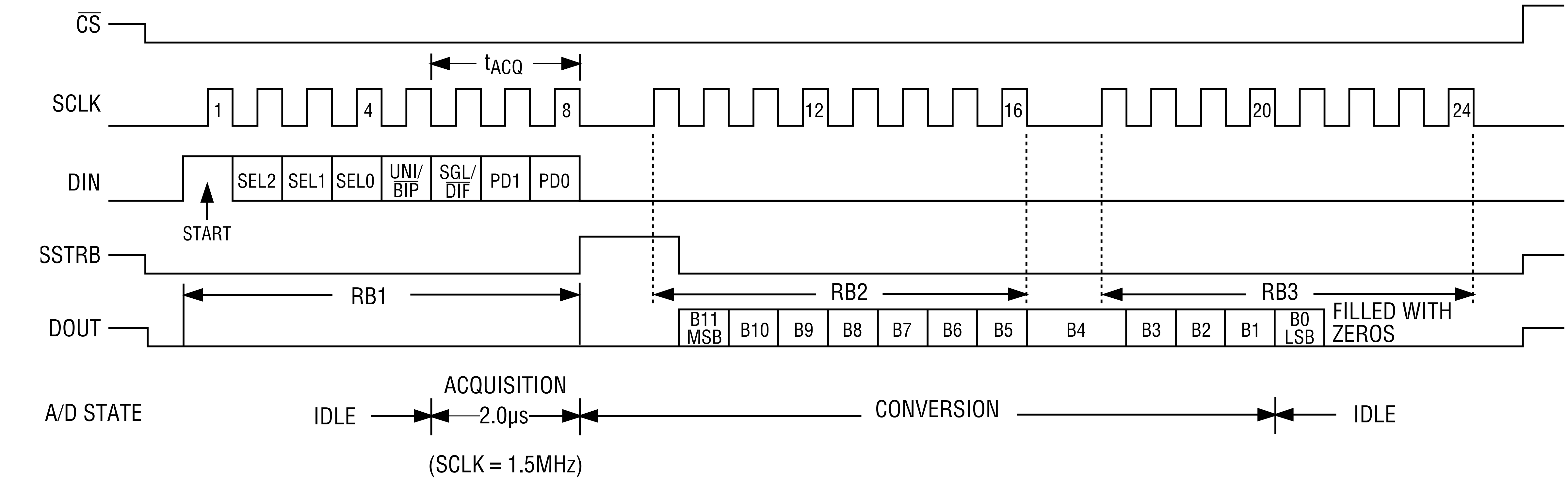


Clock options of Max 1245

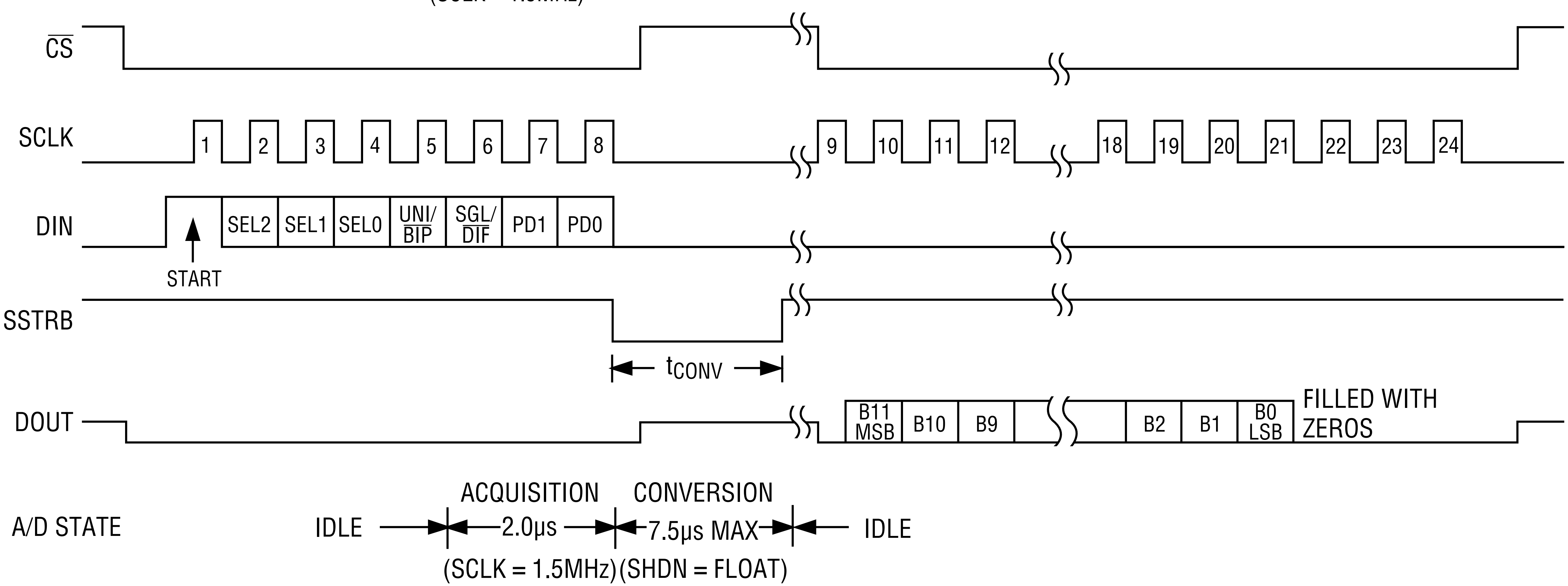
- Internal clock option
  - 1.5 MHz or 225 KHz
- External clock option
  - mode uses SPI SCLK as conversion clock!
  - SSTRB: data ready (can be an interrupt)
  - Clock can't be too slow or else capacitor loses value (for track-and-hold)

