Lecture 08
Analog Input

CE346 – Microprocessor System Design

Branden Ghena – Fall 2021

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

Northwestern

Administrivia

- Project proposal feedback late this weekend

- Various grades will be released soon

- Lab hours today 5-6:30pm

- Remember to answer the post-lab questions on Canvas

Today’s Goals

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

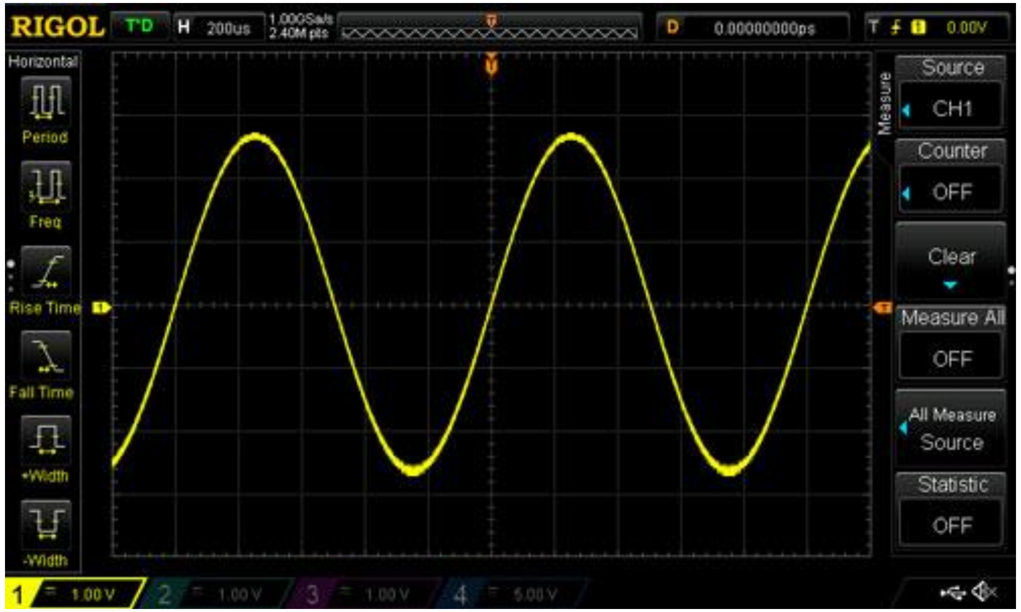
- Discuss nRF implementation of these peripherals

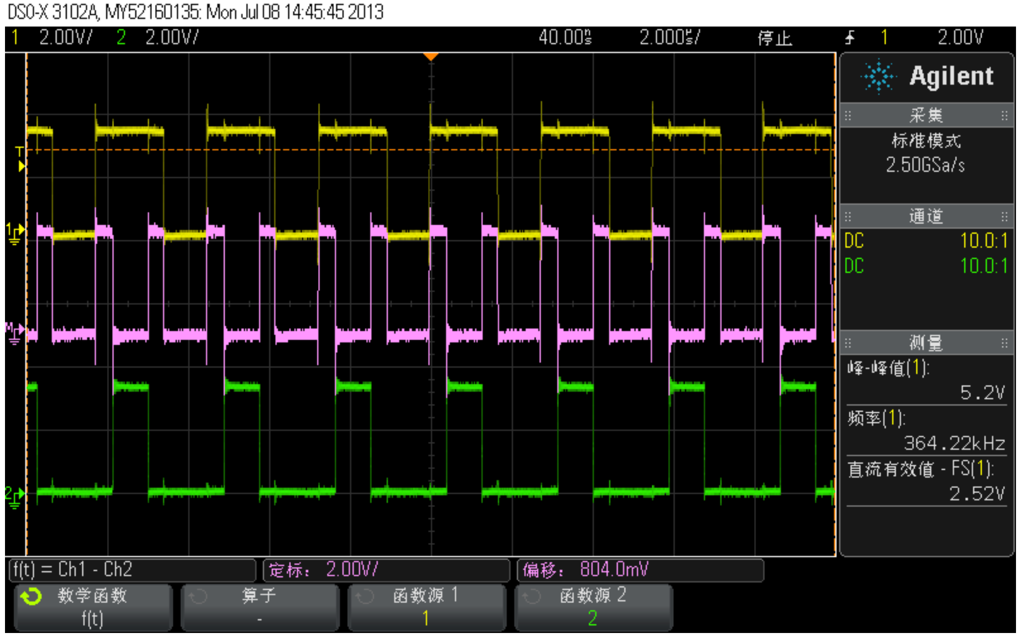
Outline

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

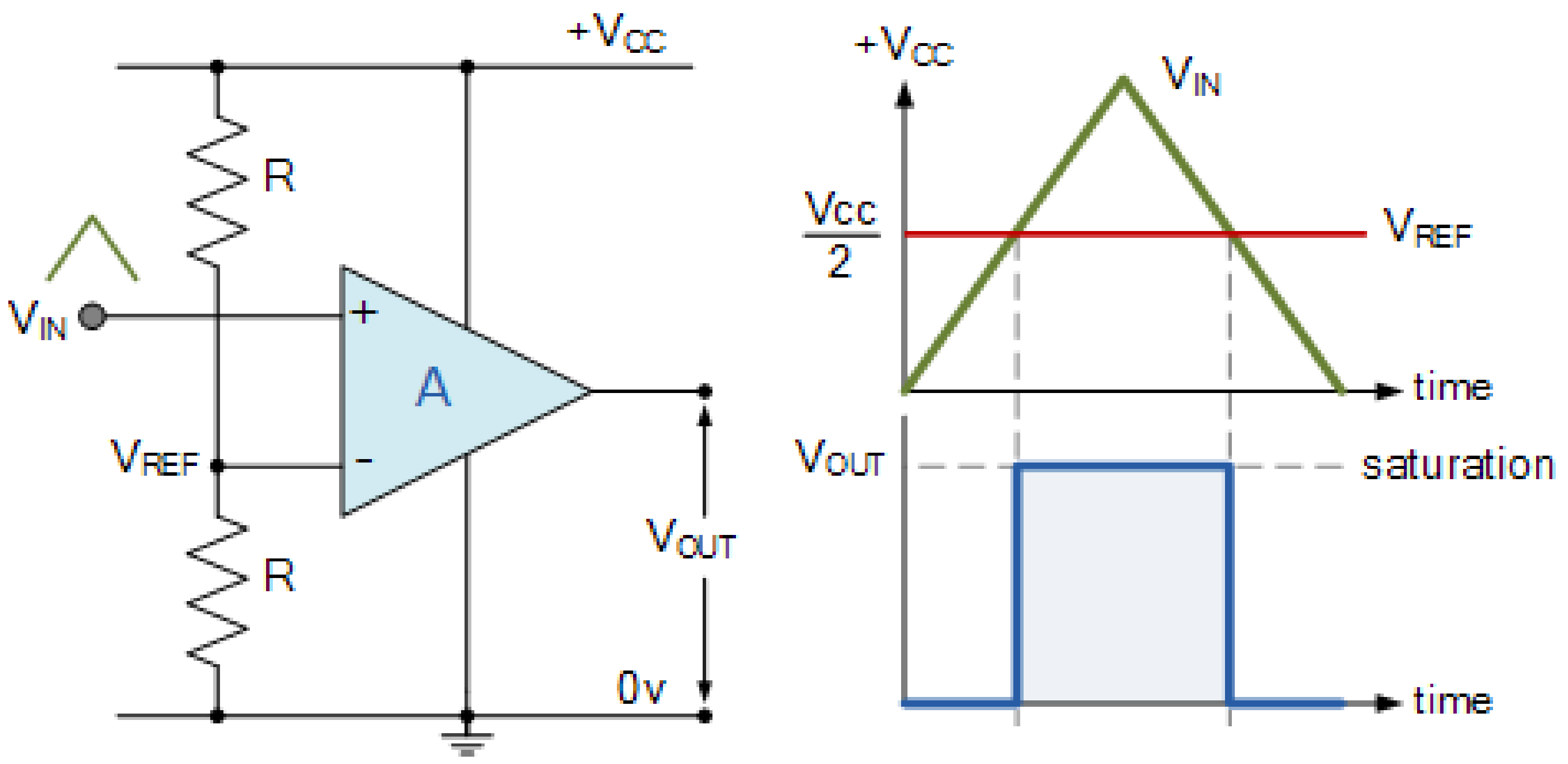
  Determination is done by a Comparator

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



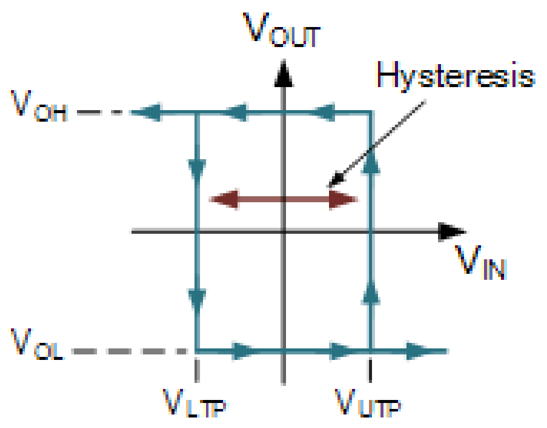
Comparator design questions

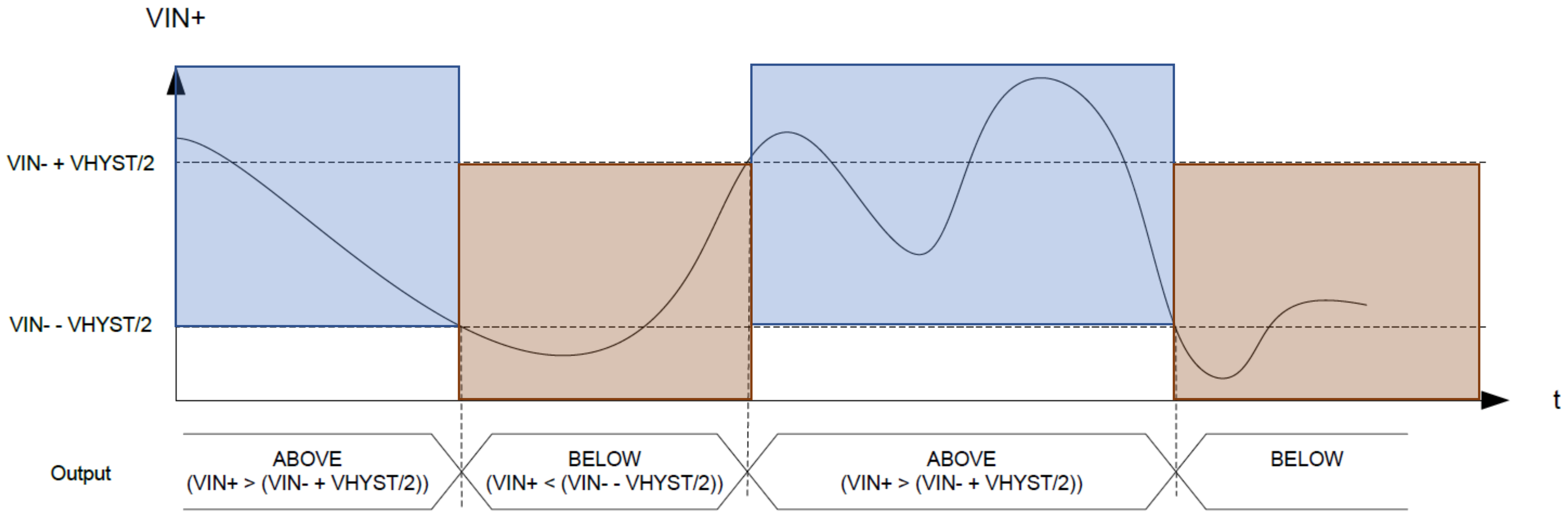
- What reference voltages are available?
  - A few internal voltages
  - Usually also allows external references from input pins

