Lecture 08
Analog Input

CE346 – Microcontroller System Design

Branden Ghena – Spring 2025

Some slides borrowed from:
Josiah Hester (Northwestern), Prabal Dutta (UC Berkeley)

Northwestern

Administrivia

- Labs continue as normal
  - This week: Breadboarding
- Next week: Design Presentations
  - Details posted to Piazza
  - Schedule will be up in the next day or two
- Quiz today
  - Tell your friends

Today's Goals

- Explore methods for sensing analog signals
  - Comparators
  - Analog-to-Digital Converters

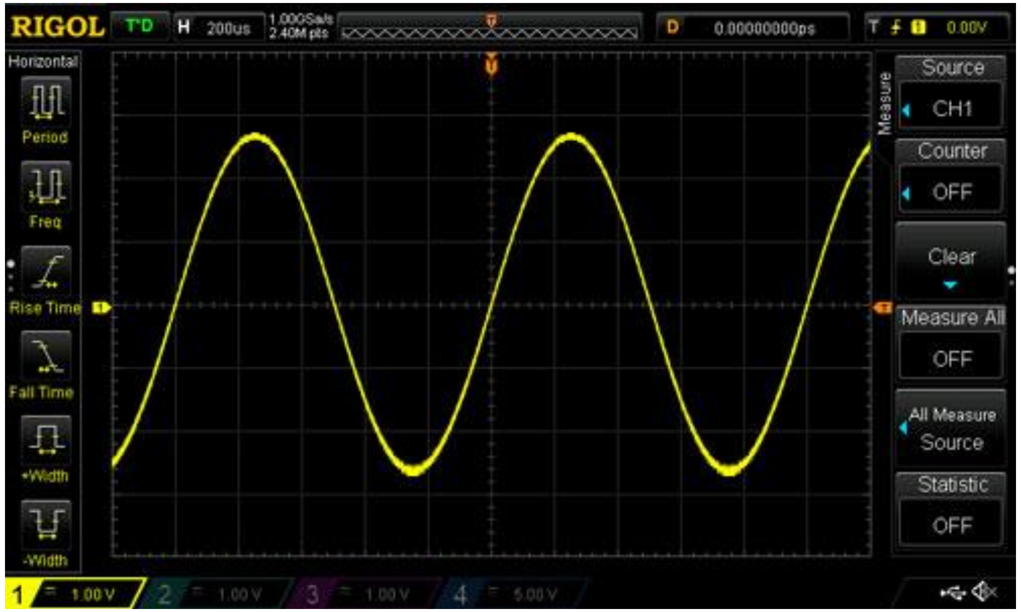
- Discuss nRF implementation of these peripherals

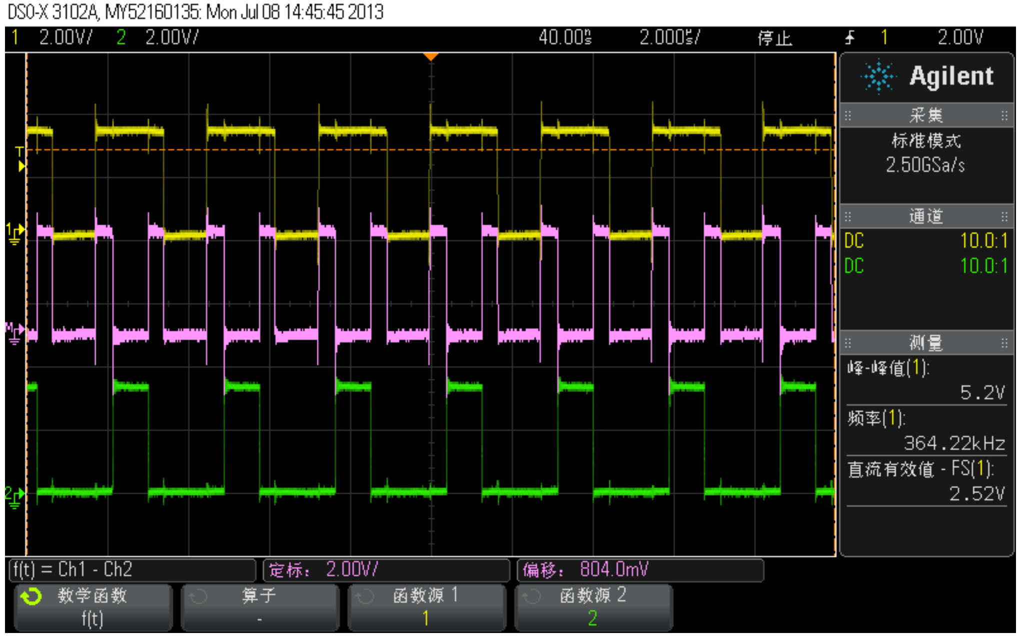
Outline

- **Comparators (and nRF implementations)**
- General ADC Design
- nRF ADC Implementation

Analog signals

- Exist in infinite states
  - From a maximum to a minimum
- Often used for interactions with the real world
  - Sensors usually generate analog signals
- Microbit example: microphone





Interacting with analog signals

- Microcontrollers are inherently digital

- Need a method for translating analog signal into a digital one

- Options:
  1. Determine if signal is higher or lower than some amount (Boolean)
  2. Determine voltage value of signal (N-bit number)

Interacting with analog signals

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- Options:
    1. **Determine if signal is higher or lower than some amount (Boolean)**
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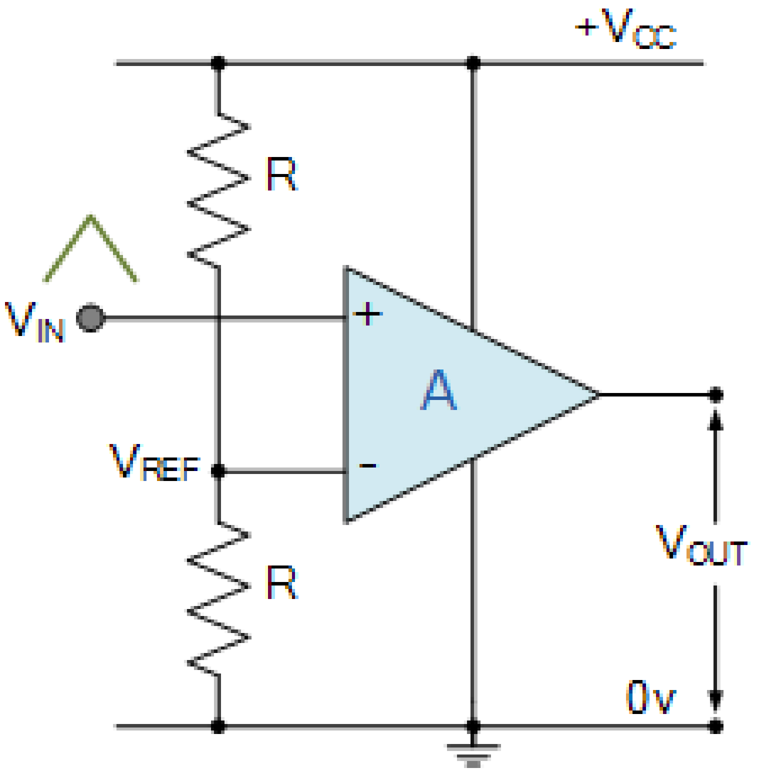
    Determination is done by a Comparator

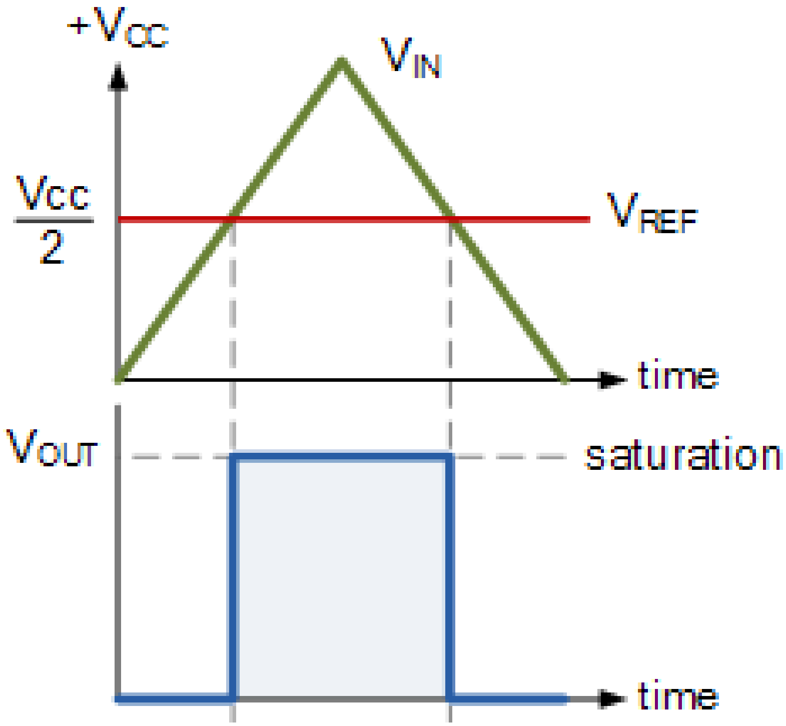
General comparator design

- Compares an analog input signal to a reference voltage

- V_{OUT} digital signal
  - High: $V_{IN} > V_{REF}$
  - Low: $V_{IN} < V_{REF}$

- Advantages:
  - Simple
  - Low power





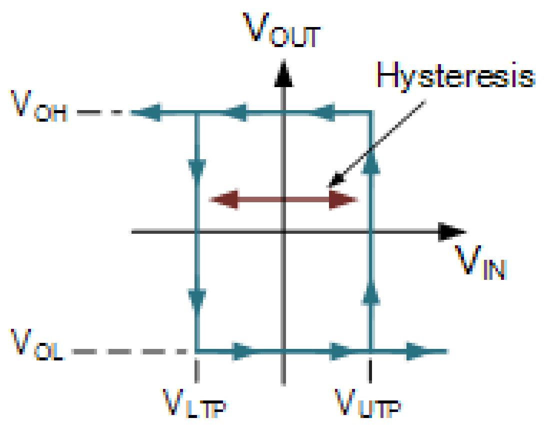
Comparator design questions

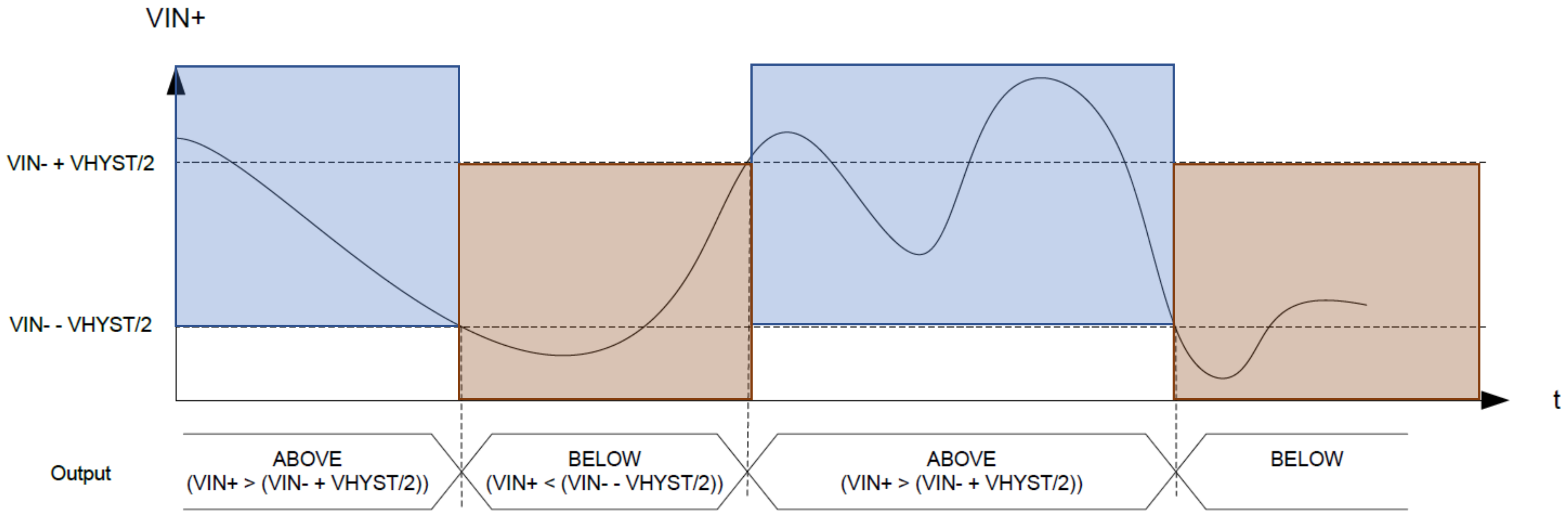
- What reference voltages are available?
  - A few internal voltages
  - Usually also allows external references from input pins