External vs. Internal clk

External

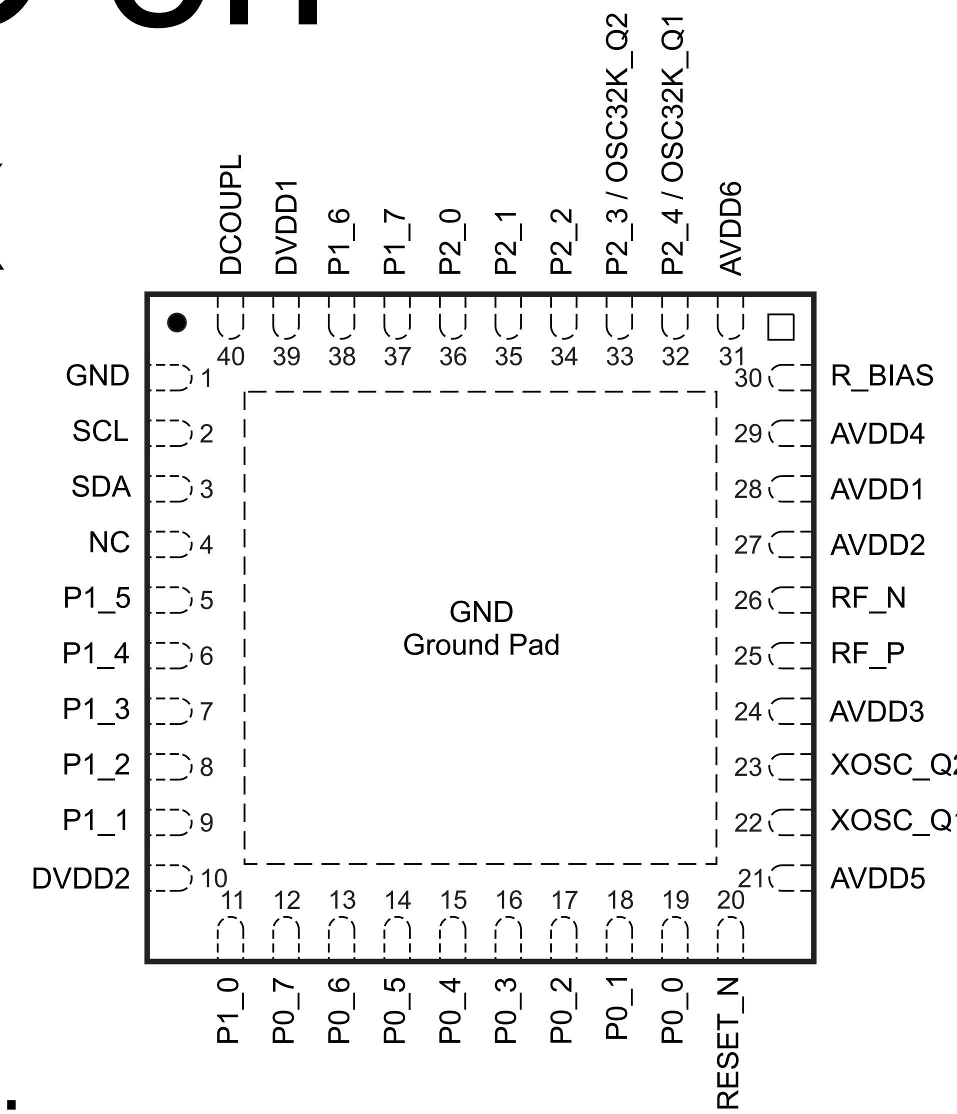


Internal



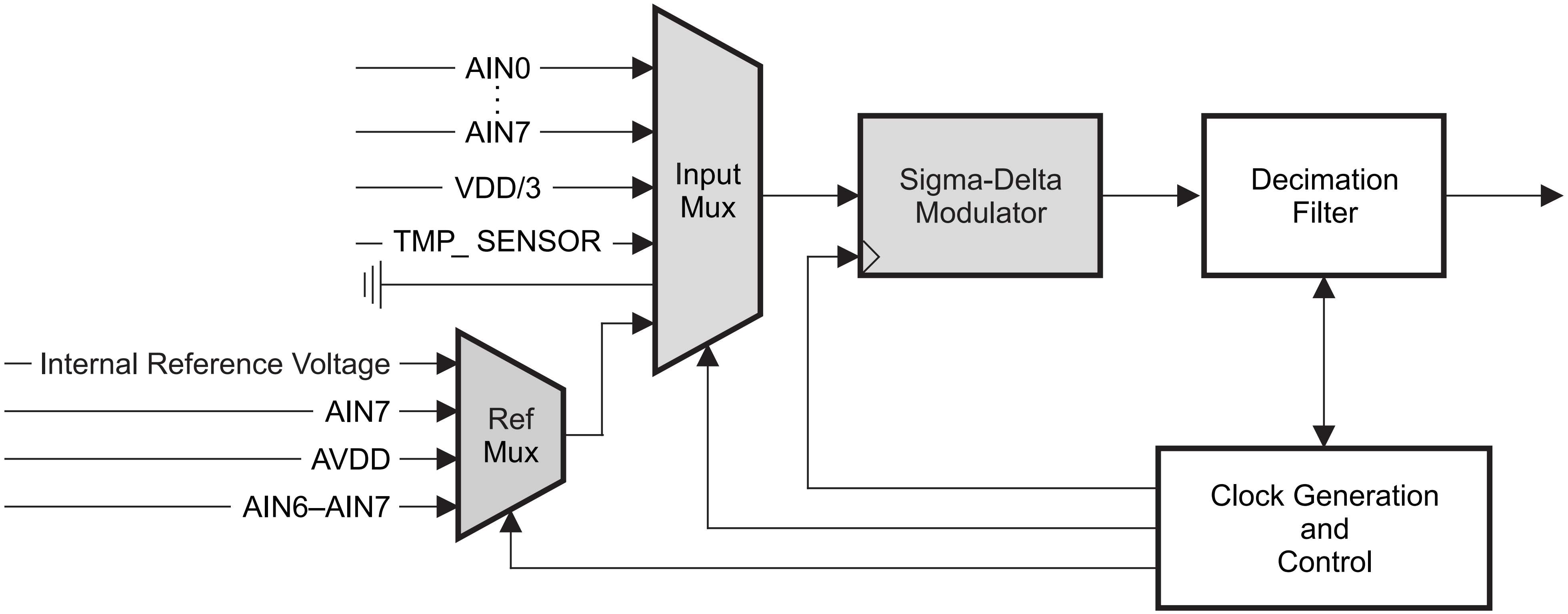
Built-in ADC on CC254x

- Input pins:
  A7-0 same as P0.7-0.0
- T = ADC trigger
- SFR: APCFG (analog peripheral configuration)
- Single ended or differential pair



Periphery/ Function	P0								P1								P2				
	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	4	3	2	1	0
ADC	A7	A6	A5	A4	A3	A2	A1	A0													T
Operational amplifier						O	–	+													
Analog comparator			+	–																	

Using Built-in ADC on CC254x



Register Name	SFR Address	Module	Description
ADCCON1	0xB4	ADC	ADC control 1
ADCCON2	0xB5	ADC	ADC control 2
ADCCON3	0xB6	ADC	ADC control 3
ADCL	0xBA	ADC	ADC data low
ADCH	0xBB	ADC	ADC data high
RNDL	0xBC	ADC	Random number generator data low
RNDH	0xBD	ADC	Random number generator data high

Using built-in ADC of CC254x

- Channels 0-7: single-ended
- Channels 8-11: differential inputs
- Channel 12: GND
- Channel 13: Reserved
- Channel 14: on-chip temperature sensor as input
    - Configure TR0.ADCTM and ATEST.ATESTCTRL bits
- Channel 15: AVDD5/3 as input
    - Can implement battery monitor

Using ADC of CC254x

- ADCCON1.EOC
  - '1' when end-of-conversion, '0' when ADCH read
- ADCCON1.ST
  - set to starts conversion, auto cleared when completed.
- ADCCON1.STSEL: selects triggering event for ADC
  - Rising edge of P2.0
  - End of previous sequence
  - Timer 1 ch 0, or
  - ADCCON1.ST = '1'

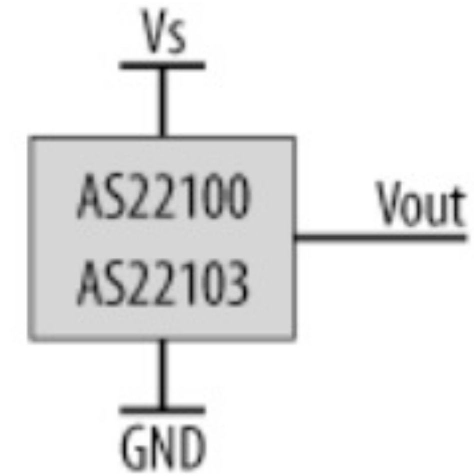
Sensors

Sensors, transducers, actuators

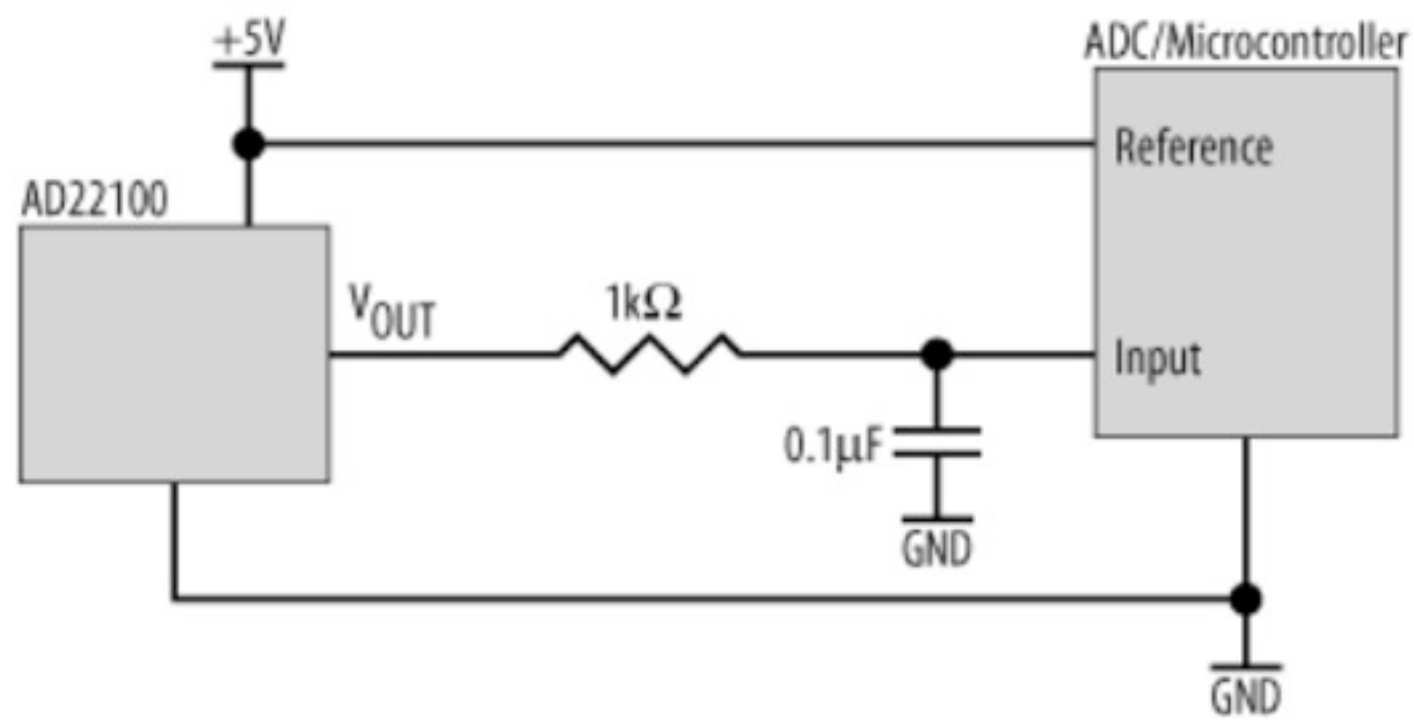
- Sensor
  - converts physical signal (temperature, etc) to electrical (voltage or current)
- Actuator
  - converts electrical signal to physical signal
- Transducer
  - converts one form of energy to another