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

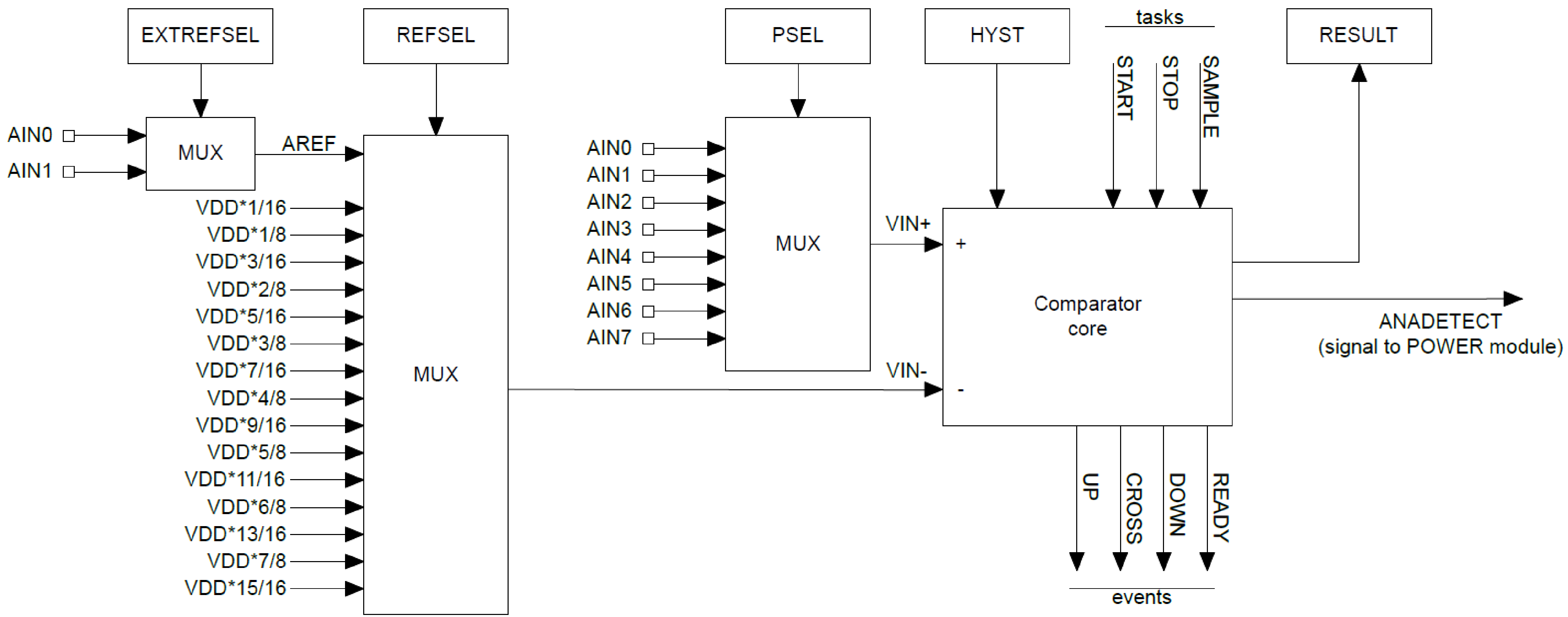
Hysteresis

- 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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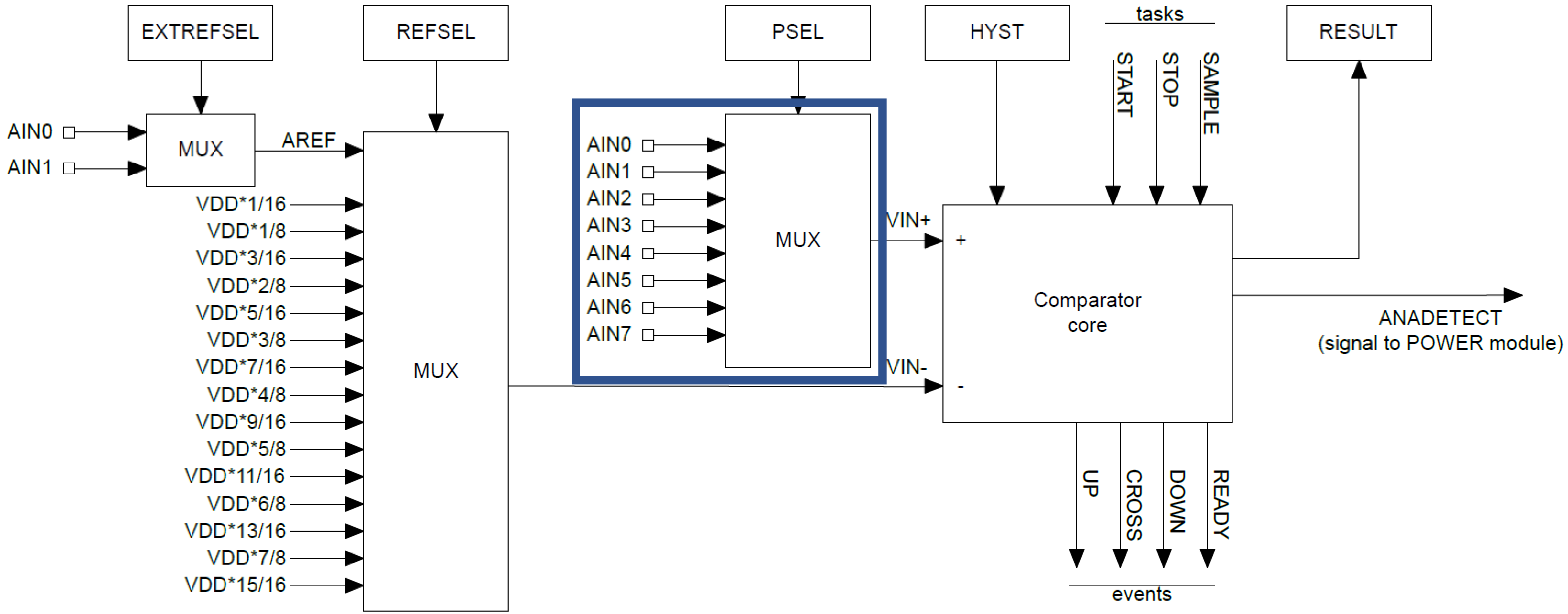
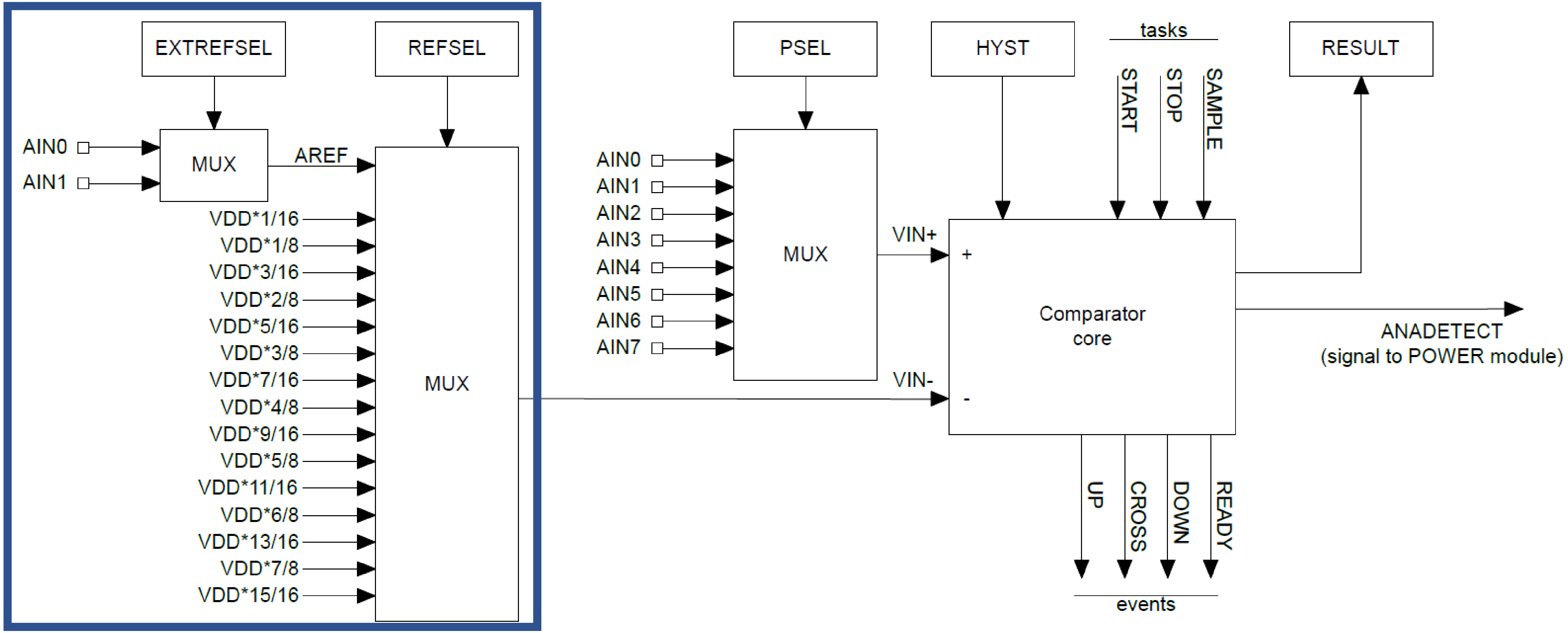