- When is an output generated?
  - Usually when status changes
    - Low-to-high, High-to-low, Both (like GPIO interrupts)

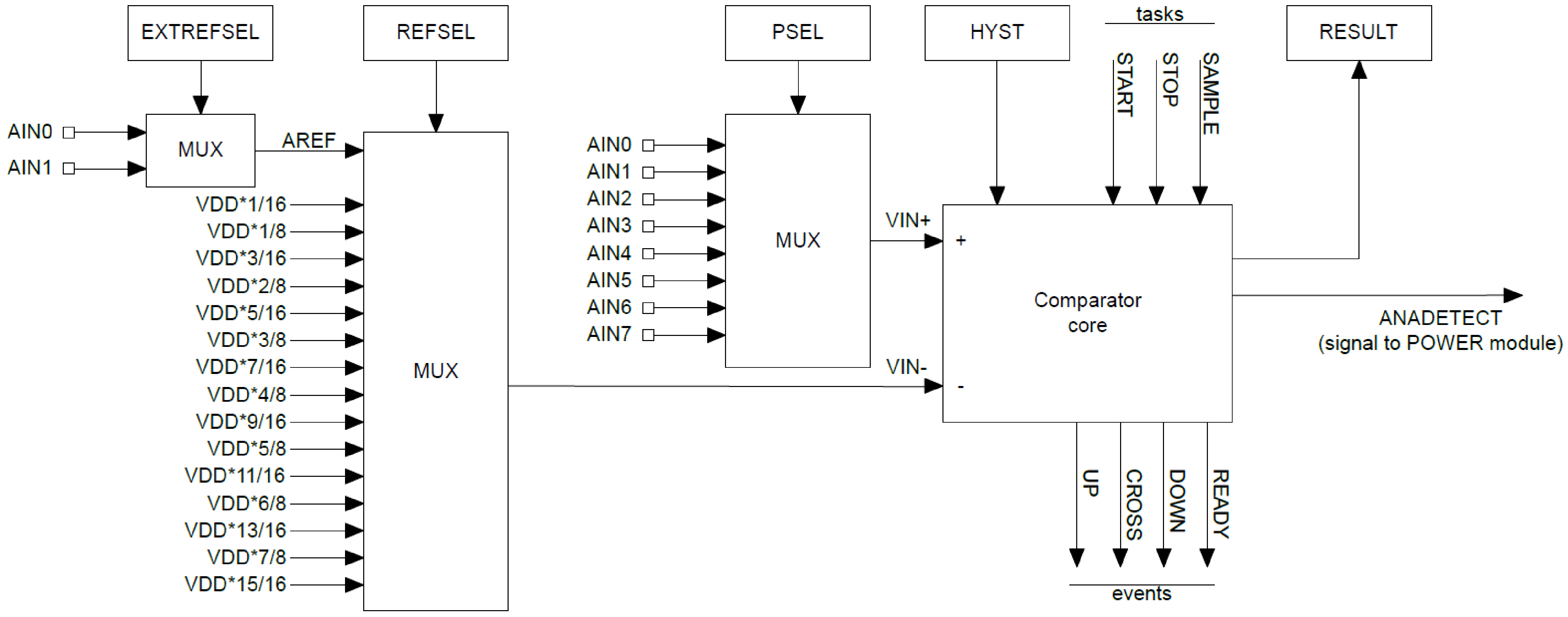
Hysteresis

- A window added around signal state changes to prevent small amounts of noise from changing the output





nRF low-power comparator (LPCOMP)



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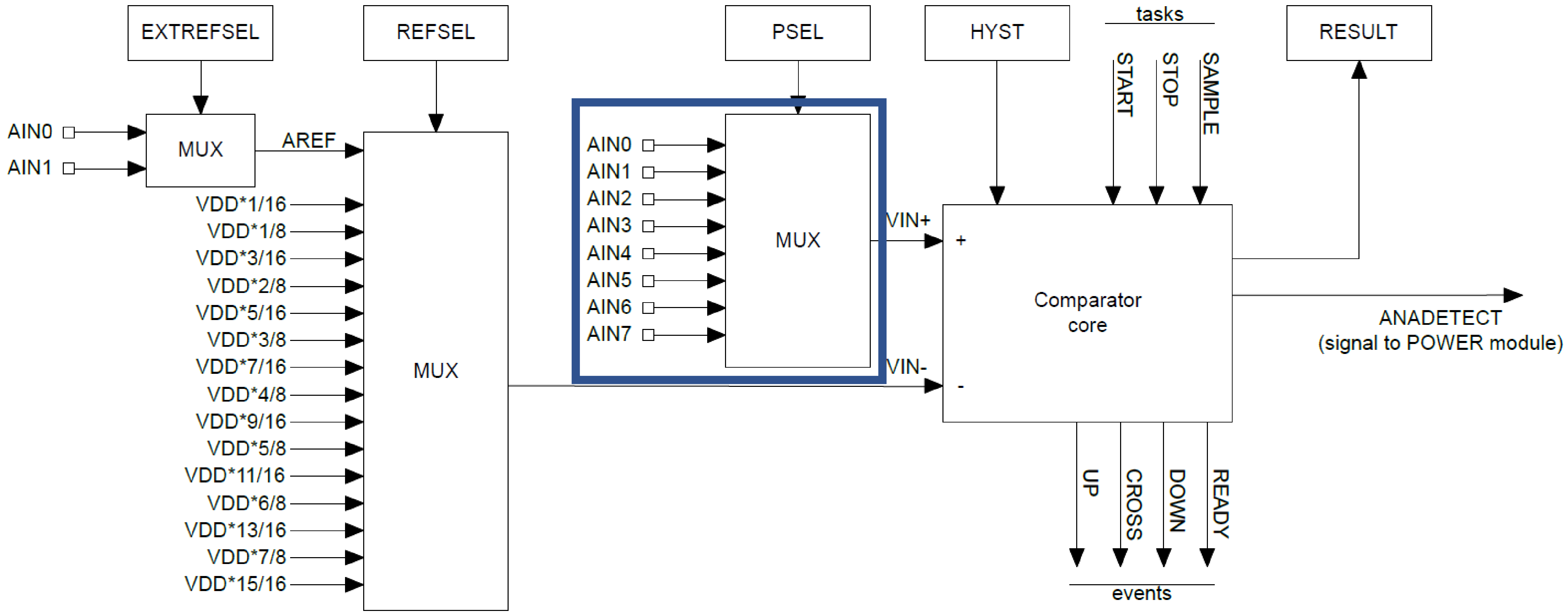
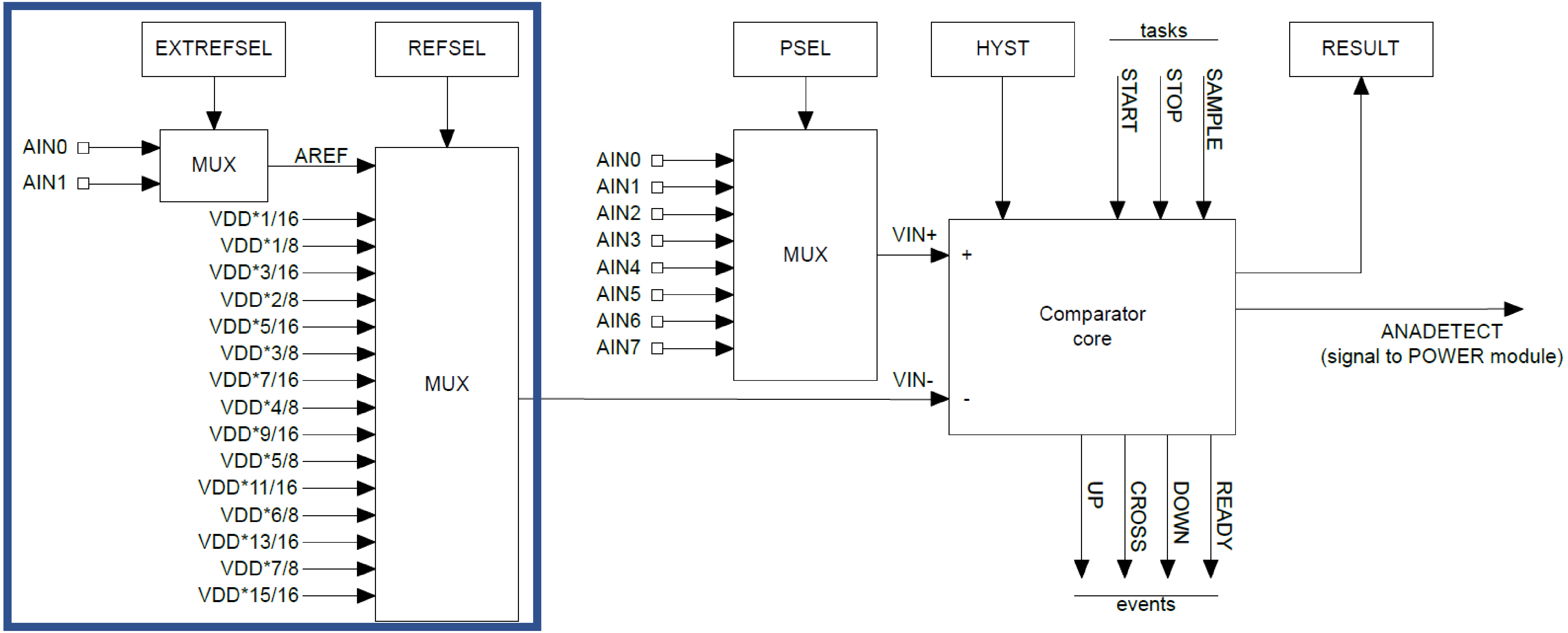