Temperature sensor

- AD 22100: -50°C to +150°C
  - 3 pin device: power, gnd, Vout
  - linear in 5V range

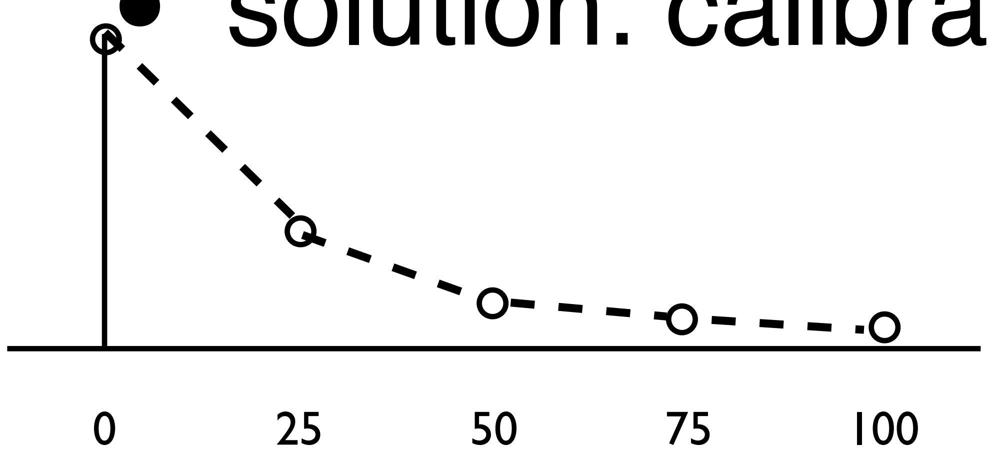


- can add an RC filter to remove noise



Linearity

- Characteristics of transducer over its operating range
- Example: thermistor
  - varies resistance over temperature but not "linear"
  - solution: calibration



Temperature (C)	Tf (K ohms)
0	29.490
25	10.000
50	3.893
75	1.700
100	0.817

From William Kleitz, *Digital Electronics*

LM34 & LM35 temperature sensors

Part	Temperature Range	Accuracy	Output Scale
LM34A	–50 F to +300 F	+2.0 F	10 mV/F
LM34	–50 F to +300 F	+3.0 F	10 mV/F
LM34CA	–40 F to +230 F	+2.0 F	10 mV/F
LM34C	–40 F to +230 F	+3.0 F	10 mV/F
LM34D	–32 F to +212 F	+4.0 F	10 mV/F

Note: Temperature range is in degrees Fahrenheit.

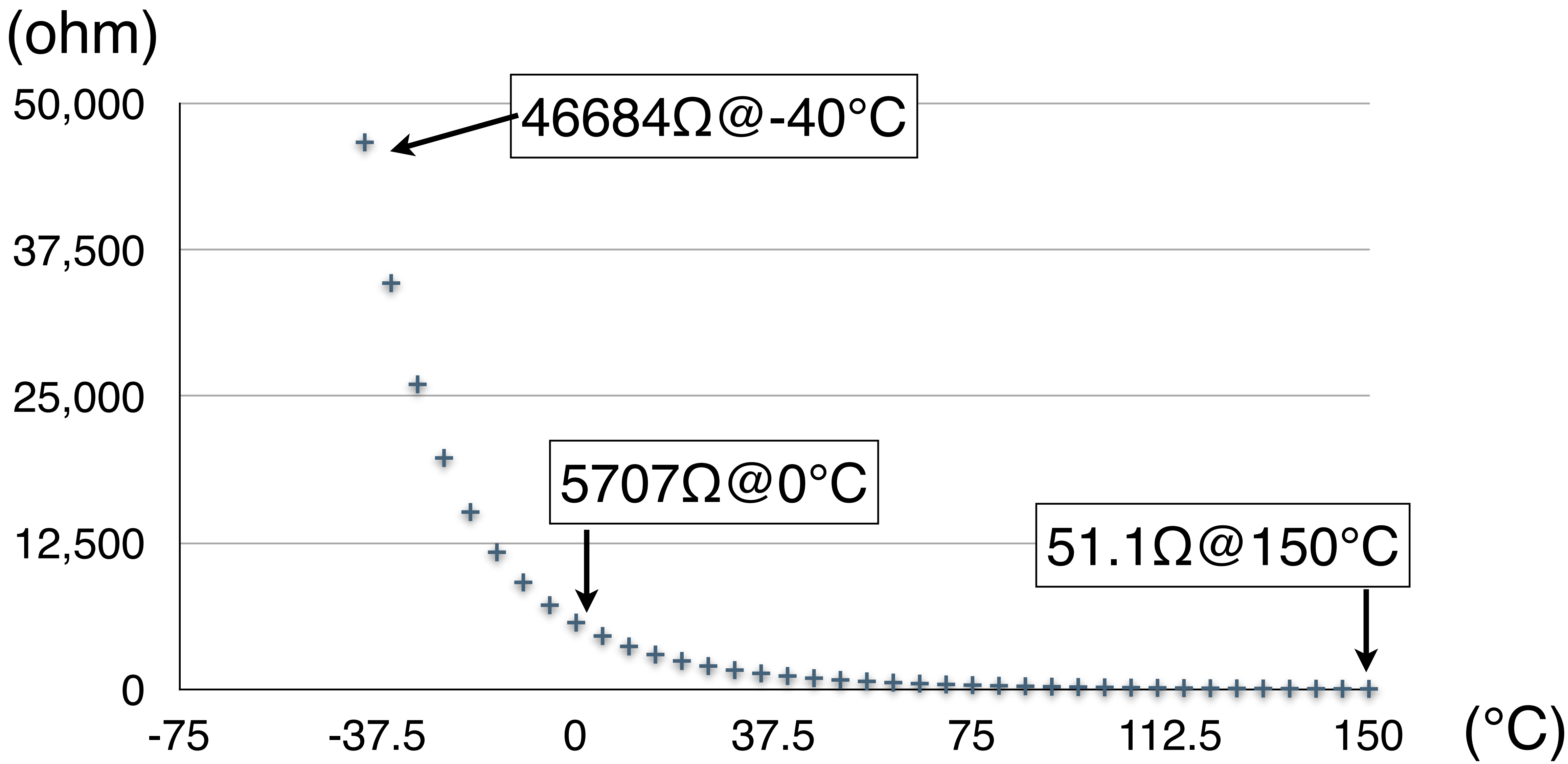
Part	Temperature Range	Accuracy	Output Scale
LM35A	–55 C to +150 C	+1.0 C	10 mV/C
LM35	–55 C to +150 C	+1.5 C	10 mV/C
LM35CA	–40 C to +110 C	+1.0 C	10 mV/C
LM35C	–40 C to +110 C	+1.5 C	10 mV/C
LM35D	0 C to +100 C	+2.0 C	10 mV/C

Note: Temperature range is in degrees Celsius.

Thermistor

- Temperature sensitive resistor
  - cheap, stable
- Problem: non-linear => ~log scale
  - can distinguish low temperature more than high temperature
  - need a table or formula to remap value