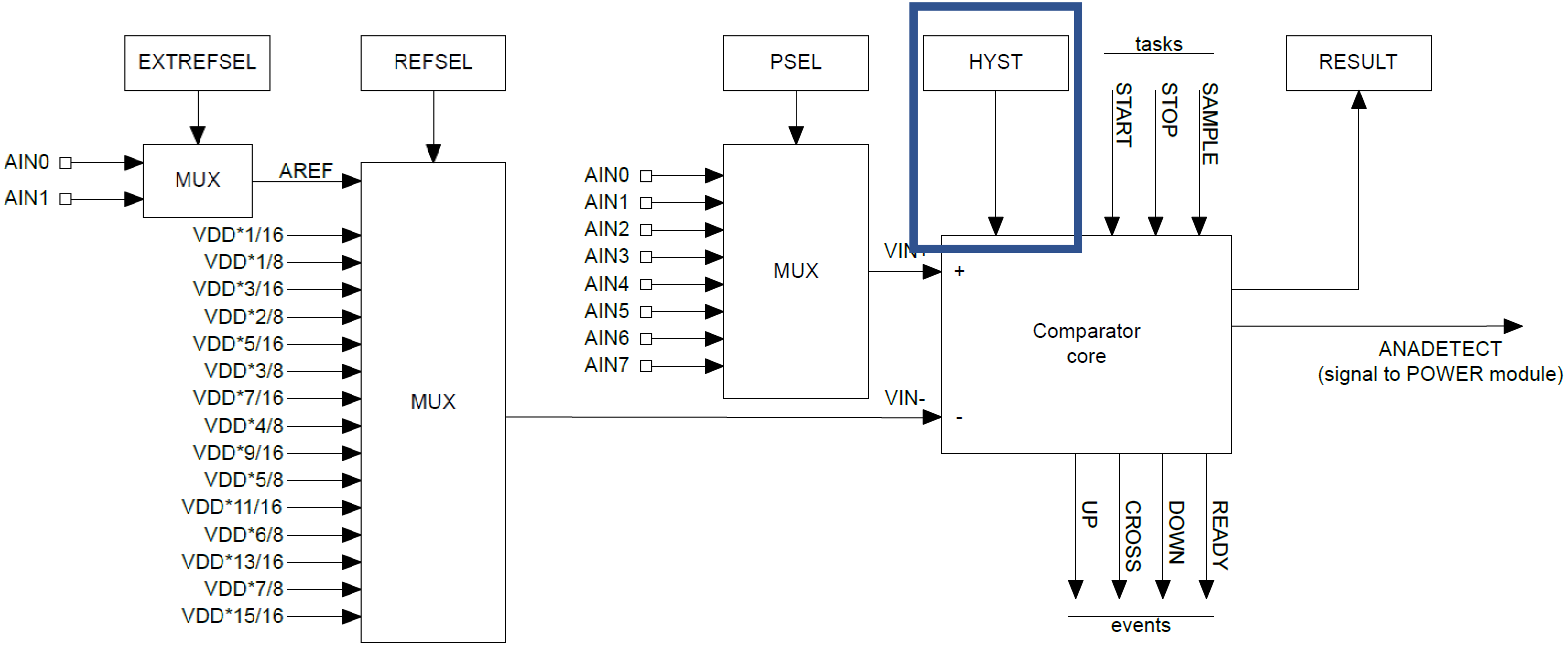
- Input: one of eight analog input pins

nRF low-power comparator (LPCOMP)



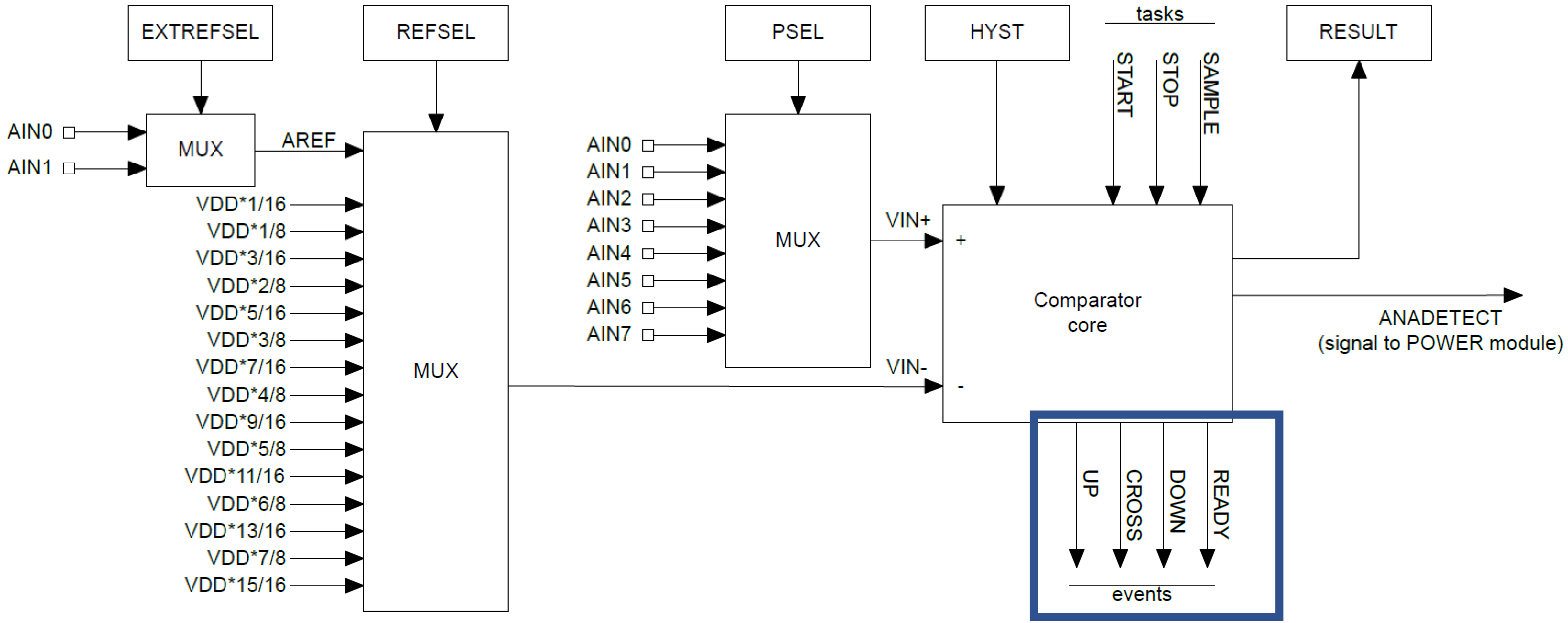
- Reference: one of two analog inputs or selection of VDD * N/16

nRF low-power comparator (LPCOMP)



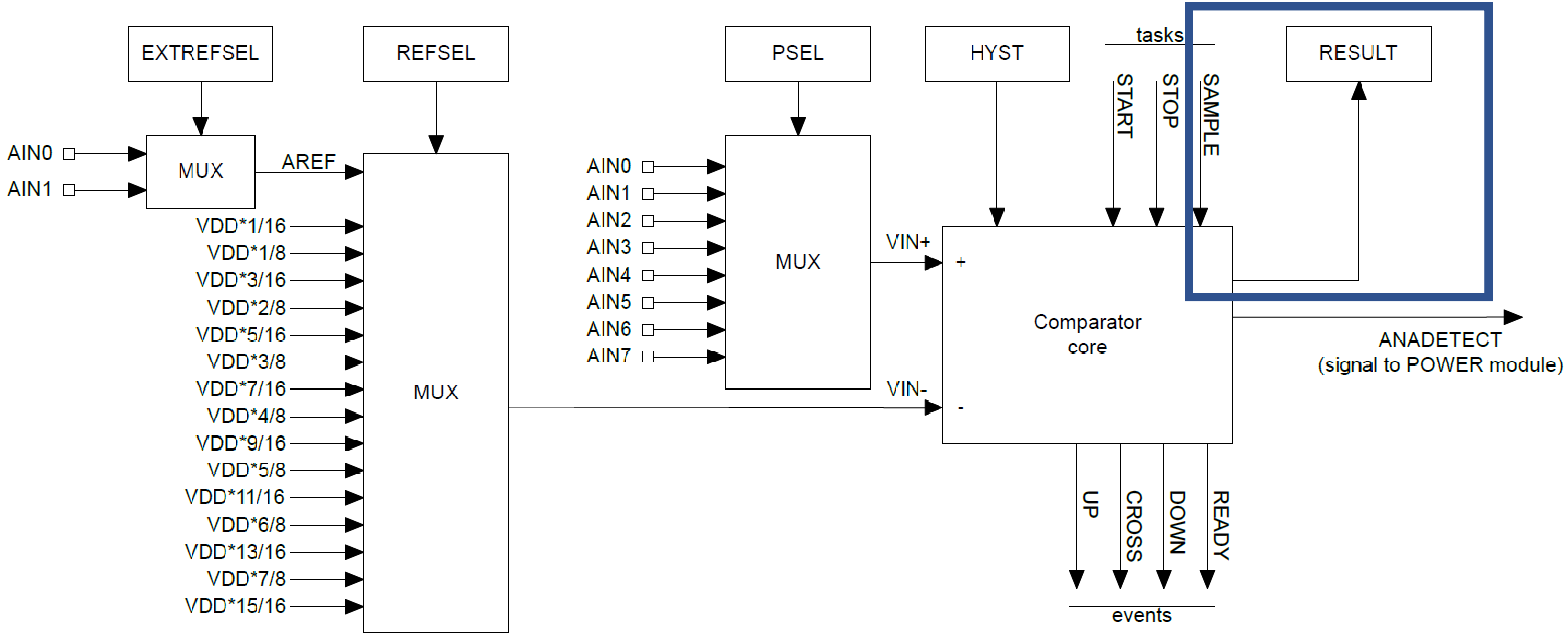
- Hysteresis: +/- 50 mV range around VIN- when enabled

nRF low-power comparator (LPCOMP)



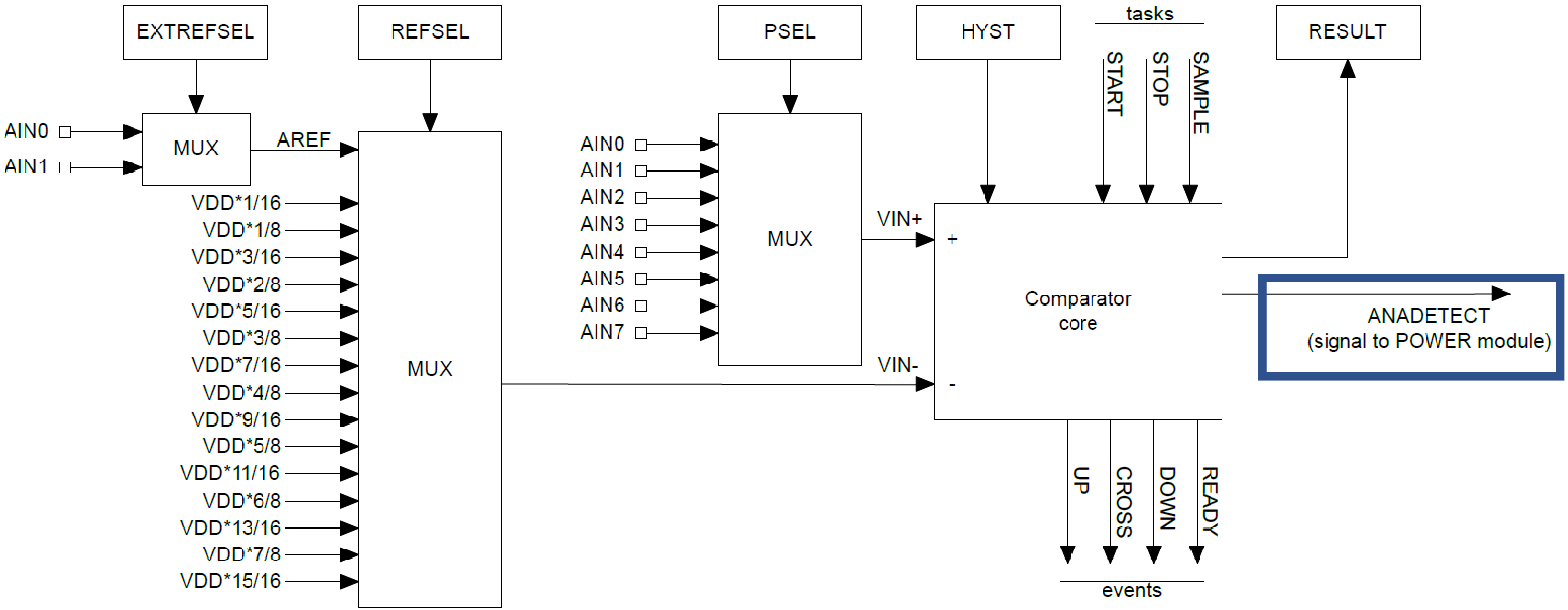
- Events: transition signals + ready (~150 µs)

nRF low-power comparator (LPCOMP)