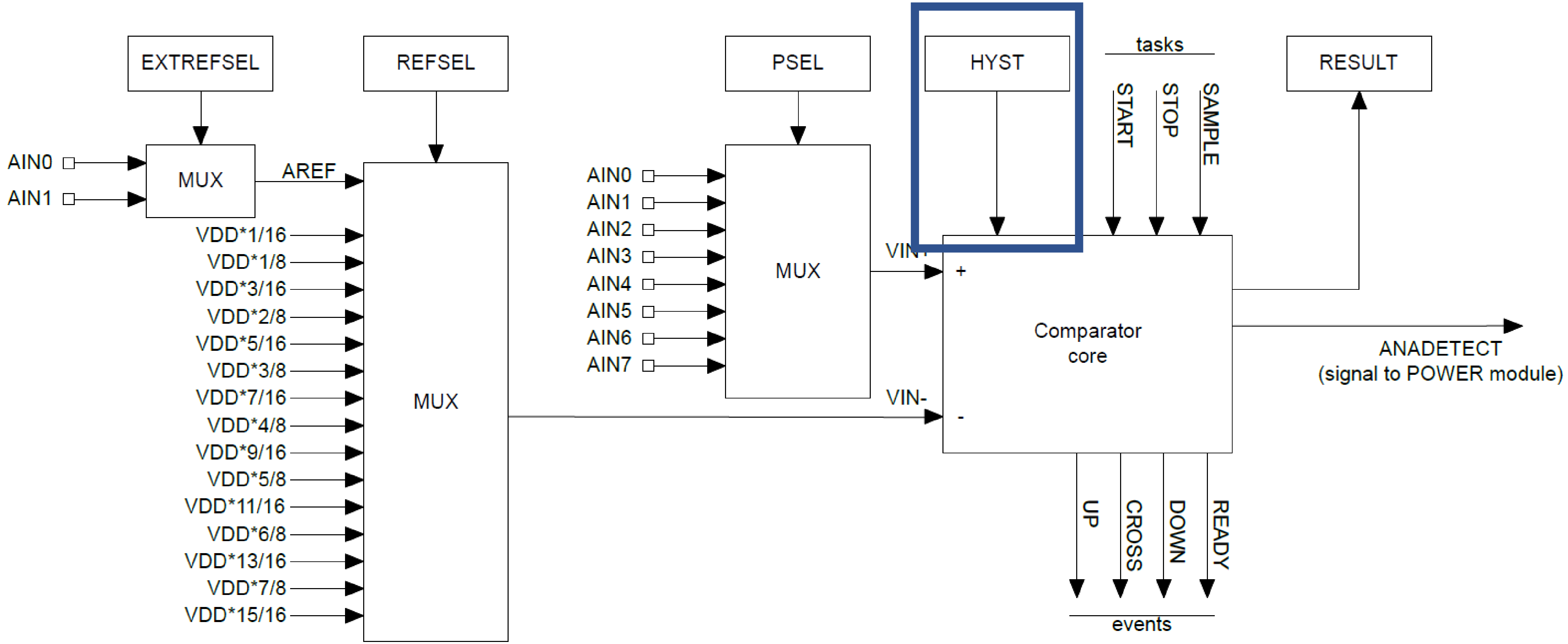
- Input: one of eight analog input pins

nRF low-power comparator (LPCOMP)



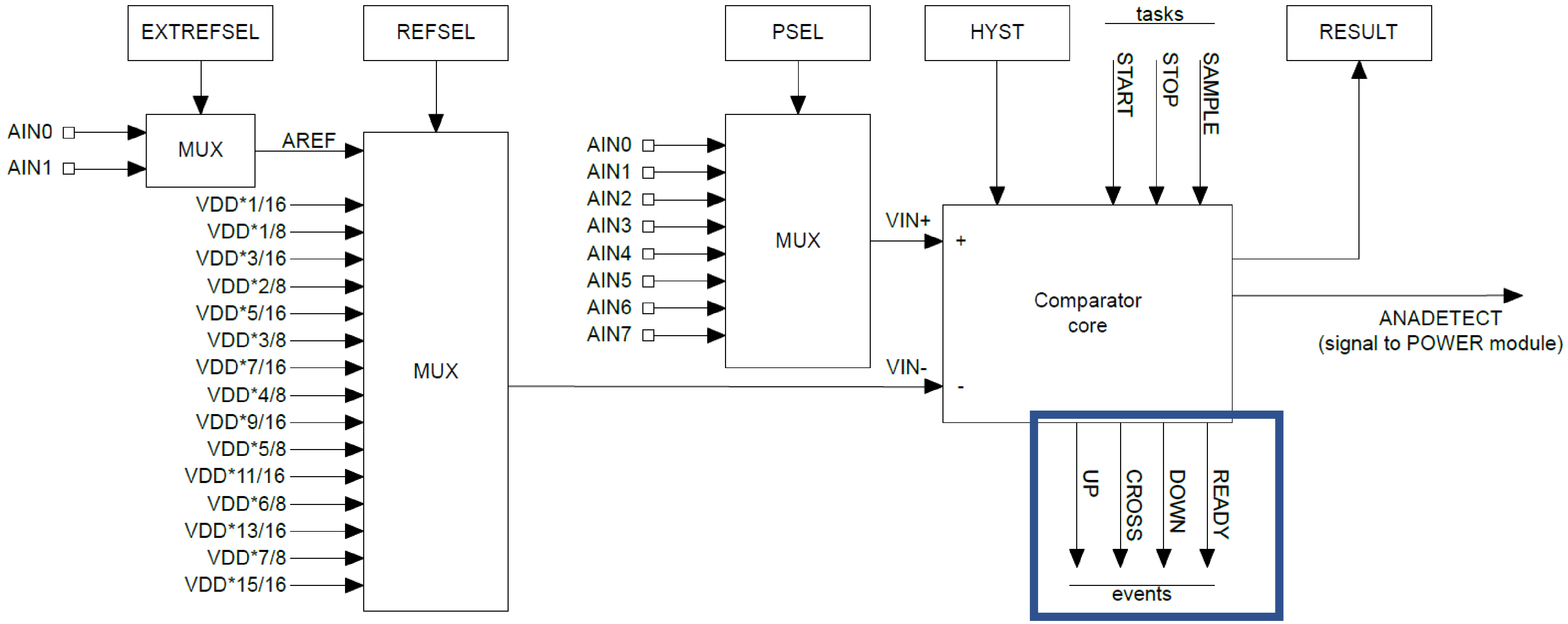
- Reference: one of two analog inputs or selection of VDD * N/16
  - VDD: Input voltage of the system

nRF low-power comparator (LPCOMP)



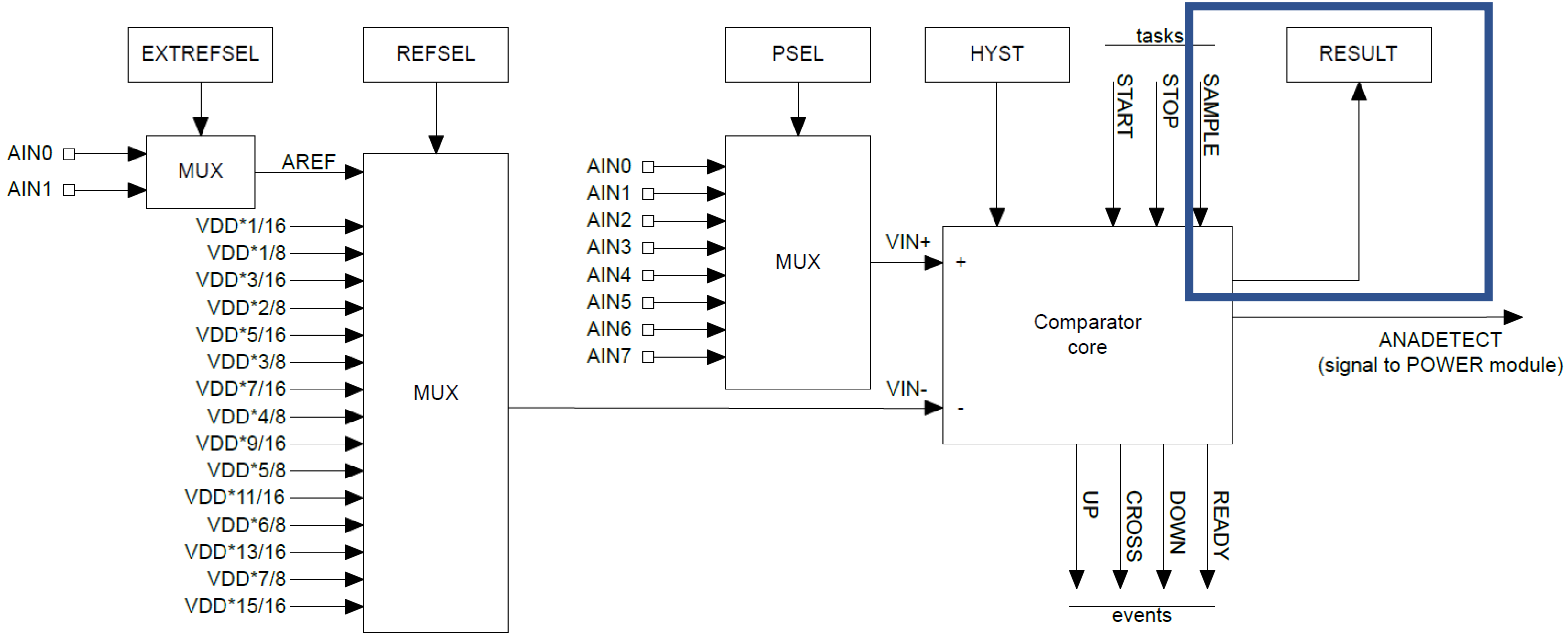
- Hysteresis: +/- 50 mV range around VIN- when enabled

nRF low-power comparator (LPCOMP)