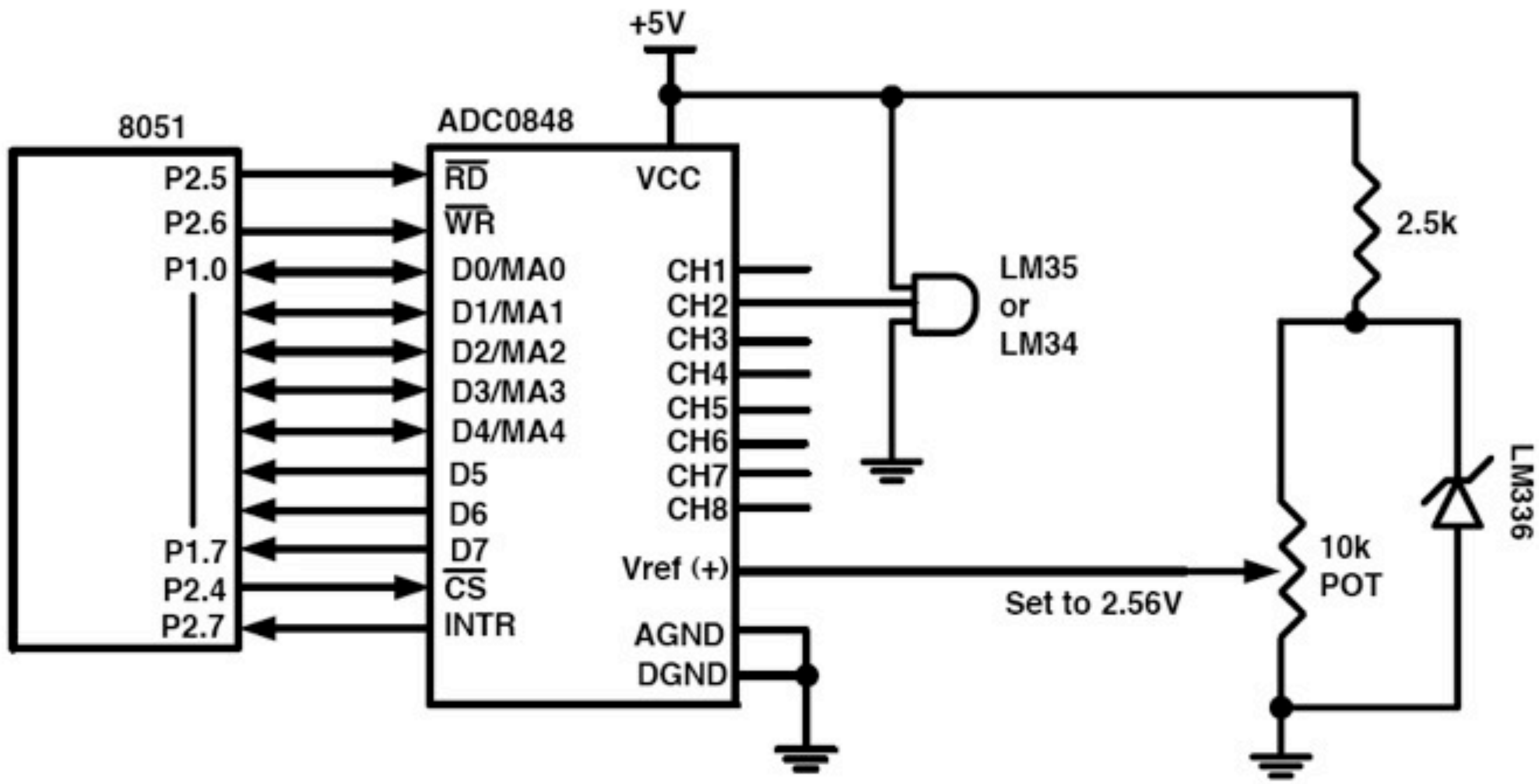
Resistance vs. Temperature plot



Data source taken from
http://rocky.digikey.com/WebLib/BC%20Components/Web%20Data/2322%20640%205%20NTC%20Thermistors.pdf

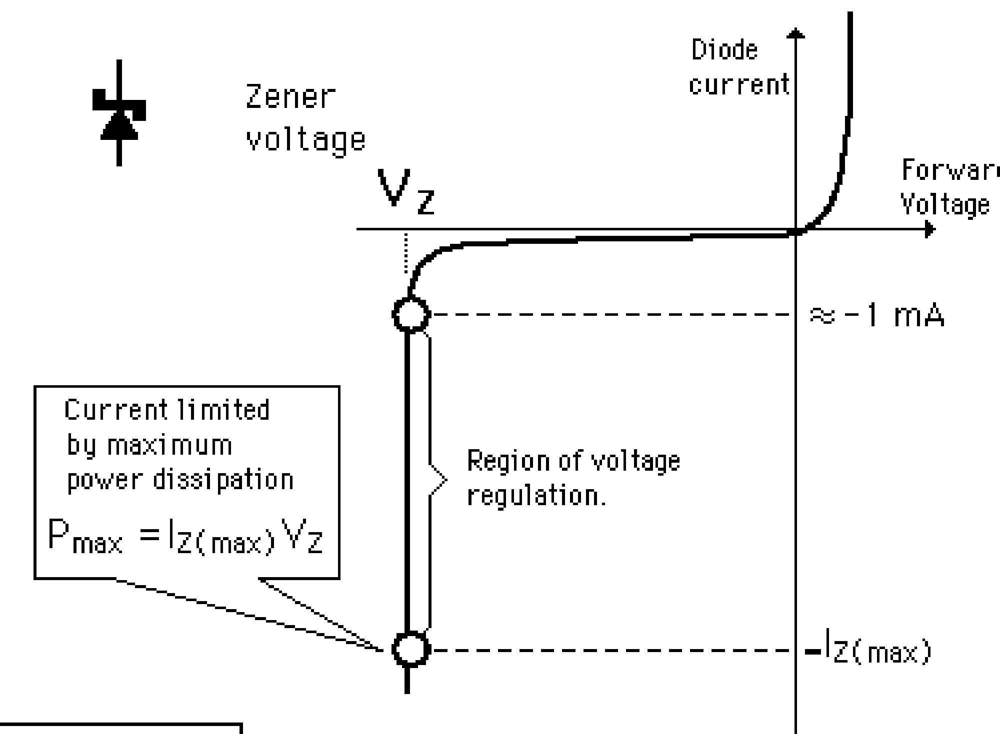
Signal Conditioning

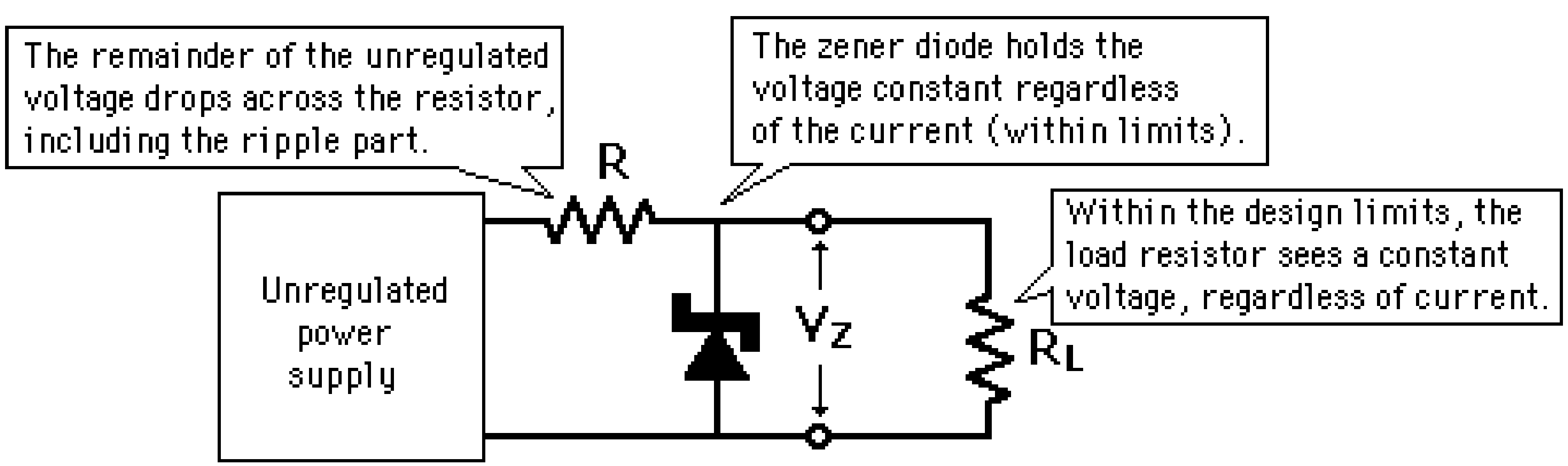
- Step between transducer and ADC
- e.g., keep power clean for reference voltage LM336 Zener diode keeps voltage stable