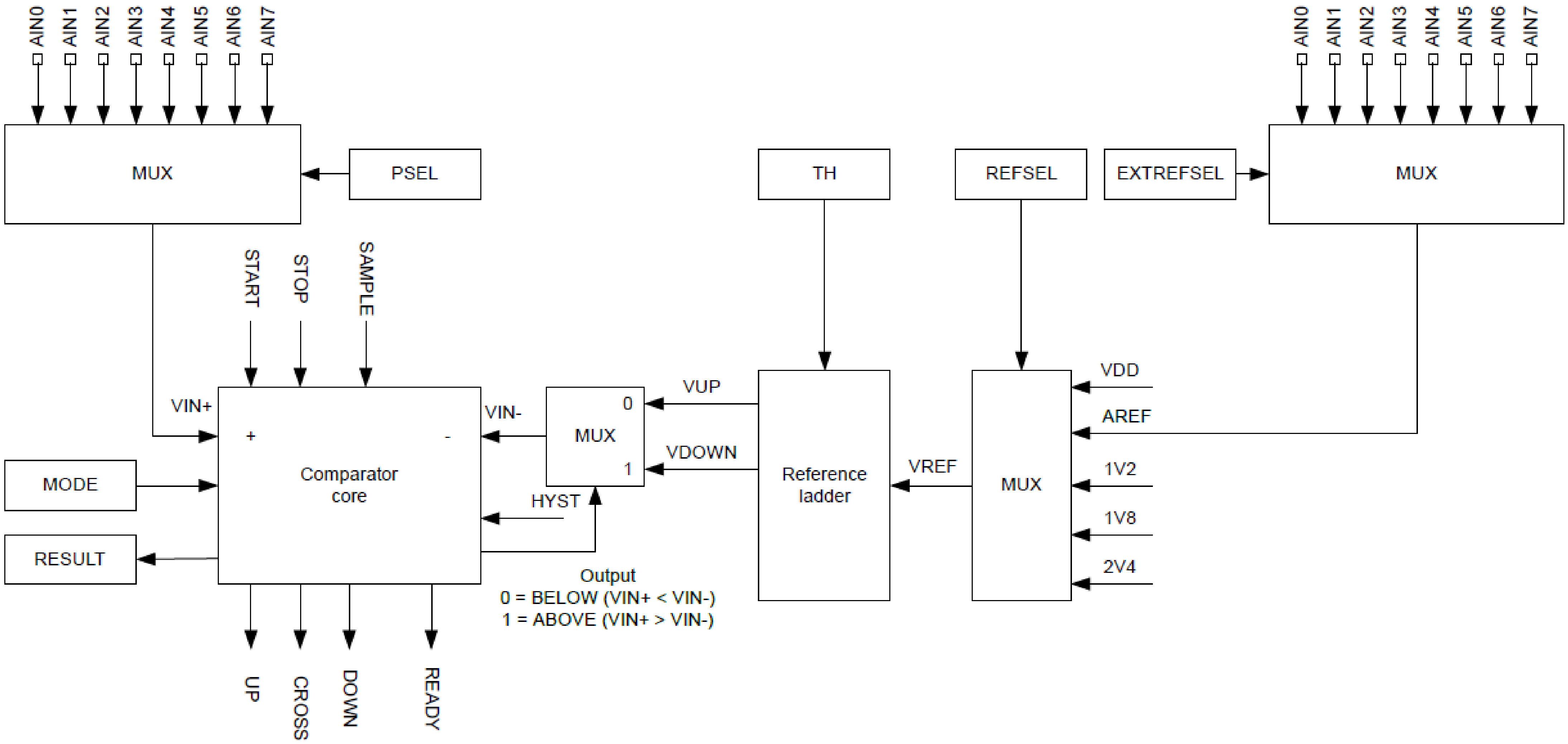
- Can also request what the current comparison state is (high/low)

nRF low-power comparator (LPCOMP)



- Can be used for low-power wakeup of microcontroller

nRF COMP peripheral



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 VDD?**

Break + Question: Internal reference voltages

- **Why have internal voltage references other than 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

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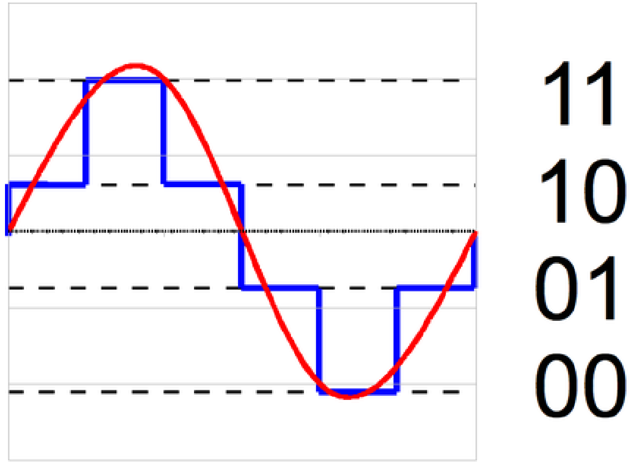
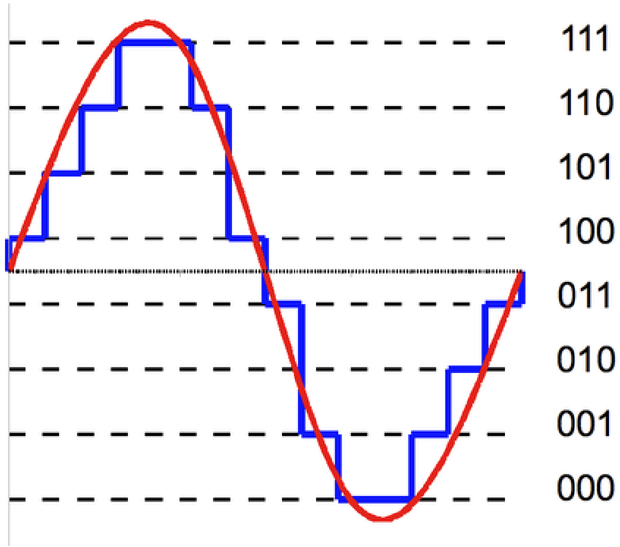
- Options:
    1. Determine if signal is higher or lower than some amount (Boolean)
    2. **Determine voltage value of signal (N-bit number)**