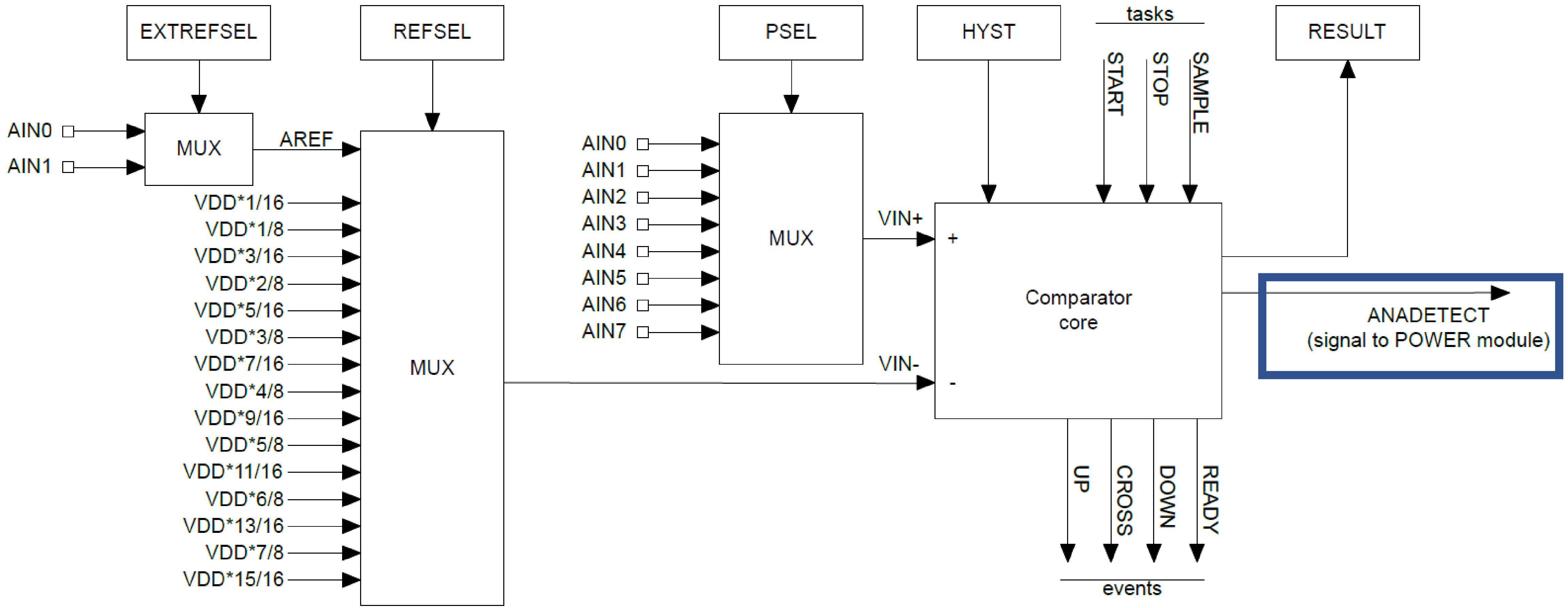
- Events: transition signals + ready (~150 μs startup time)

nRF low-power comparator (LPCOMP)



- Can also request what the current comparison state is (high/low)

nRF low-power comparator (LPCOMP)



- Can be used for low-power wakeup of microcontroller

nRF COMP peripheral

- Analog Comparator (not low power)
  - More advanced version of a comparator (otherwise similar)

- What advantages would a more capable comparator have?
  - Configurable hysteresis
    - LPCOMP: +/- 50 mV COMP: any of the N/64 voltage levels
  - Faster detection
    - LPCOMP: 5 μs COMP: 0.1-0.6 μs (depending on power mode)
  - More possible reference voltages
    - LPCOMP: VDD or input COMP: VDD, 1.2v, 1.8v, 2.4v, or input
    - LPCOMP: 16 levels COMP: 64 levels

Break + Question: Internal reference voltages

- **Why have internal voltage references other than the system voltage (VDD)?**

Break + Question: Internal reference voltages

- **Why have internal voltage references other than the system voltage (VDD)?**

  - What if want you want to measure *is* VDD?
    - Battery voltage
    - Did someone just unplug me?
    - etc.

  - What if VDD isn’t stable?
    - Battery voltage
    - Energy-harvesting system
    - Hard to know what any particular value means…

Outline

- Comparators (and nRF implementations)
- **General ADC Design**
- nRF ADC Implementation

Interacting with analog signals

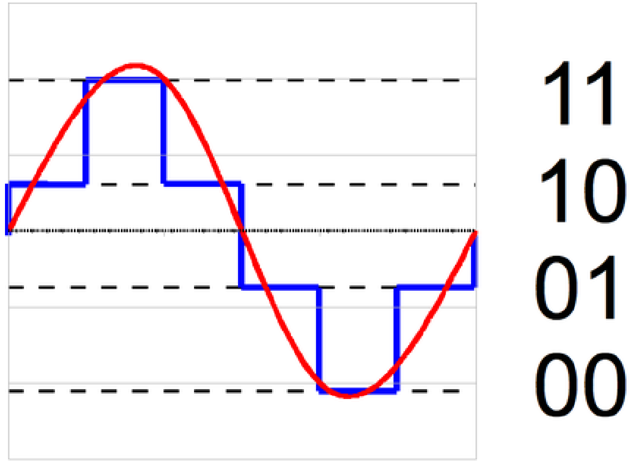
- Microcontrollers are inherently digital

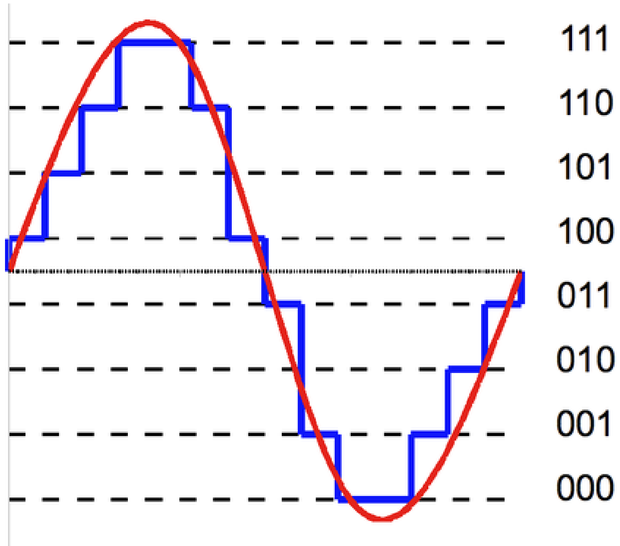
- Need a method for translating analog signal into a digital one

- Options:
    1. Determine if signal is higher or lower than some amount (Boolean)
    2. **Determine voltage value of signal (N-bit number)**

    Translation is done by an Analog-to-Digital Converter (ADC)

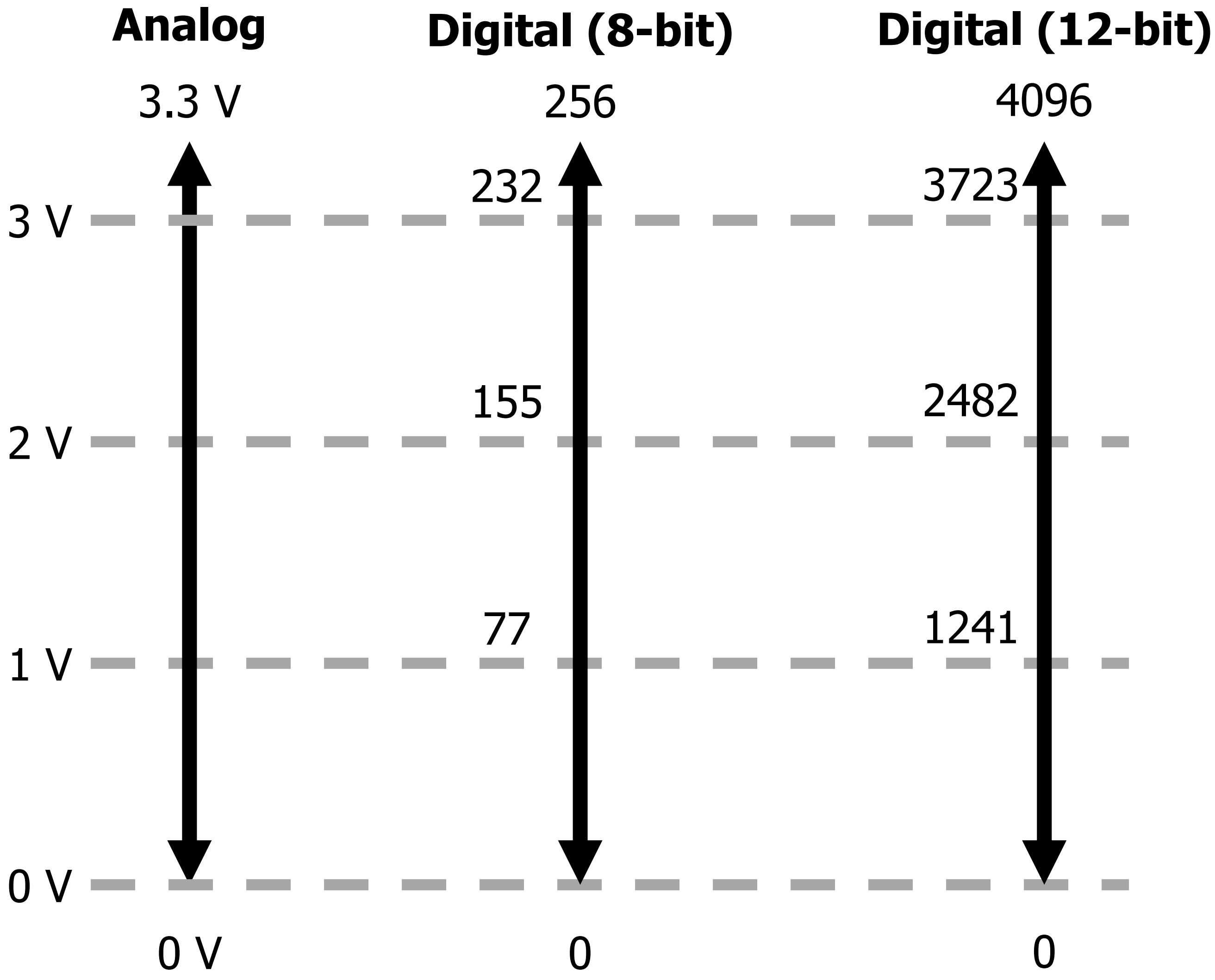
Quantization





- Analog voltages are represented by discrete voltage levels
- Comparators are 1-bit ADCs
  - Split into two regions
  - Good ADCs split into 4000-16000 regions
- More levels gives a more accurate representation of the signal

Translating voltage and ADC counts



$$Value = \frac{V_{IN}}{V_{REF}} * \left(2^{Resolution}\right)$$

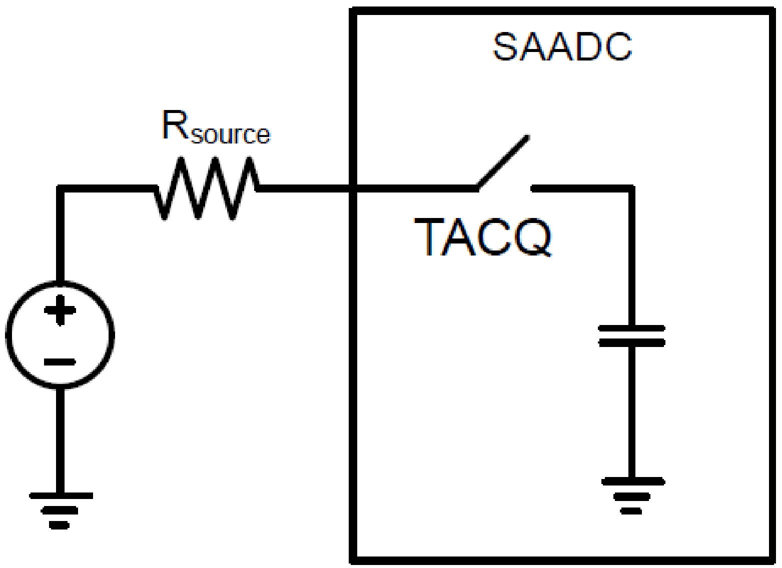
- V_{REF} selects maximum range
- Ground is usually minimum range
- Resolution depends on hardware
  - Either hardcoded or a selection

Analog to digital translation process

- Two steps:

1. Acquisition
   - Read in signal for some amount of time

   - Signal connected to a capacitor
   - Fills capacitor up to voltage level
   - Speed depends on input resistance
     - 1-100 μs is common