Zener diode

- in reverse voltage
- applications:
  - regulators



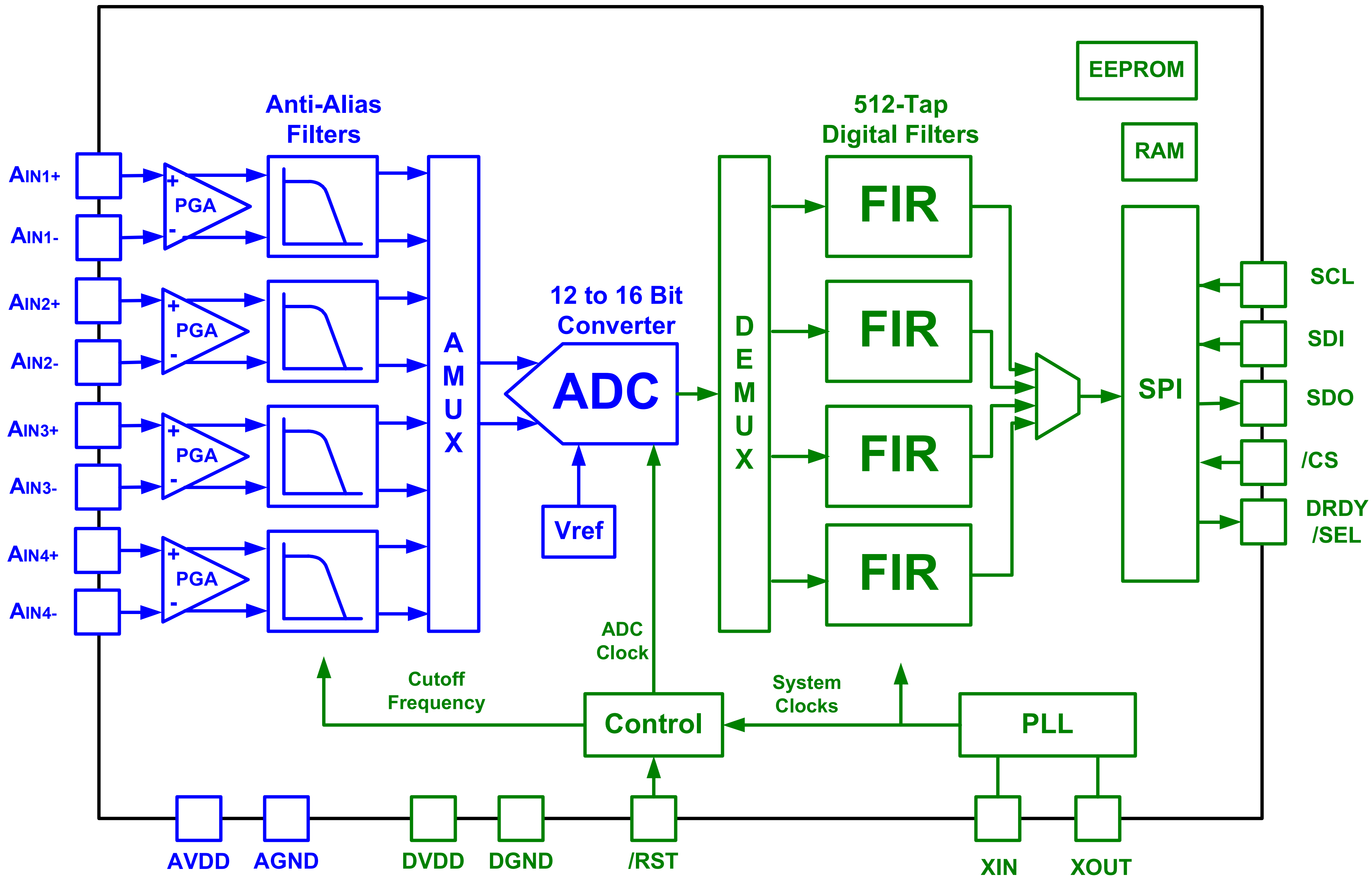


Credits: http://hyperphysics.phy-astr.gsu.edu/hbase/solids/zener.html

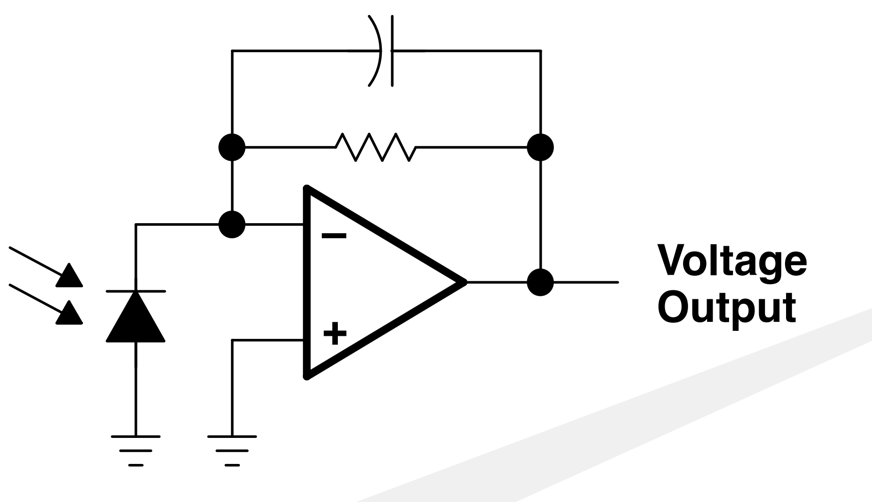
Example: QuickFilter QF4A512

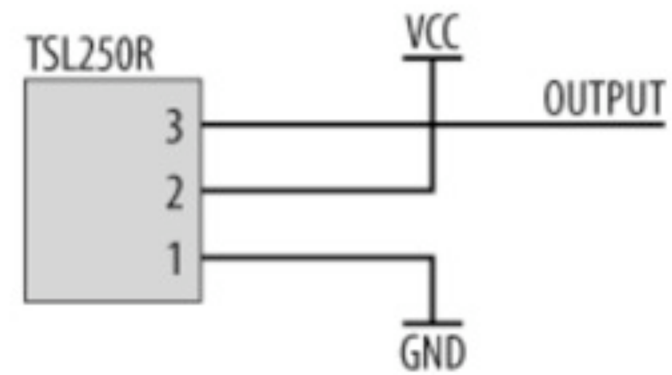
- Combo Signal Conditioner + ADC
  - 4-channel 16-bit ADC
  - 4 programmable gain amplifiers
  - Anti-aliasing filter per channel
  - internal Vref
  - Four 512-tap digital FIR filter
  - SPI output
- http://www.quickfiltertech.com/files/QF4A512%20Data%20Sheet.pdf

QF4A512 block diagram

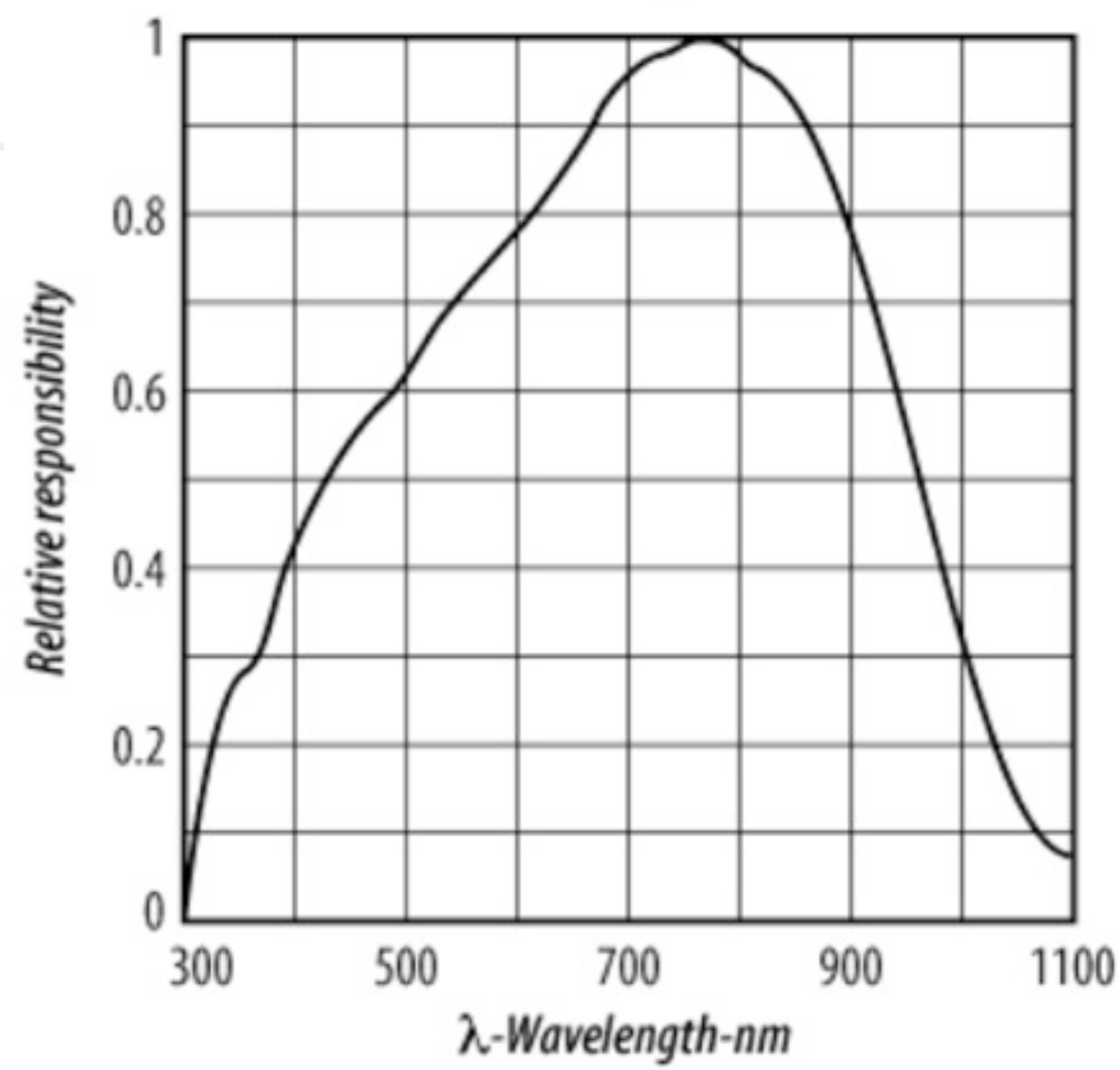


Light Sensor TSL250R





- interface Similar to thermometer chip
  - Vcc, GND, Vout
- responds to visible light spectrum