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

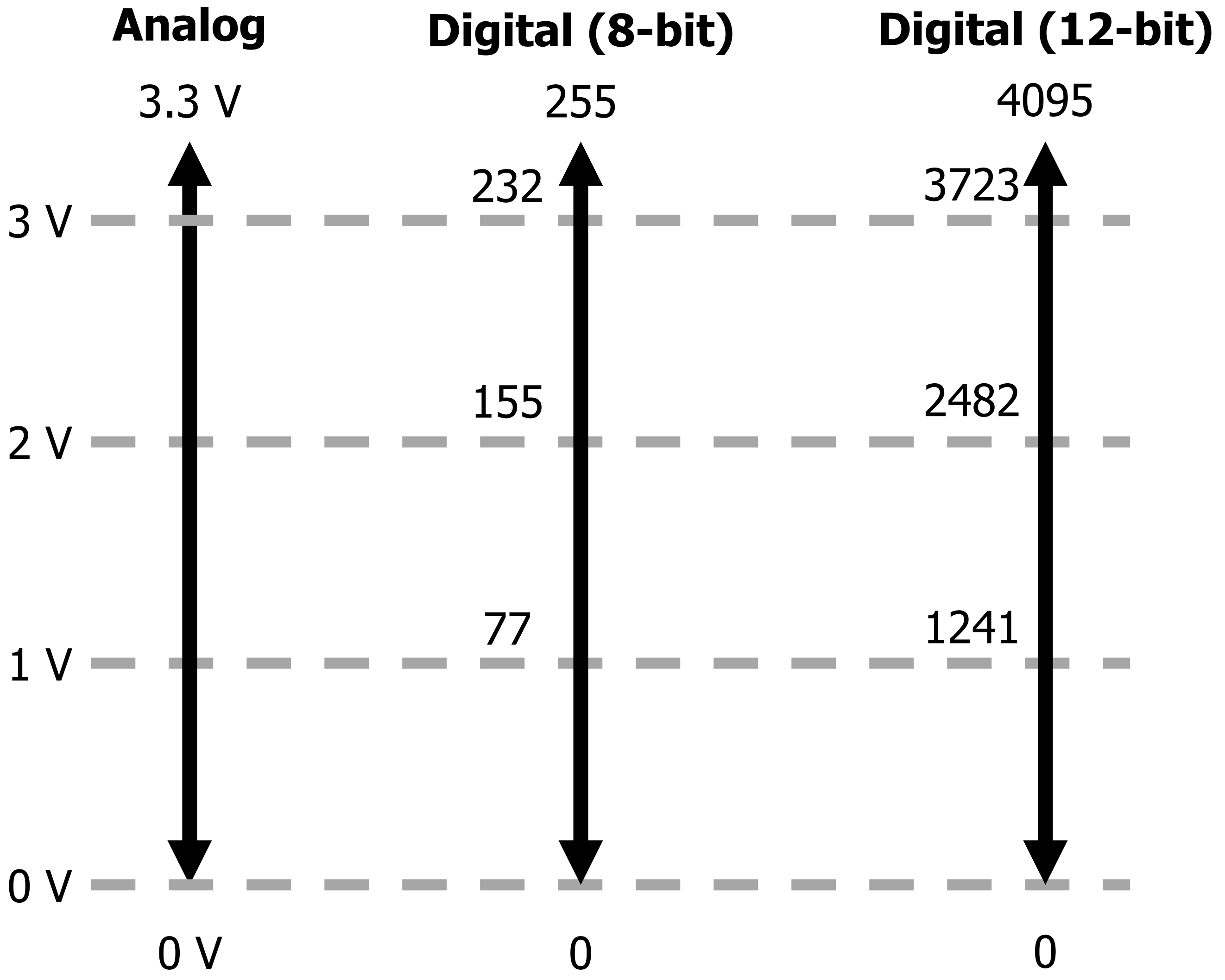
Quantization





- 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

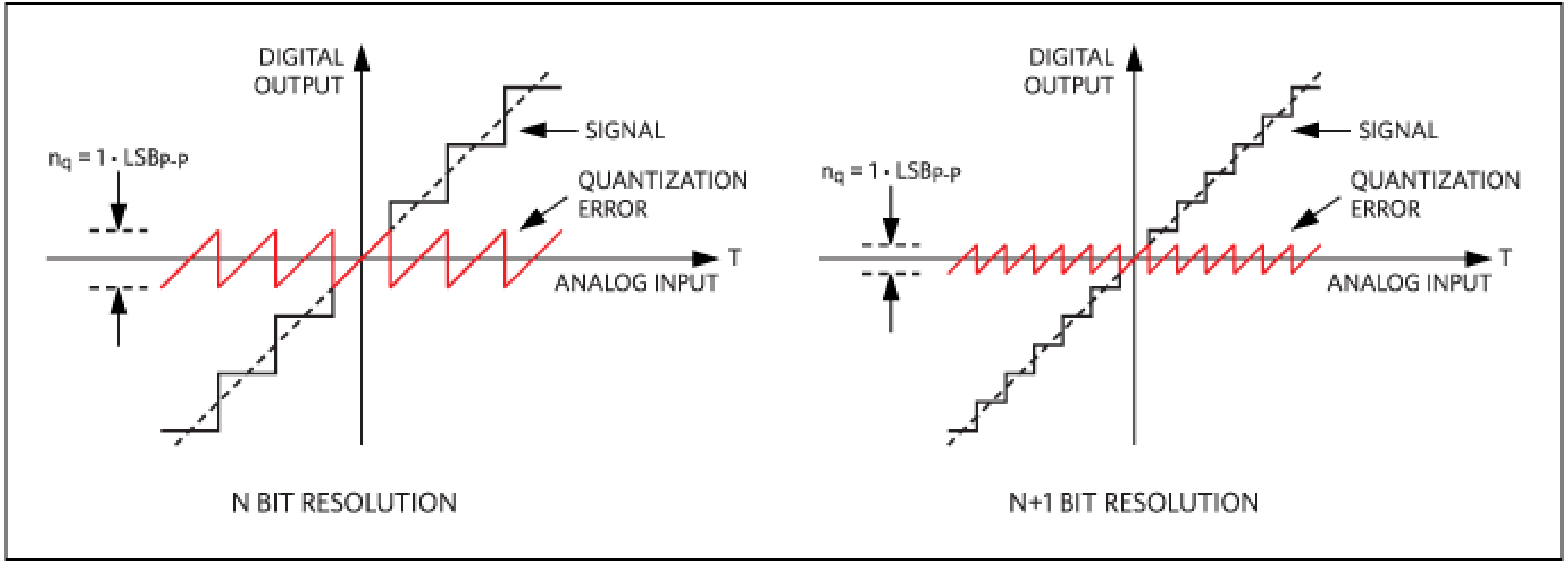
Translating voltage and ADC counts



$$Value = \frac{V_{IN}}{V_{REF}} * \left(2^{Resolution} - 1\right)$$

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

Quantization error



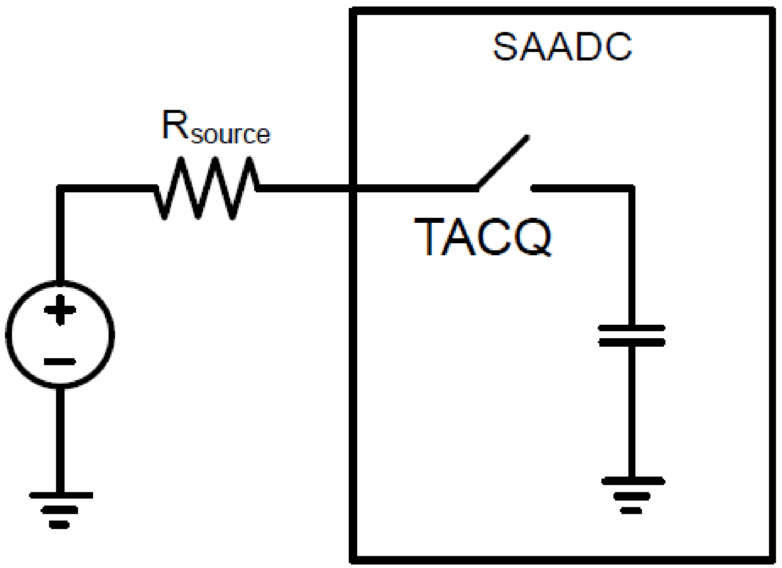
- Resolution choice determines magnitude of error
  - Each extra bit halves the magnitude of error

Analog to digital translation process

- Two steps:

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

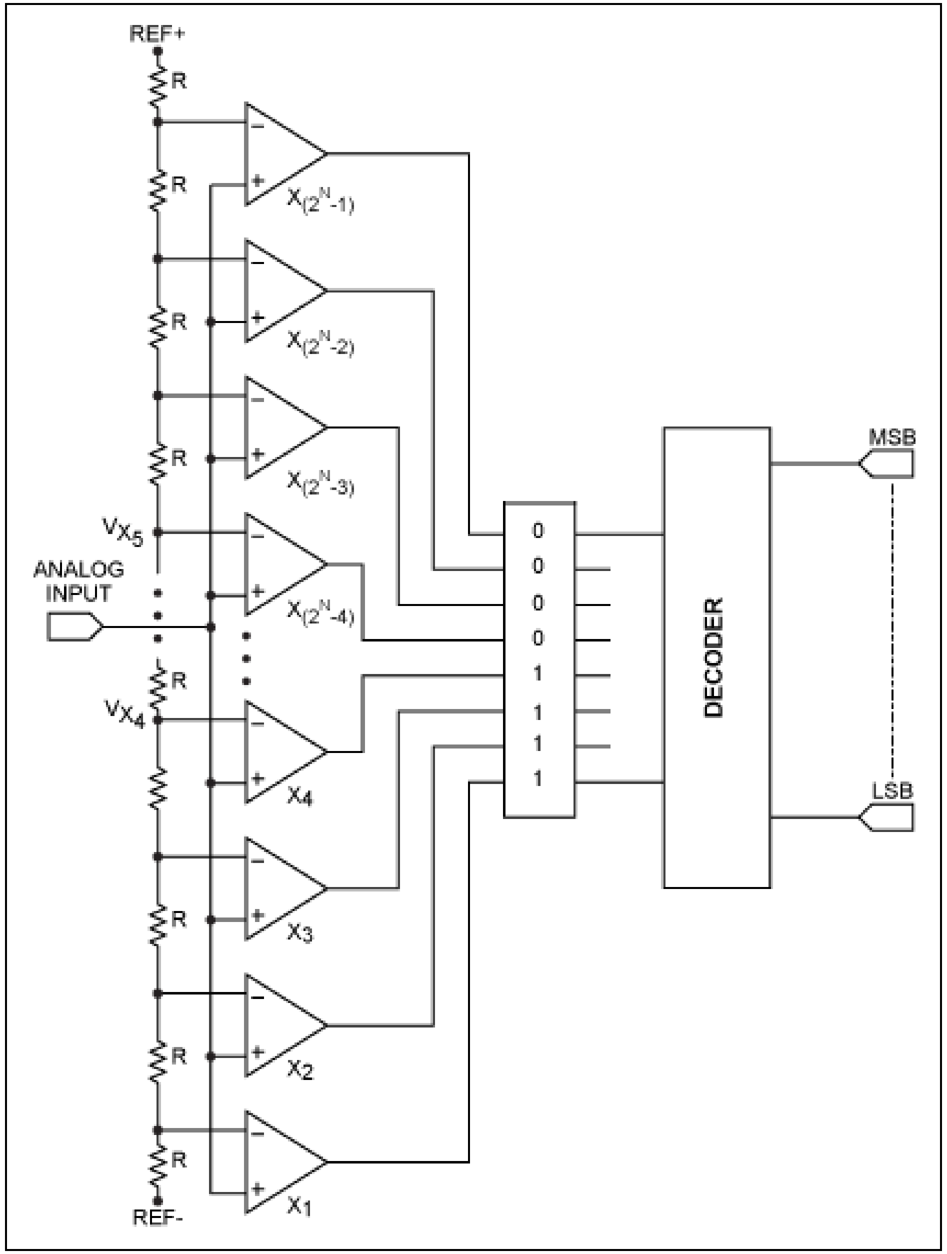
    - Signal connected to a capacitor
    - Fills capacitor up to voltage level
    - Speed depends on input resistance
        - 1-100 μs is common