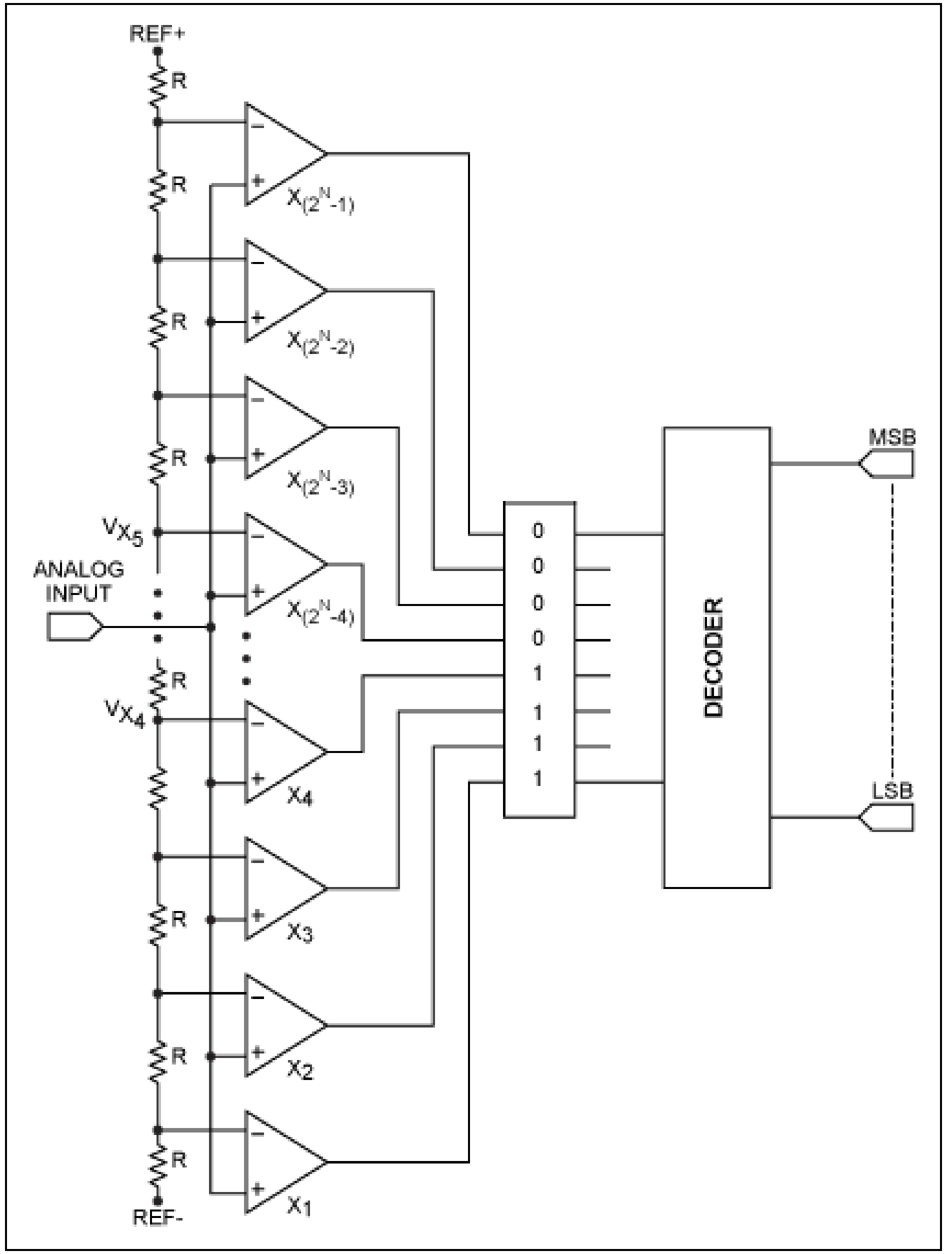
2. Conversion
   - Determine which digital value the read signal corresponds to

Direct-conversion ADC

- Chain comparators together
  - Each with a separate reference voltage

- Digital value determined immediately
  - Also known as "Flash" ADCs

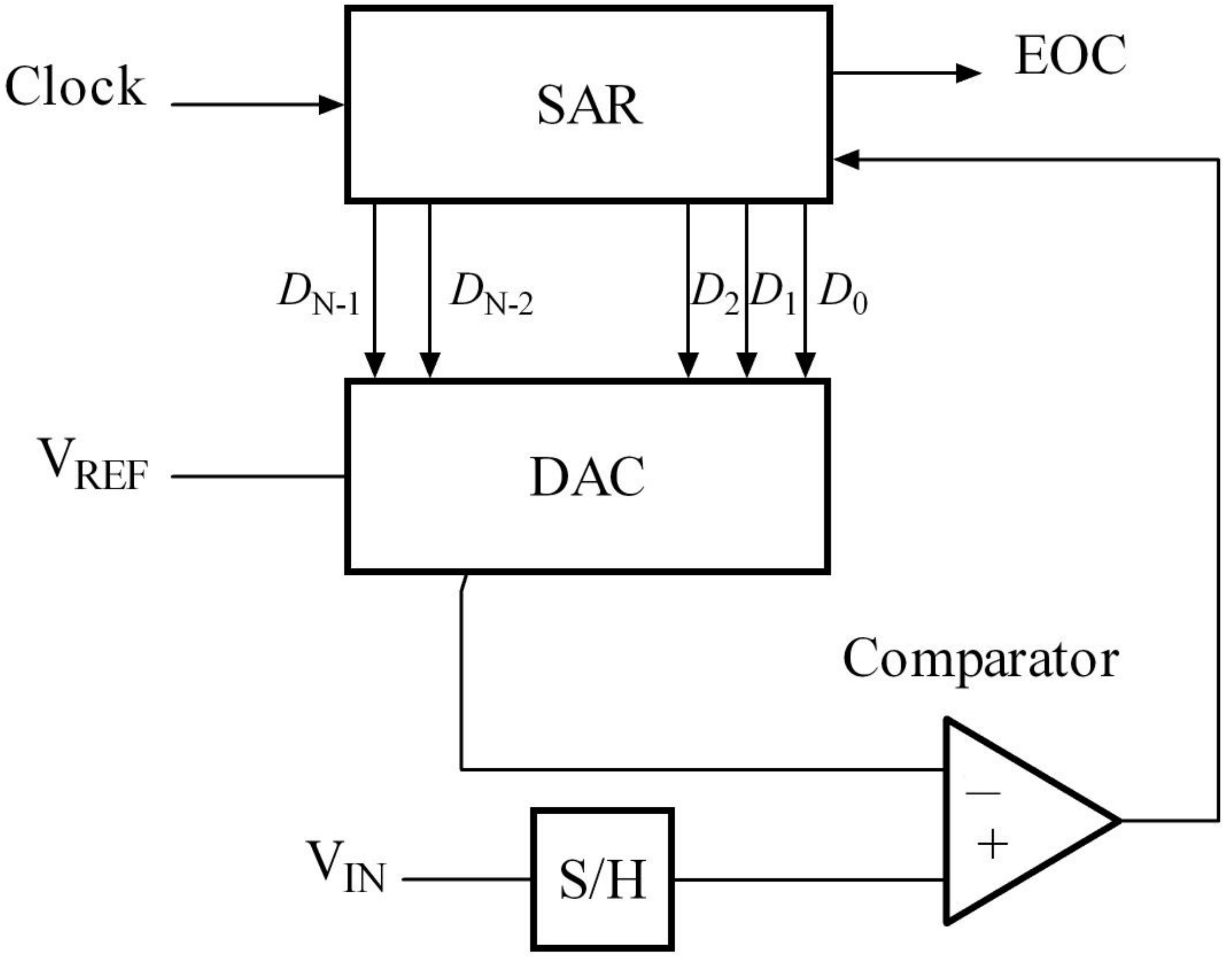
- Downside: needs 2^n-1 comparators
  - Reserved for expensive applications



Successive-Approximation ADC

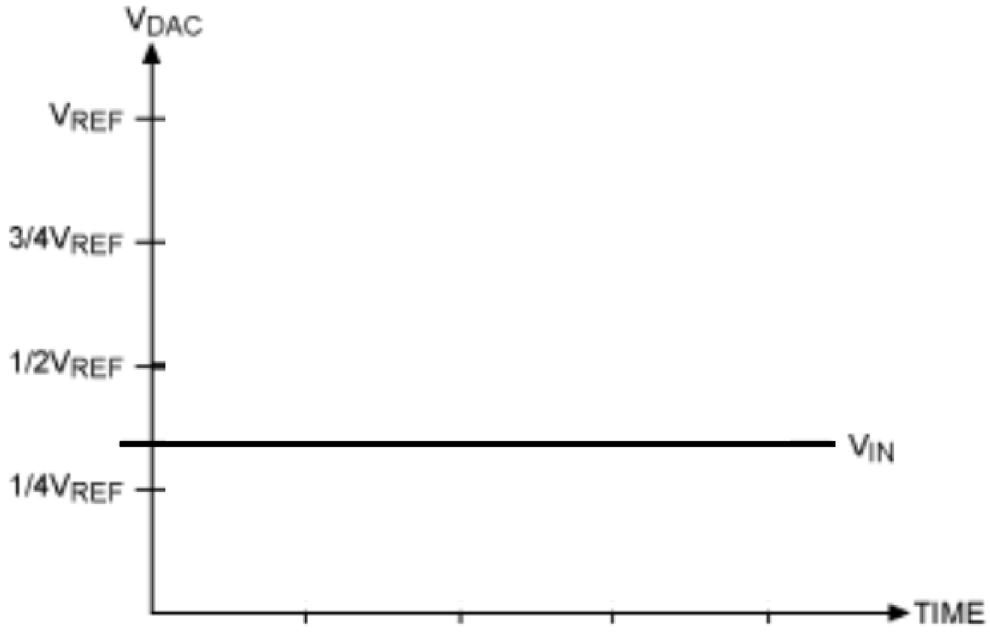
- Method: Binary Search
  - Compare signal to generated reference
  - Increase or decrease reference as needed
  - Repeat

- DAC creates reference (Digital-to-Analog Converter)
  - Final value of DAC is the ADC value