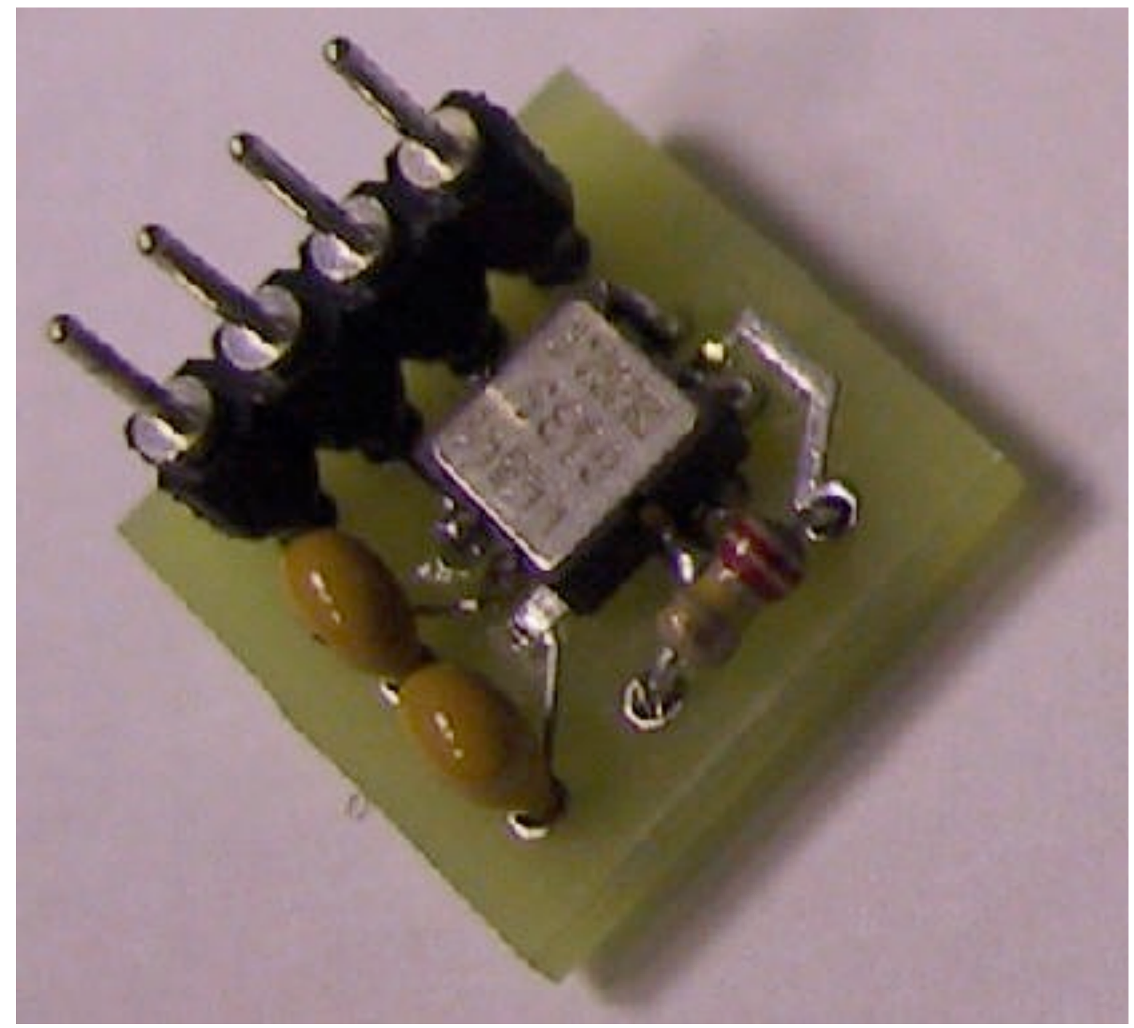


Accelerometer

- Technologies: MEMS, Piezoelectric
- Axes: 1, 2, 3
- Output types: analog, digital
- Threshold Detection
- Self Calibration

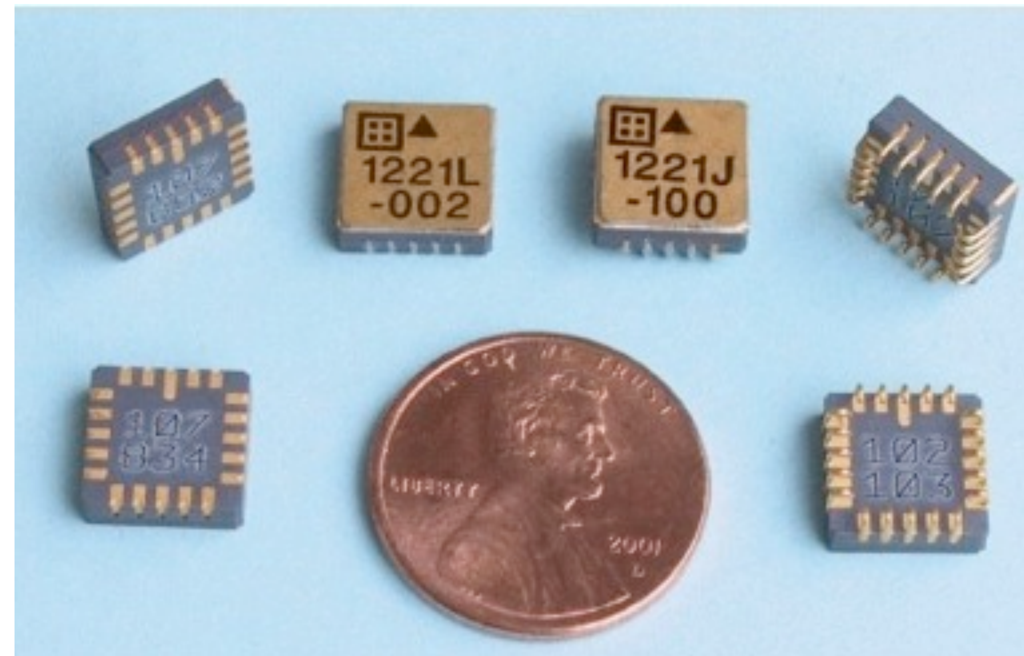
ADXL accelerometers

- ADXL 202E
  - "2" => 2-axes
- Low cost, designed for airbags
- Analog output
- Issue: drift



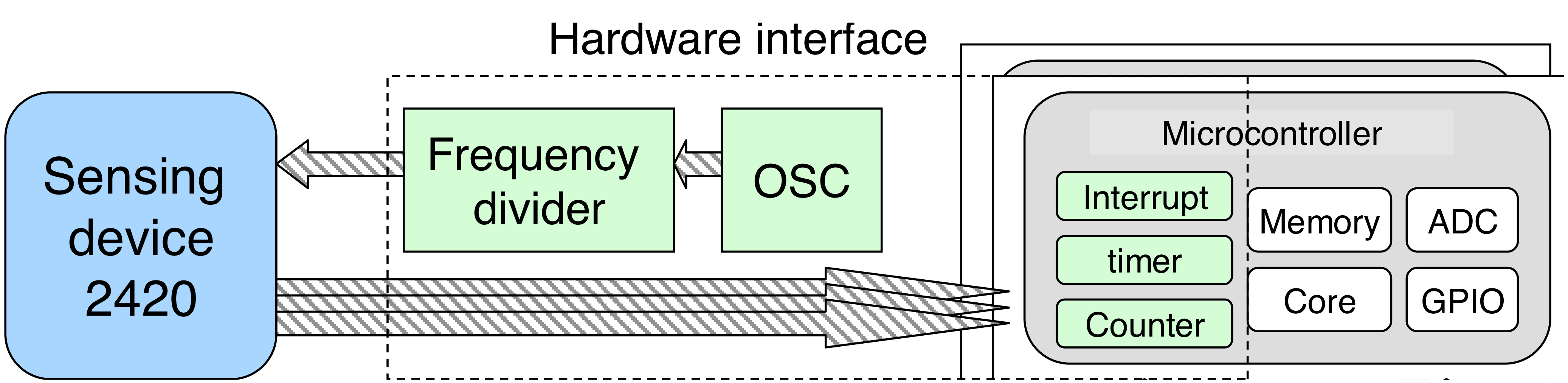
Silicon Designs accelerometer

- High accuracy
  - ±2g~±400g,
  - DC to 200Hz
  - Self calibration
  - Expensive!
- SD 1221: Analog
- SD 2420: pulse freq