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

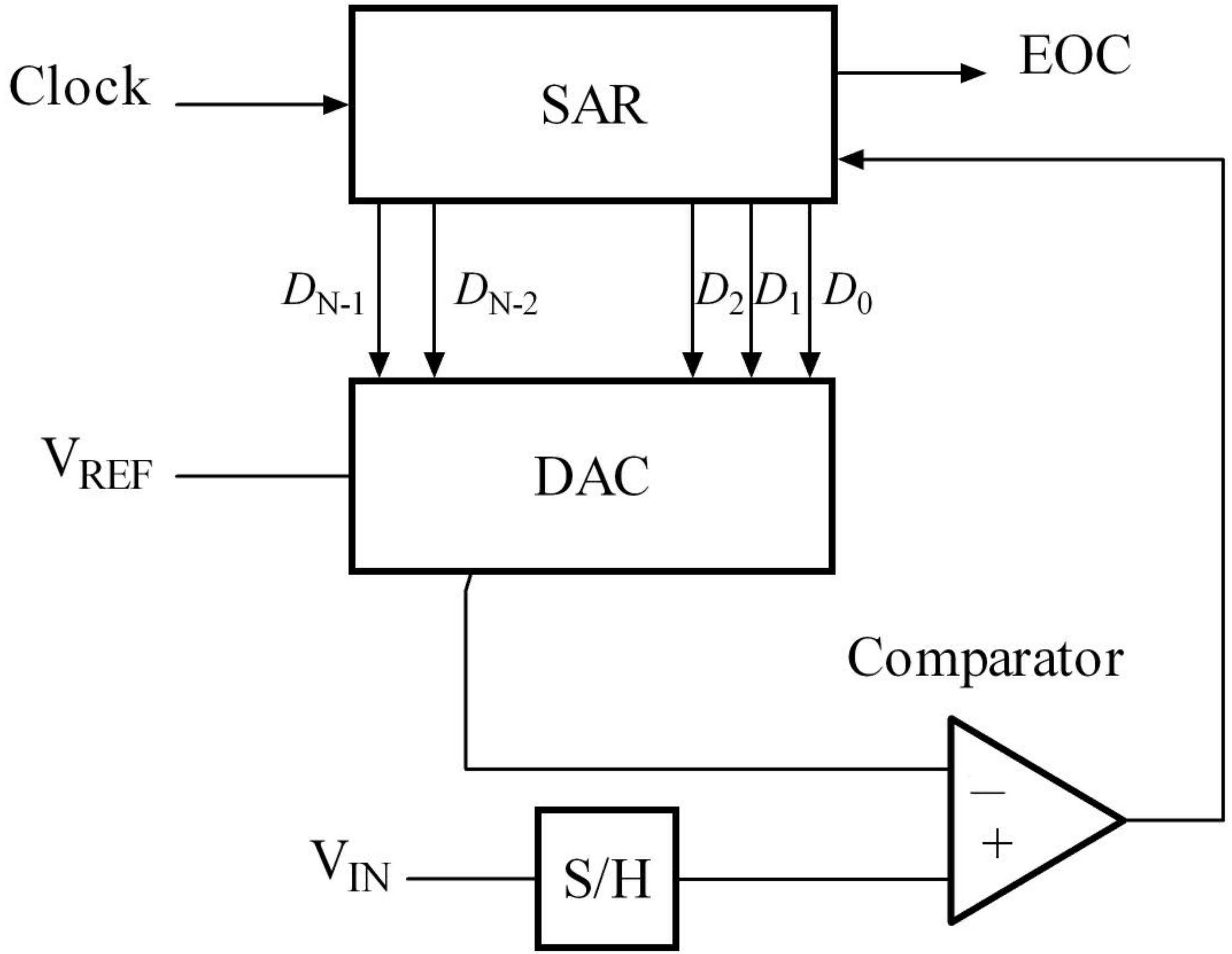
Direct-conversion ADC

- 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



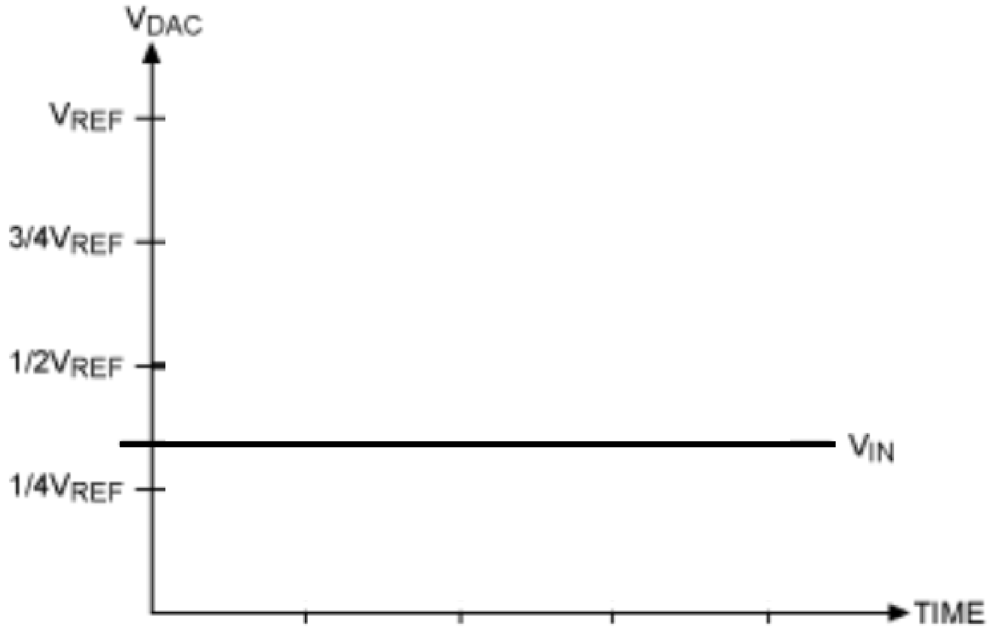
Successive-Approximation ADC

- 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



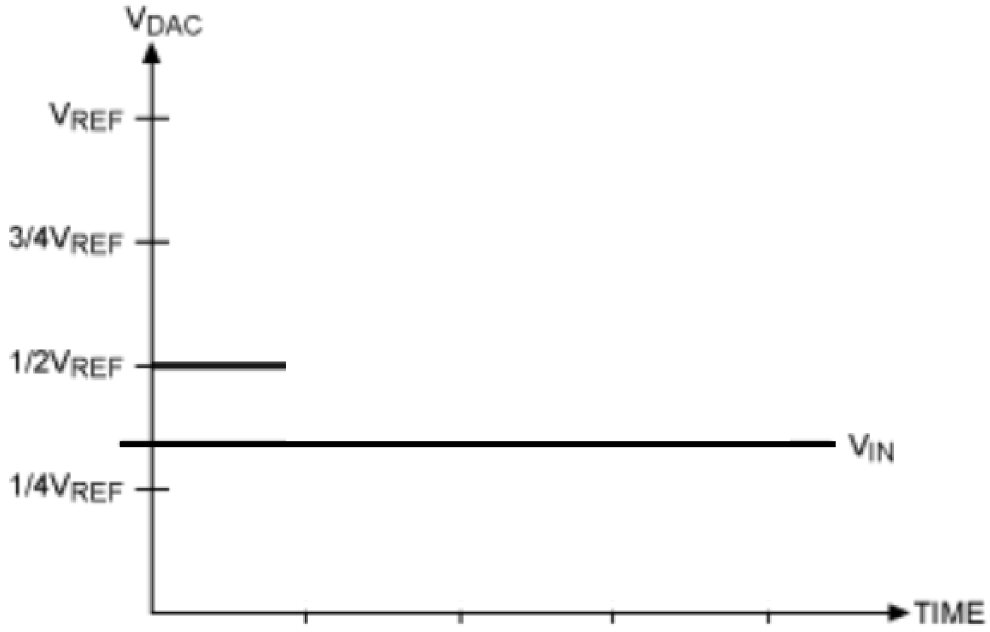
Successive Approximation Example

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



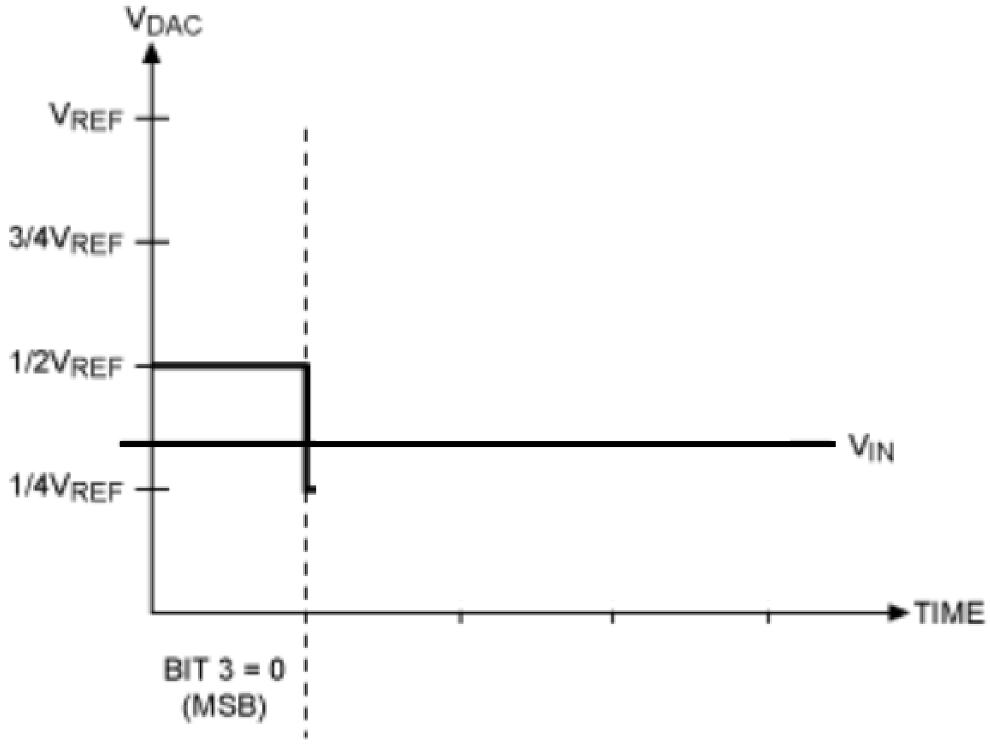
Successive Approximation Example

1. Compare ½ V_{REF} (0b<u>1</u>000) to V_{IN}
   - If greater, bit is 1. Else zero



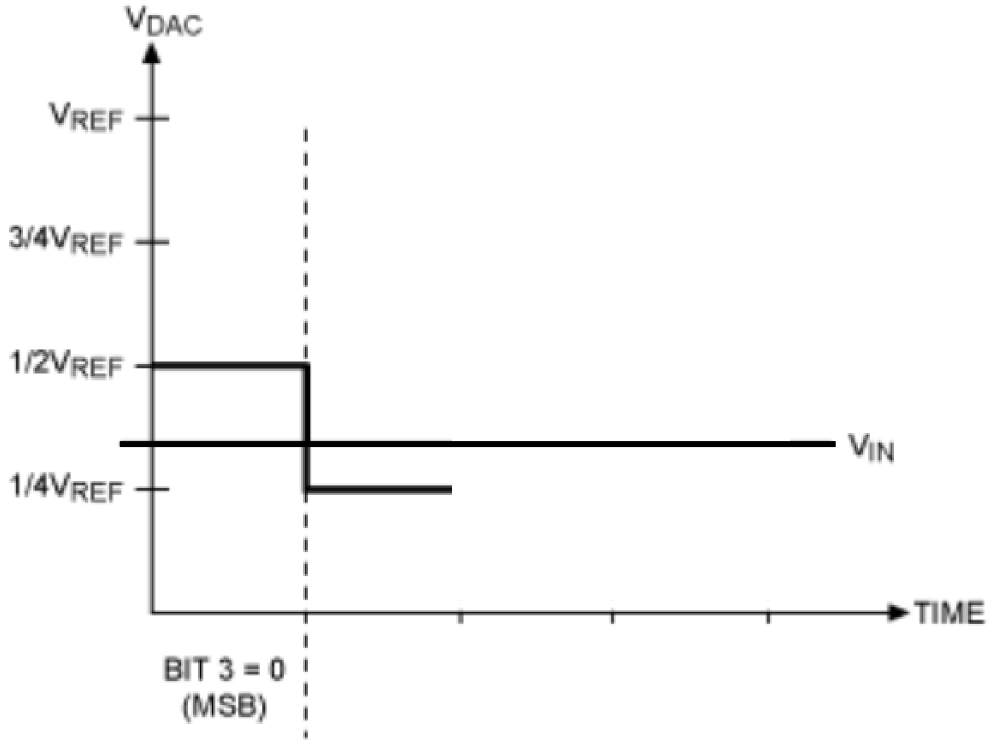
Successive Approximation Example

1. Compare ½ V_{REF} (0b**0**000) to V_{IN}
   - If greater, bit is 1. Else zero
   - V_{IN} is less. So set that bit to zero