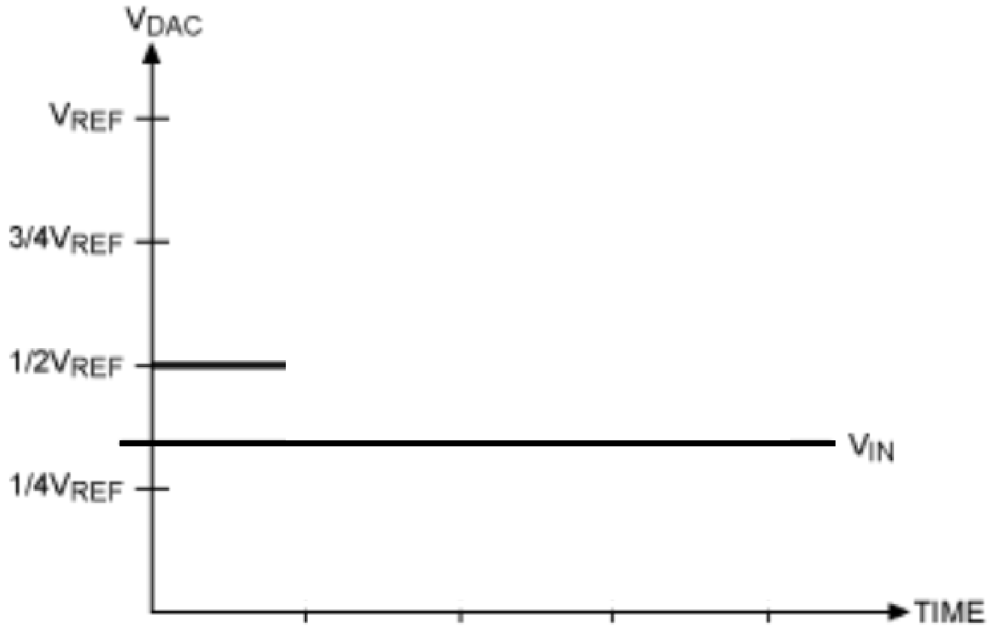
Successive Approximation Example

- 4-bit ADC with an input signal V_{IN}



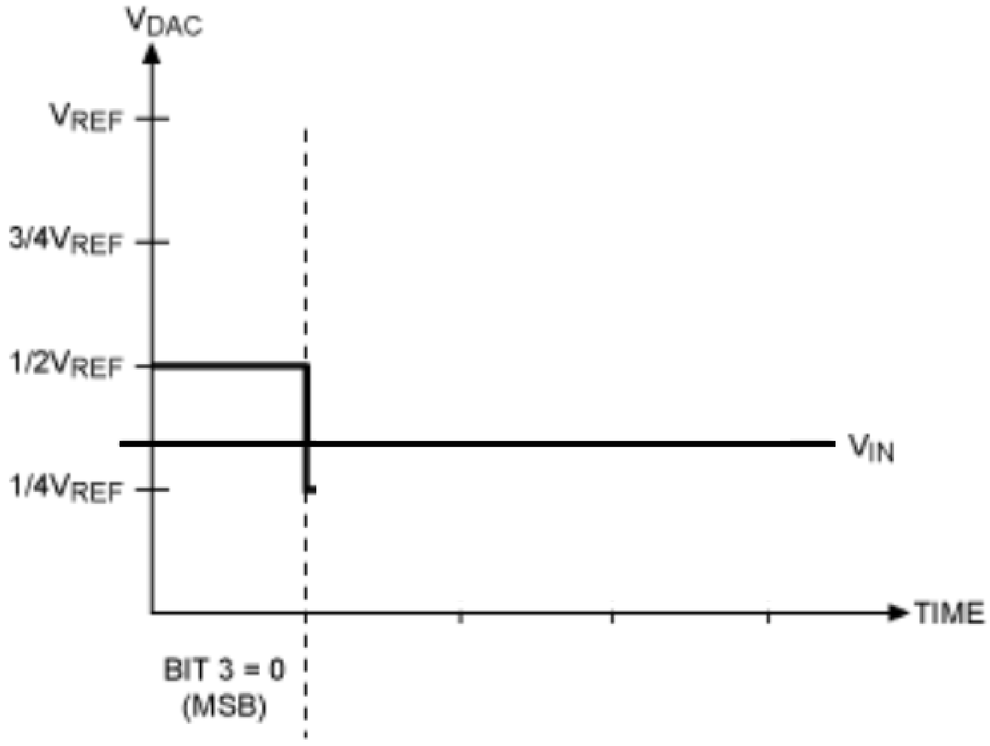
Successive Approximation Example

1. Compare ½ V_{REF} (0b<u>?</u>???) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero



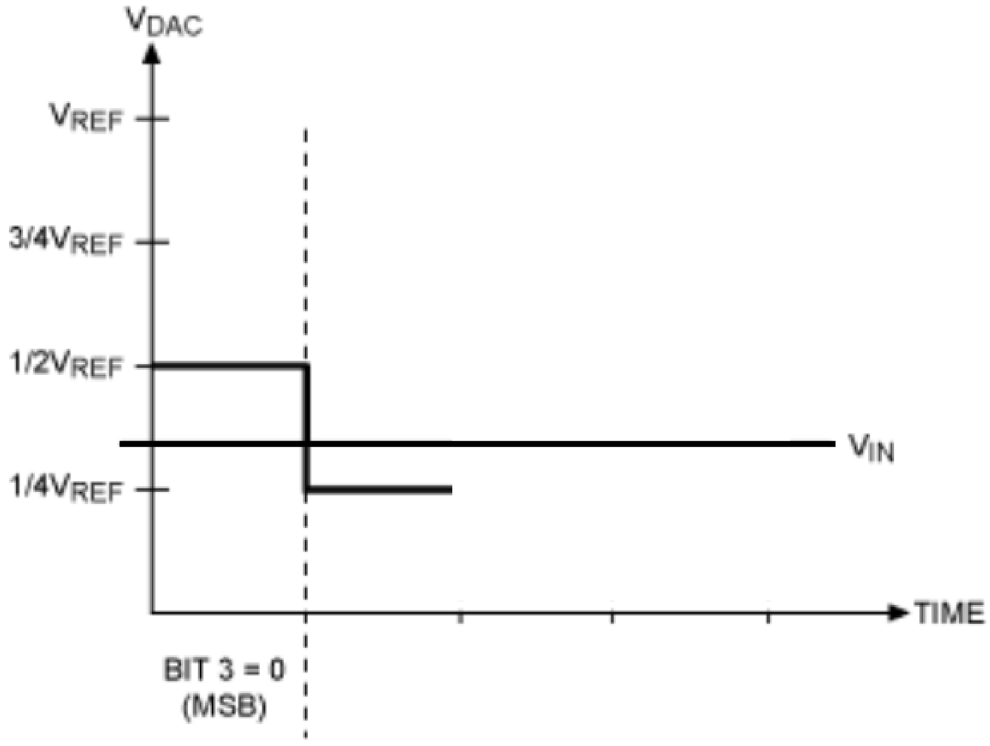
Successive Approximation Example

1. Compare ½ V_{REF} (0b**0**???) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero
   - V_{IN} is less. So set that bit to zero



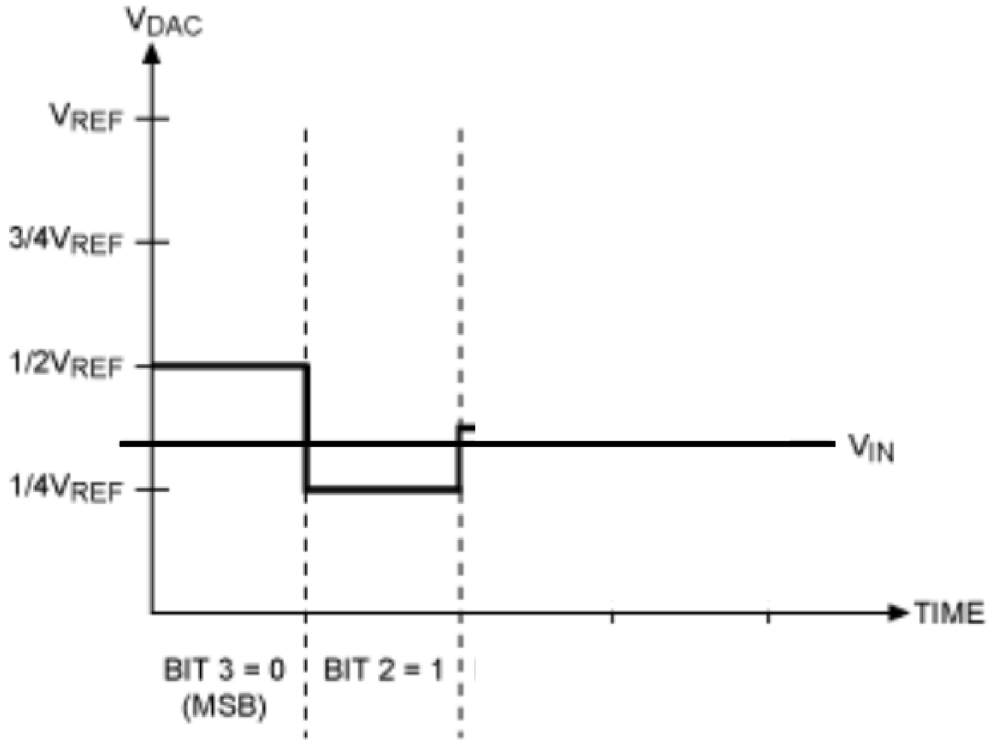
Successive Approximation Example

2. Compare 1/4 V_{REF} (0b**0**?̲??) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero



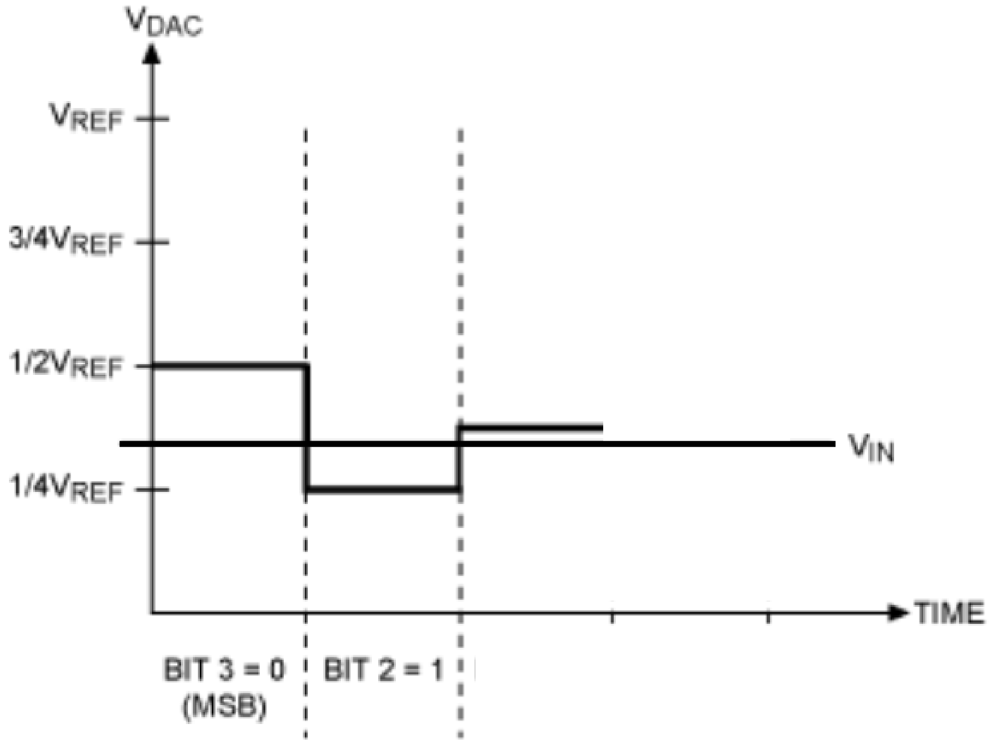
Successive Approximation Example

2. Compare 1/4 V_{REF} (0b**01**??) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero
   - V_{IN} is greater. So set that bit to one