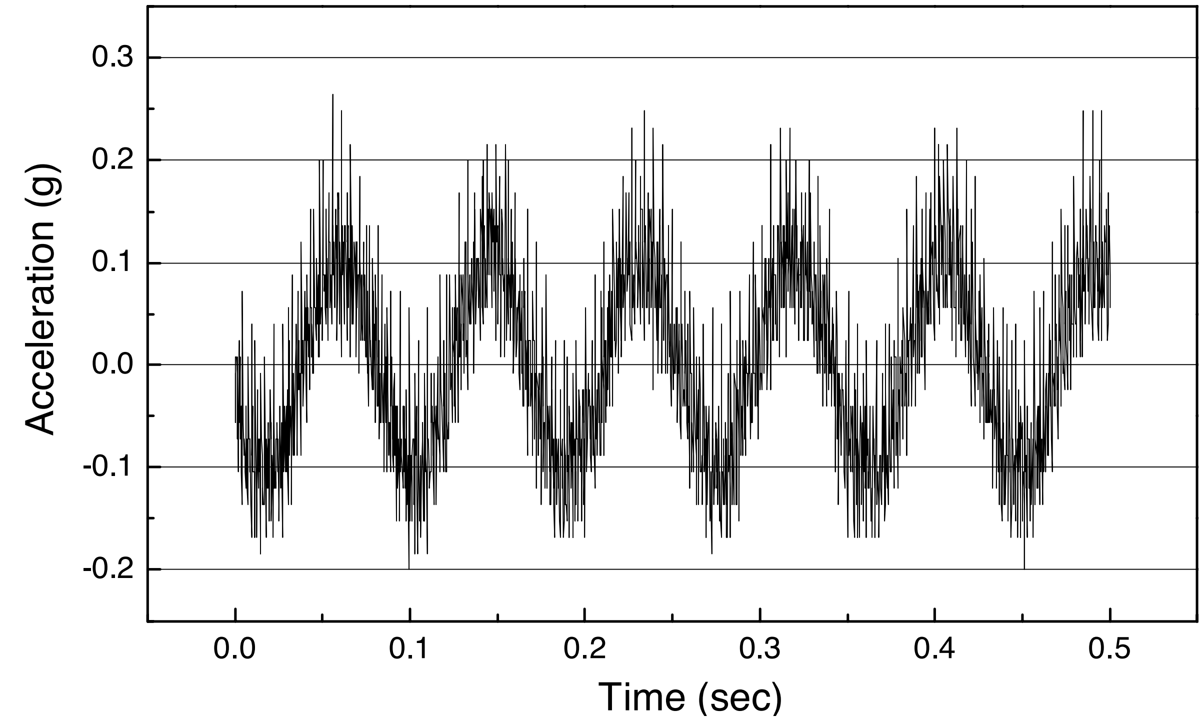
Decoding the 2420

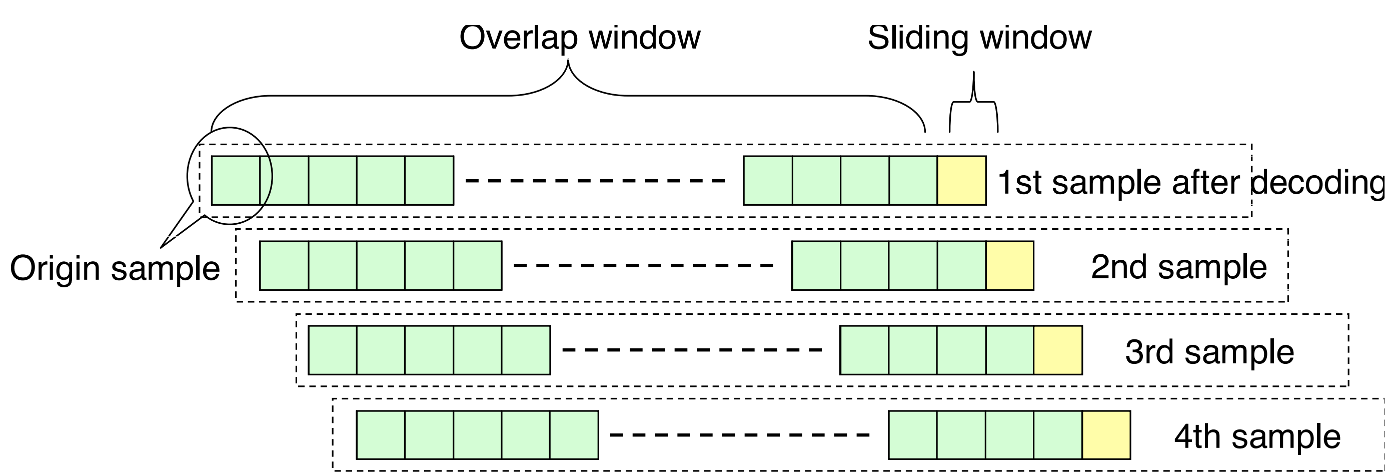
- Input: pulses
- Count pulses, calculate ratio of #1's : #all pulses

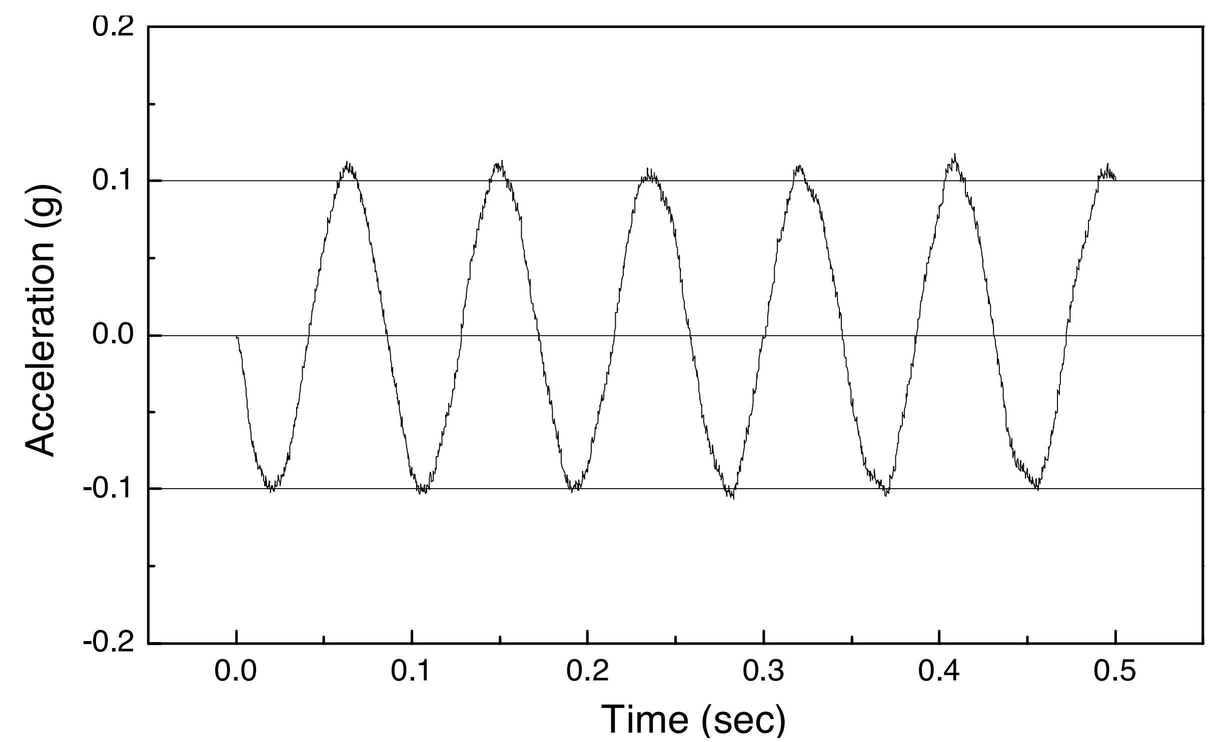


Problem: unfiltered data

- Discretization
- Solution: FIR filter
  - overlapping window
  - smoothes out data

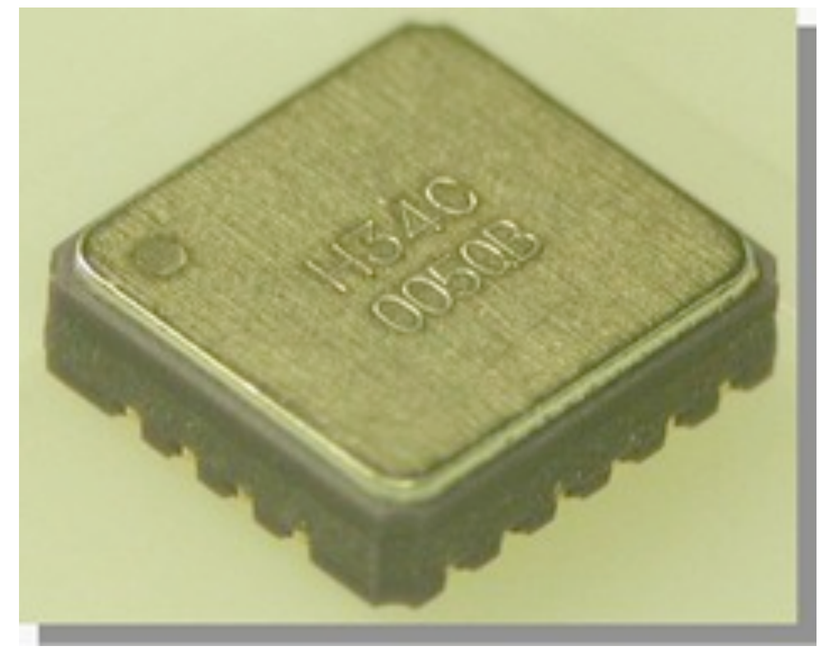






Hitachi Metals H34C accelerometer

- ±3g triaxial
- analog output
- built-in temperature sensor for self calibration
- small size: 3.4x3.7x0.92mm