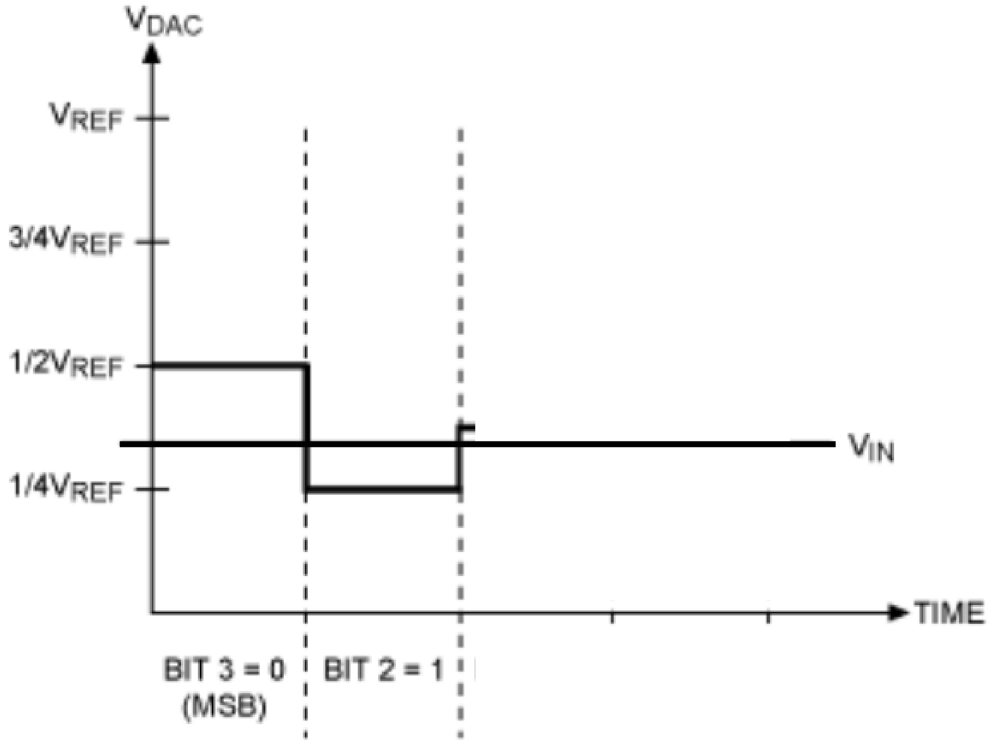
Successive Approximation Example

2. Compare 1/4 V_{REF} (0b**0**1̲00) to V_{IN}
    - If greater, bit is 1. Else zero



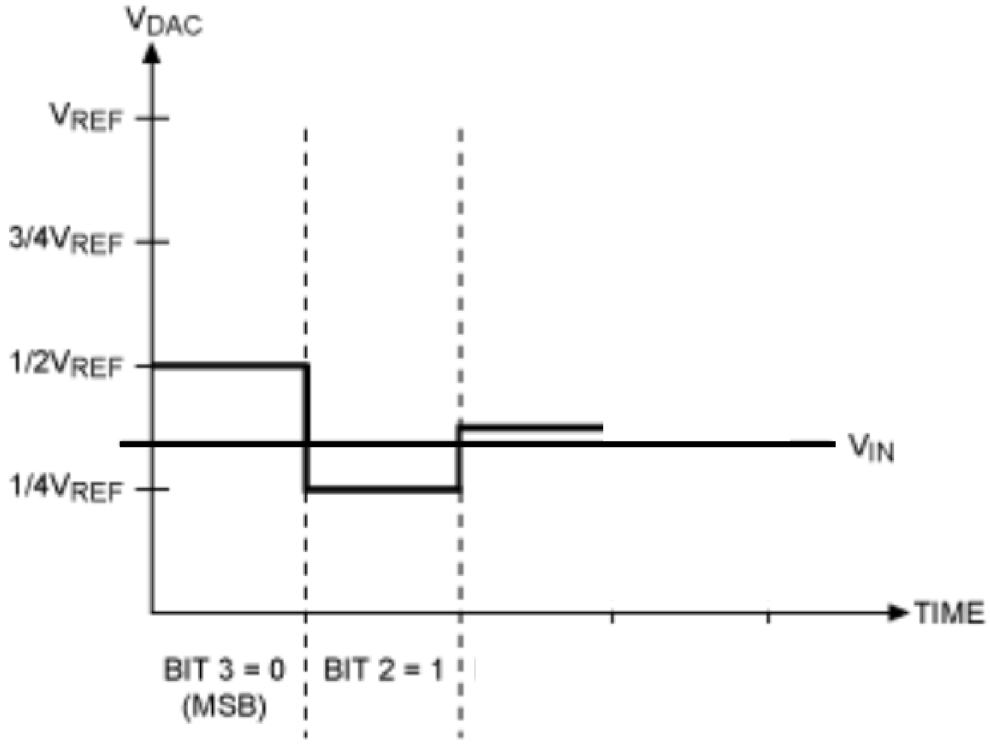
Successive Approximation Example

2. Compare 1/4 V_{REF} (0b**01**00) to V_{IN}
   - If greater, bit is 1. Else zero
   - V_{IN} is greater. So set that bit to one