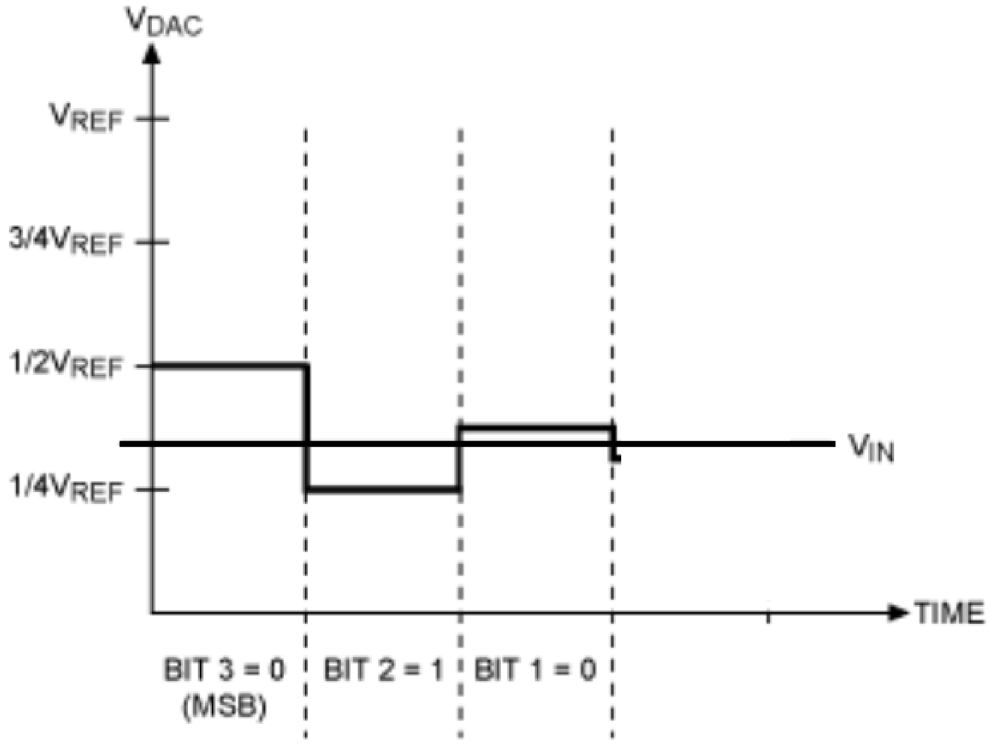
Successive Approximation Example

3. Compare 3/8 V_{REF} (0b**01**<u>?</u>?) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero



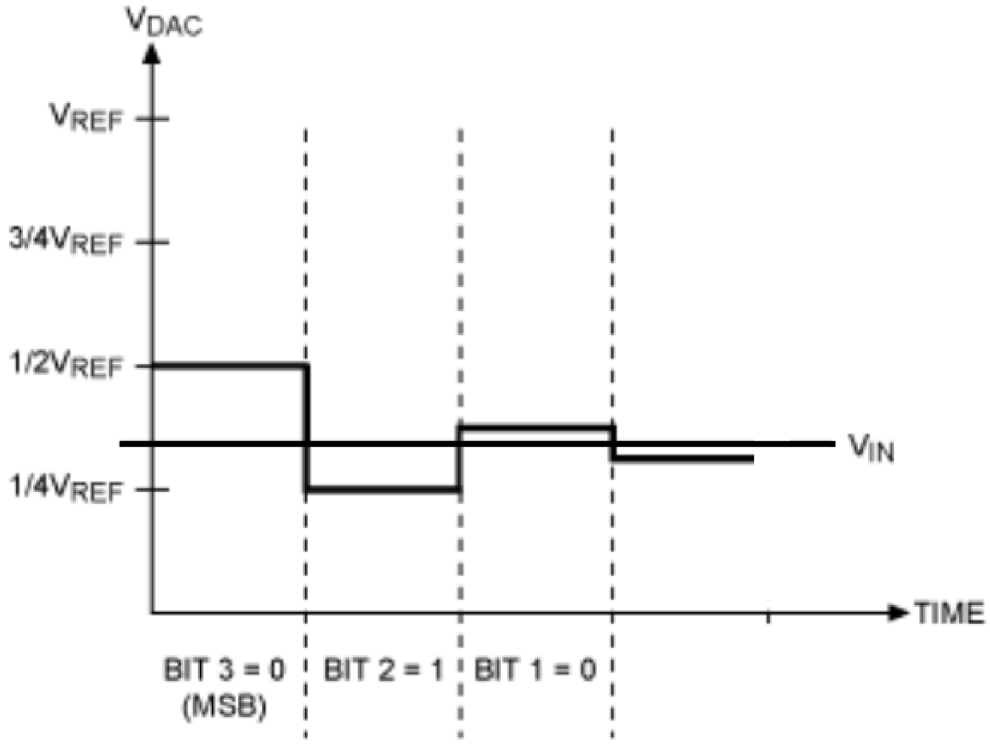
Successive Approximation Example

3. Compare 3/8 V_{REF} (0b**010**?) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero
   - V_{IN} is less. So set that bit to zero



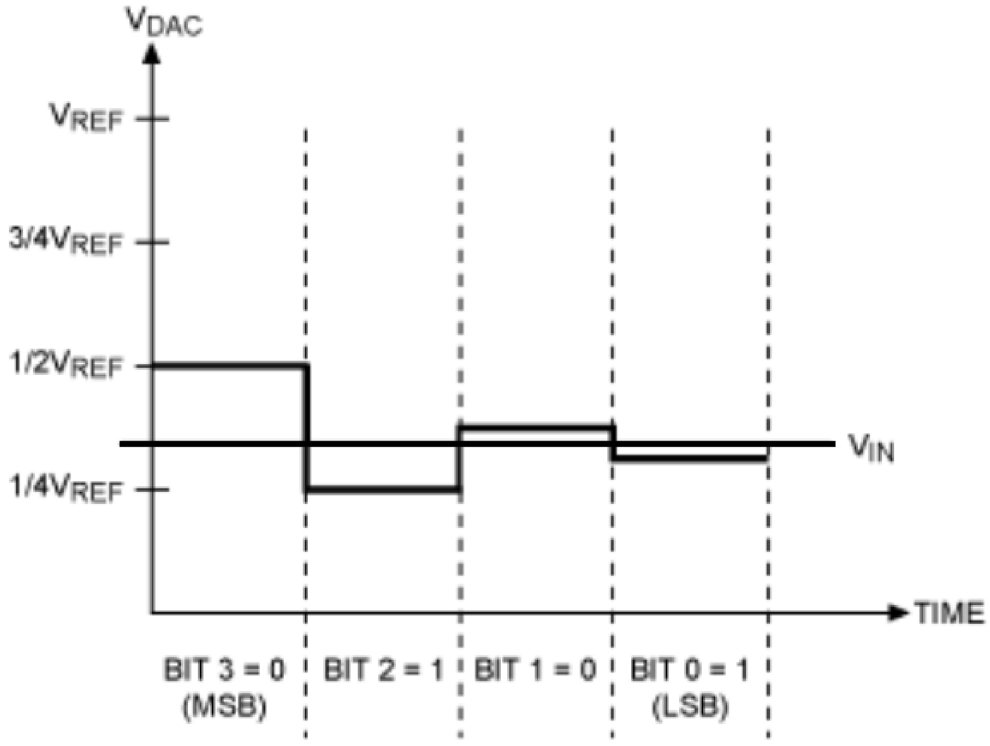
Successive Approximation Example

4. Compare 5/16 V_{REF} (0b**010**?) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero



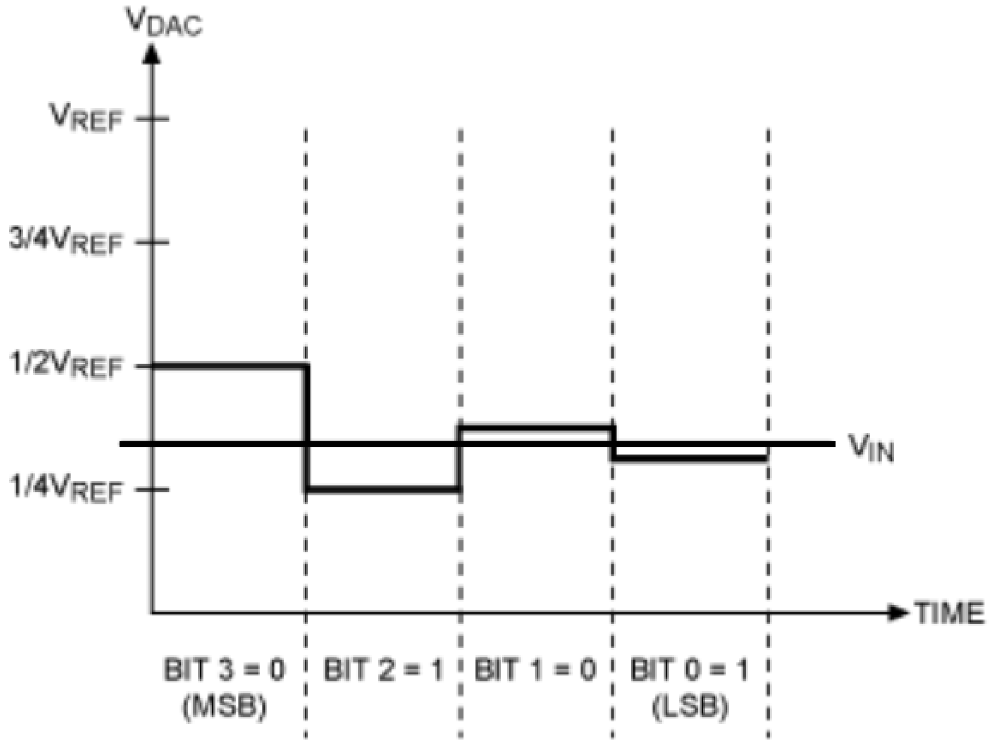
Successive Approximation Example

4. Compare 5/16 V_{REF} (0b**0101**) to V_{IN}
   - If V_{IN} is greater, bit is 1. Else zero
   - V_{IN} is greater. So bit is one



Successive Approximation Example

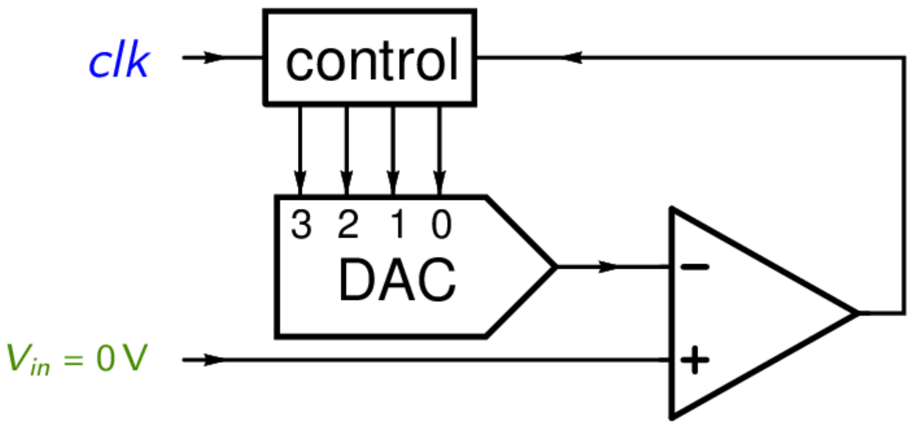
5. Output is 5/16 V_{REF} (0b0101)
   - Slight underestimate of the real value, but as close as we can get
   - More bits would get us even closer



Successive Approximation Example

Successive Approximation – example of a 4-bit ADC

- Performs a binary search to determine correct reference signal value



Resolution:

5 V × 1/2	2.5000 V
5 V × 1/4	1.2500 V
5 V × 1/8	0.6250 V
5 V × 1/16	0.3125 V
...	
5 V × 1/1024	0.0049 V

https://en.wikipedia.org/wiki/Successive-approximation_ADC

Tradeoffs in ADC design

- Direct-Conversion: more expensive (more silicon)
- SAADC: more time consuming (more binary search time)

- Most microcontrollers land on successive-approximation designs
  - The slowdown isn't an issue for slowly changing signals
  - Quickly changing signals probably need special hardware anyways

Break + Critical Thinking

- How much ADC resolution is needed?