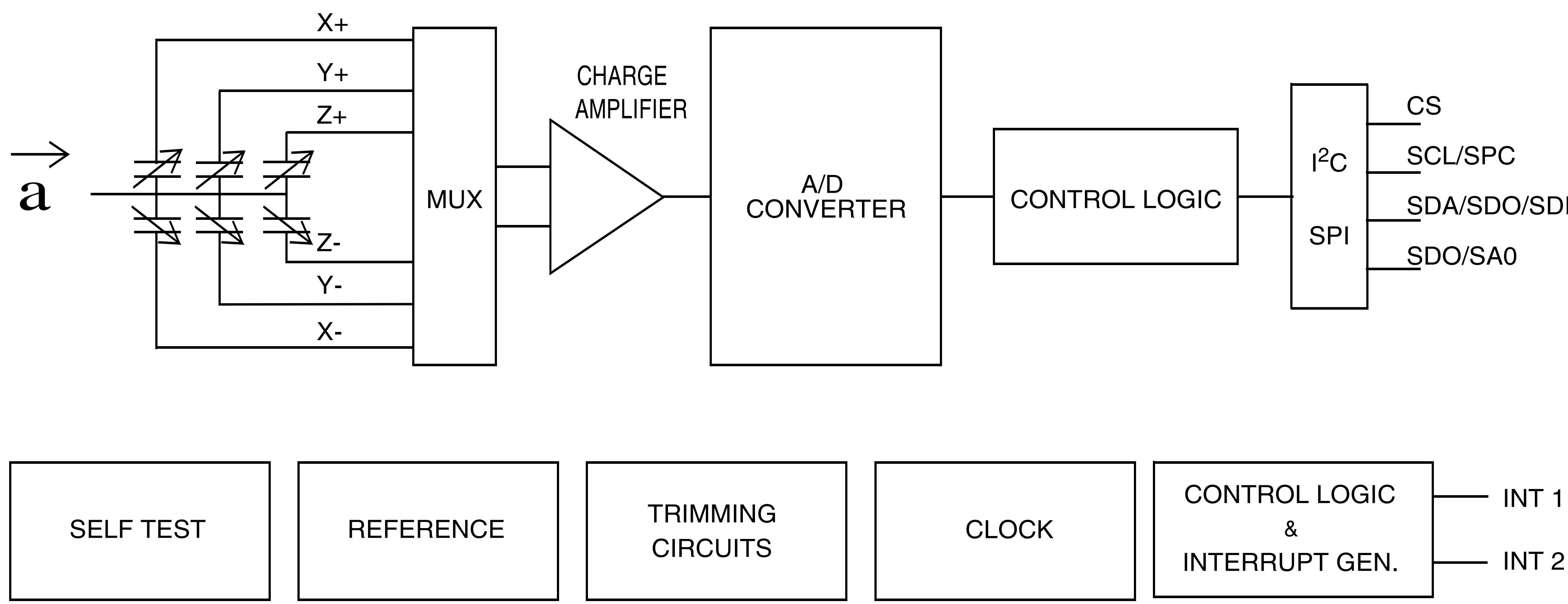


ST LIS331DLH accelerometer

- Range ±2, ±4, ±8 g
- Size 3 x 3 x 1 mm^3
- built-in 12-bit ADC, 0.5 Hz to 1 KHz sampling rate
- SPI or I2C output
- Threshold detection (inertial) and Freefall detection
  - User-defined threshold
  - AND/OR of 3 axes
  - separate interrupt output for threshold & freefall

http://www.st.com/st-web-ui/static/active/en/resource/technical/document/datasheet/CD00213470.pdf

Block diagram of LIS331DLH

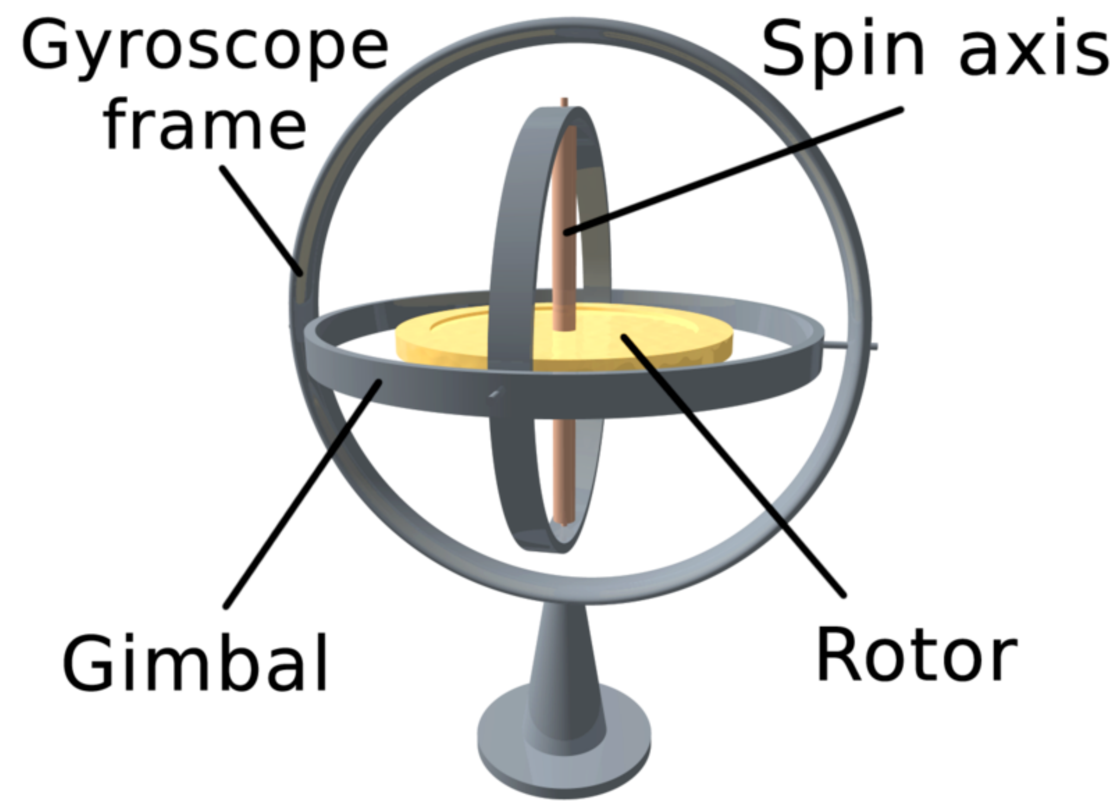


Other sensors

- Pressure sensors
- Magnetic sensors
- Displacement
- Bending sensors
- Gyroscope, Inertial Measurement Unit, Compass
- Humidity
- poisonous gas

Traditional Gyroscope

- Maintains orientation
  - due to angular momentum
- One fixed axis
  - measure tilt, orientation

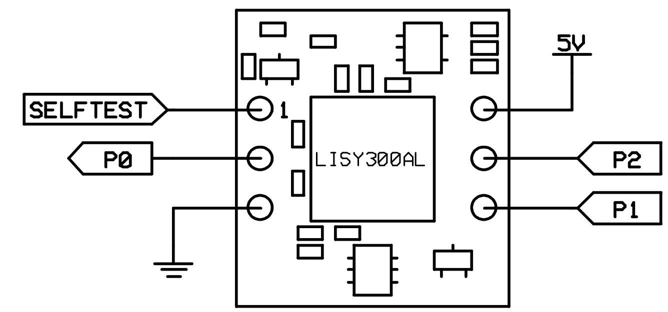


MEMS Gyroscope: LISY300 (Parallax)

- Vibrating mass, no rotor
- single axis yaw-rate
- ±300°/s full scale, up to 88 Hz
- SPI (4 MHz max), using built-in 10-bit ADC
- 3.4-6.5V DC (5V typ) @5.25mA
- $19x17x12mm^3$

http://www.parallax.com/Portals/0/Downloads/docs/prod/sens/27922-LISY300GyroscopeModuleV1.0.pdf

LISY300 Gyroscope



- Internally 1.6V when stable
- clockwise => voltage drops
- counterclockwise => voltage rises
- 3.3 mV/degrees/sec, about 88 sps
- internal 10-bit ADC