Break + Critical Thinking

- How much ADC resolution is needed?
  - Resolution requirement depends on signal being sensed
  - Temperature sensor probably doesn't need 16-bit ADC
    - Difference between 30.001°C and 30.002°C is usually irrelevant
  - Microphone might though!
    - Differences are audible until they are small enough
    - 16-bit or 24-bit tend to be common choices for audio data

Outline

- Comparators (and nRF implementations)
- General ADC Design
- **nRF ADC Implementation**

nRF SAADC (Successive Approximation ADC)

- Only one actual ADC peripheral in the chip
  - One measurement at any given time

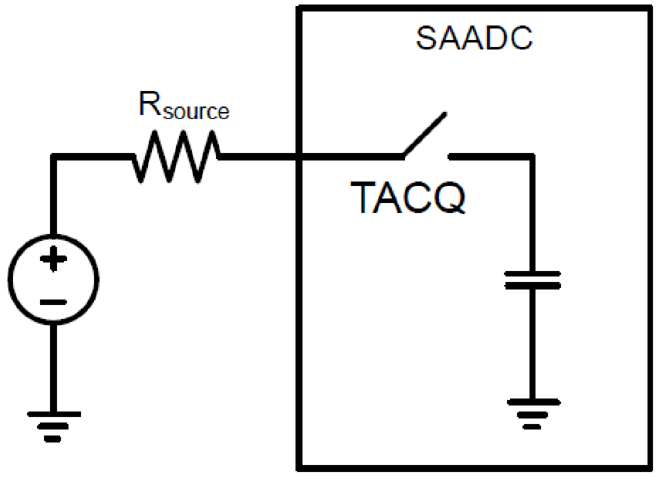
- However, provides 8 different “channels” with unique configurations
  - Virtualization in hardware!
  - Typical setup is to sample each channel one-after-the-other

SAADC Resolution and Sampling

- Resolution is selectable (for the whole peripheral)
  - 8, 10, 12, or 14 bits
  - Result stored as 16-bit value regardless

- Sampling time is selectable (for each channel)
  - 3-40 μs

  - Longer sampling time is important for very low-current signals



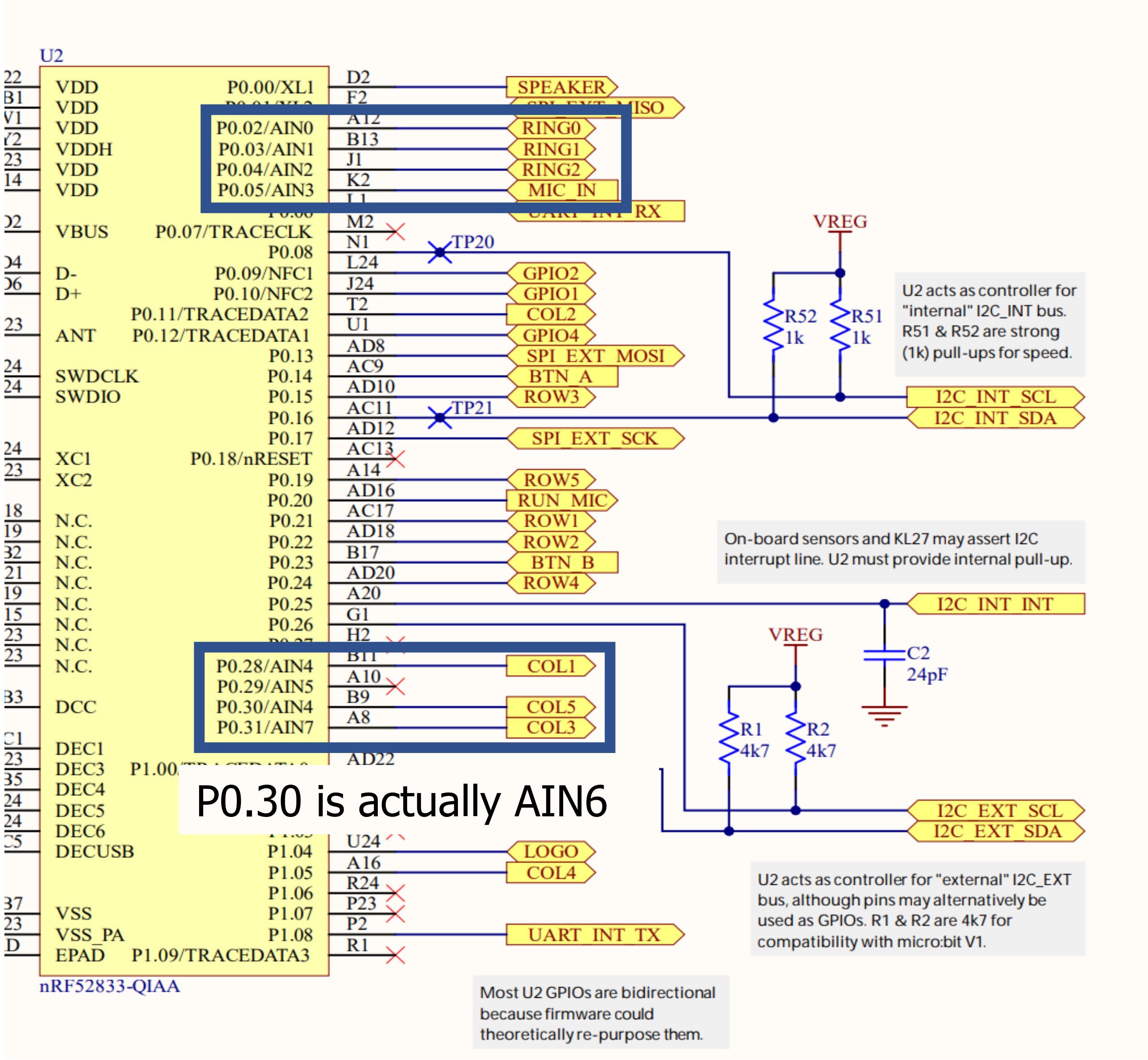
nRF SAADC Inputs

- Can read the system voltage directly
- Or read one of 8 different analog input pins
  - These pins ARE fixed and not totally reconfigurable
  - Analog signals are more susceptible to interference
- Need to make sure that you’re connecting to an analog input pin

Analog inputs on the Microbit

- Of the 8 analog input pins
  - One for microphone
  - One is not connected
  - Three are repurposed for the LED matrix
  - **Three are available as external inputs**

- For projects, students sometimes end up with external ADCs



Triggering sample collection

- Can be triggered with TASK_START on demand
  - Including through EVENT->TASK chaining

- Includes a timer within itself to automatically trigger sampling
  - Rate = 16 MHz / (2^{Scale})   where scale is 11 bits
  - Maximum rate is 7.8 kHz

EasyDMA on the SAADC

- There is no register to read ADC results from

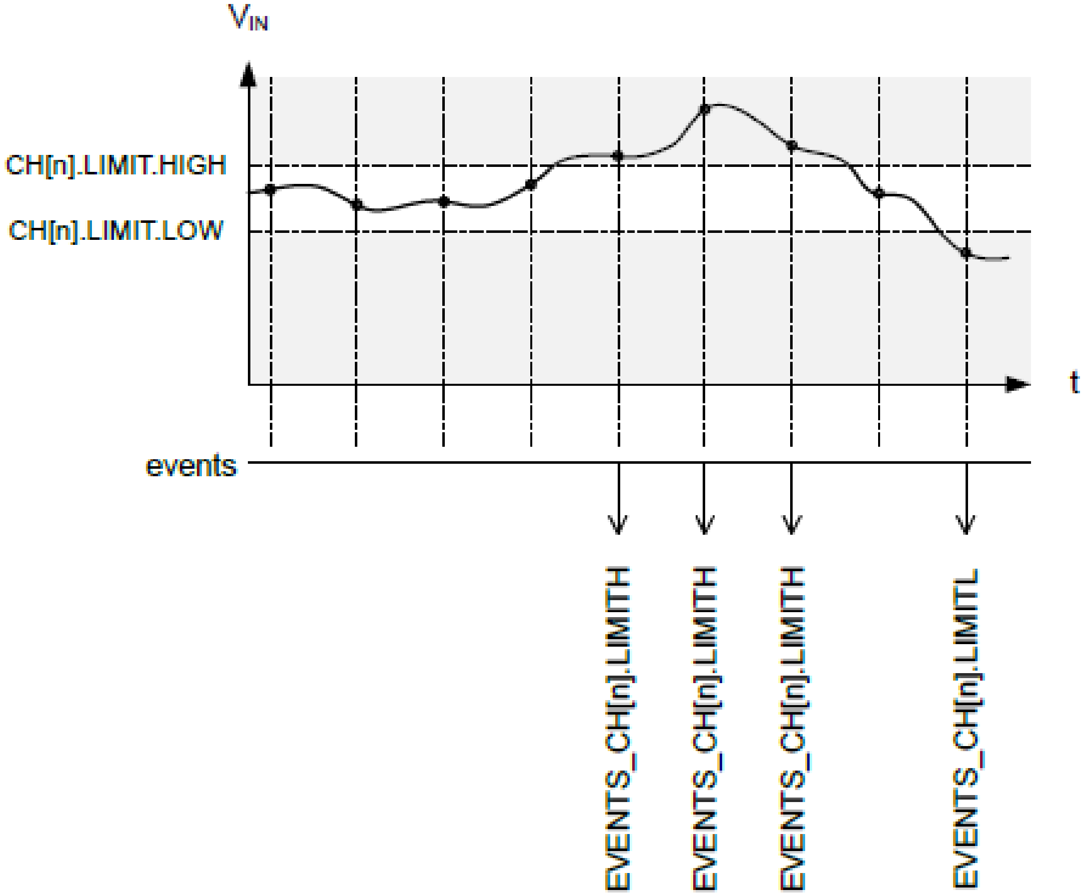
- Instead, you must use DMA to collect samples
- At configuration time, provide:
  - Pointer to RAM
    - Must be RAM, not Flash
  - Maximum count of 16-bit samples to be written starting at address
    - Up to 32768

- When complete, a register tells you the amount of samples written to RAM

Analog signal monitoring

- Includes two comparators for each channel
  - High and Low limits

- Generates events whenever transitioning above High or below Low
  - Events can generate interrupts if desired



Design question

- How many analog samples can the Microbit hold?

Design question

- How many analog samples can the Microbit hold?
  - Available: 128 kB RAM, 512 kB Flash
    - 64000 samples in RAM
  - Questions
    - Are they packed or padded to 16-bit?
    - How much memory are you using for other things?
    - Are you moving them into Flash periodically? (or external storage)

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