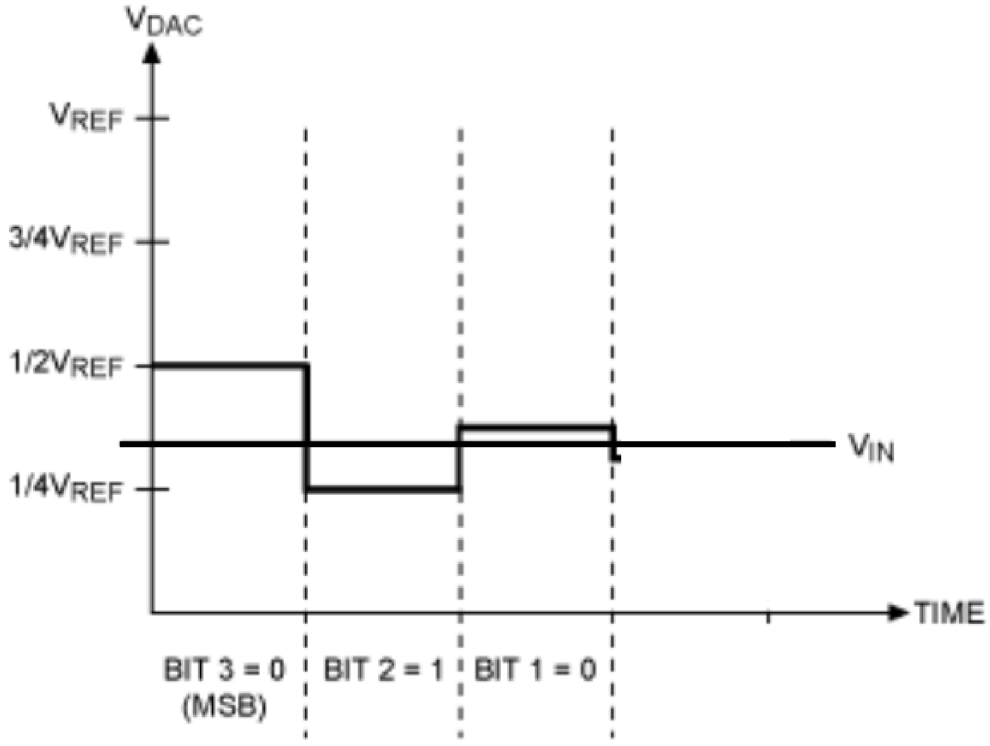
Successive Approximation Example

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



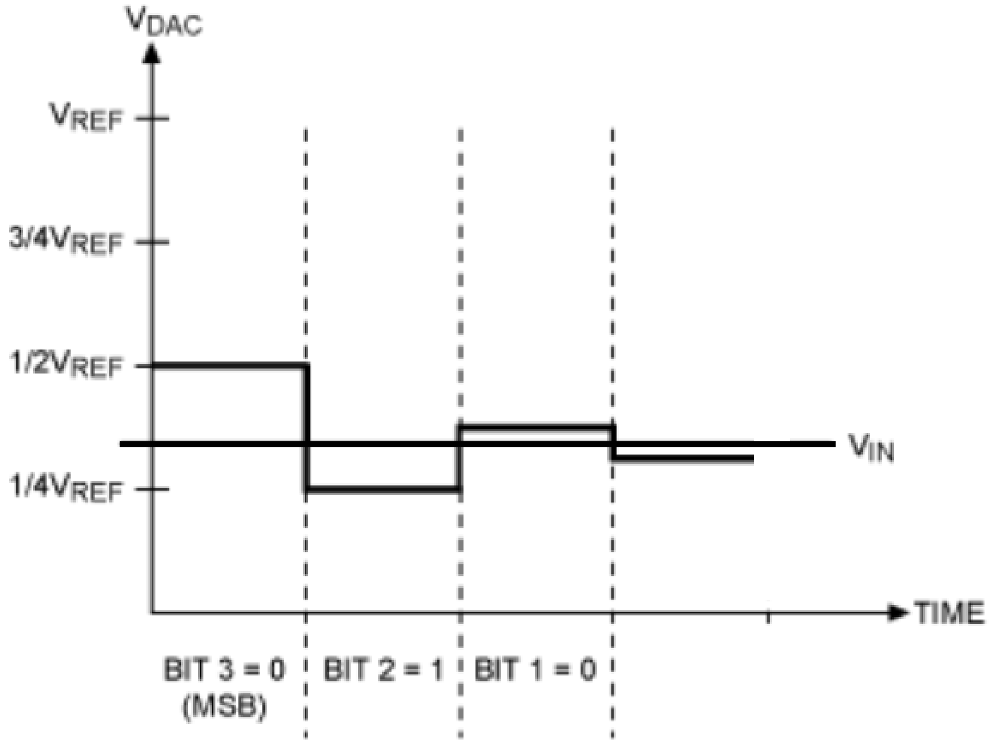
Successive Approximation Example

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



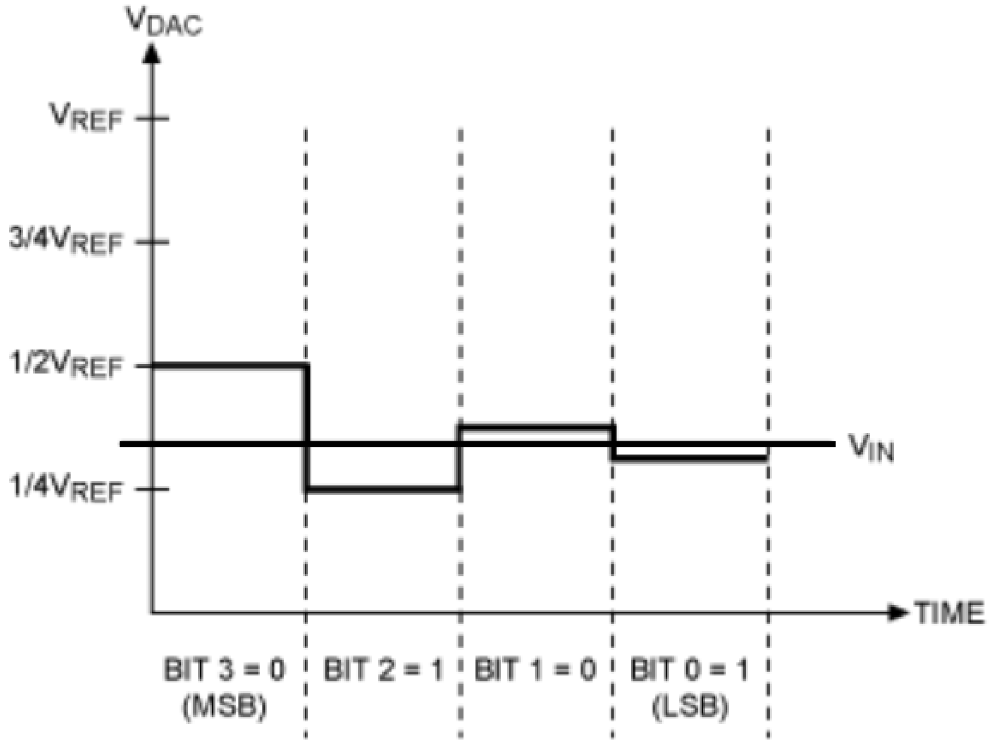
Successive Approximation Example

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



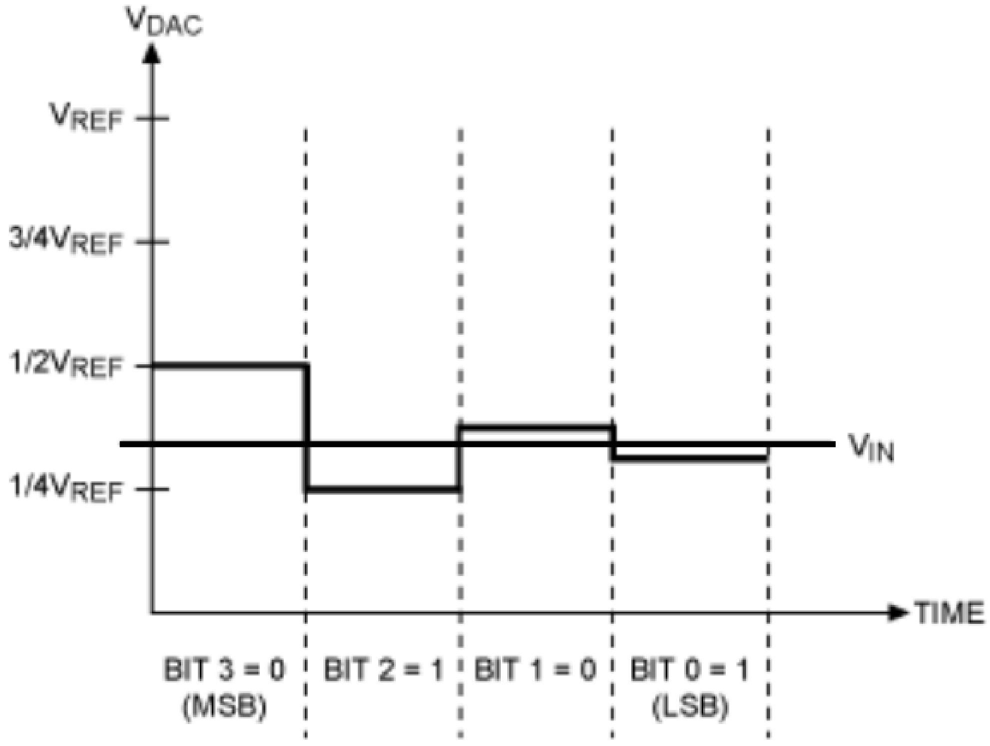
Successive Approximation Example

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



Successive Approximation Example

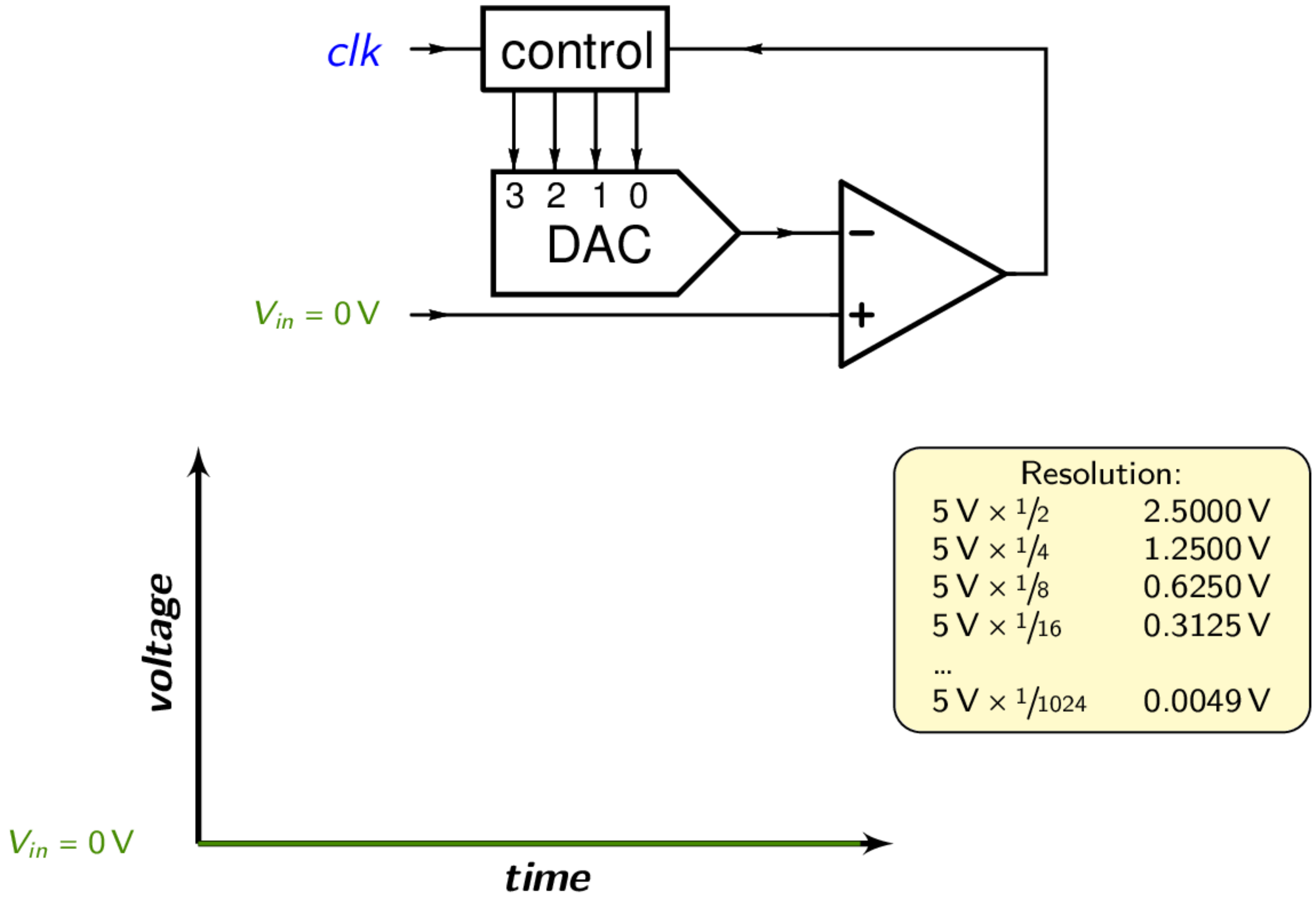
5. Output is 5/16 V_{REF} (0b0101)
   - Slight underestimate of the real value, but as close as we can get
   - More bits would get us even closer



Successive Approximation Example

Successive Approximation – example of a 4-bit ADC

- Performs a binary search to determine correct reference signal value



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

Higher resolution ADCs are not free

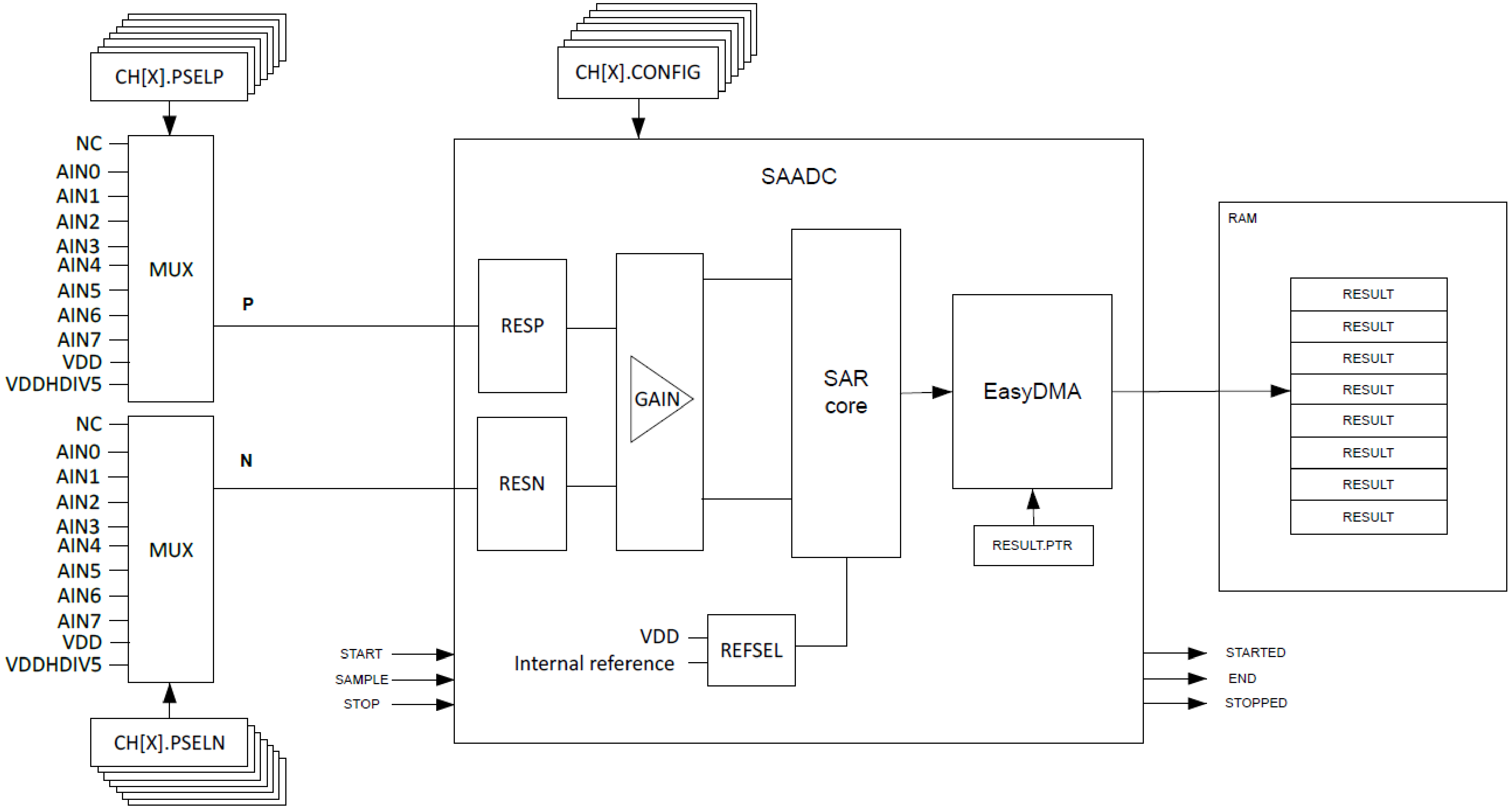
- Direct-Conversion: more expensive (more silicon)
- SAADC: more time consuming (more binary search time)

- Resolution requirement depends on signal being sensed
    - Temperature sensor probably doesn’t need 16-bit ADC
    - Microphone might though!

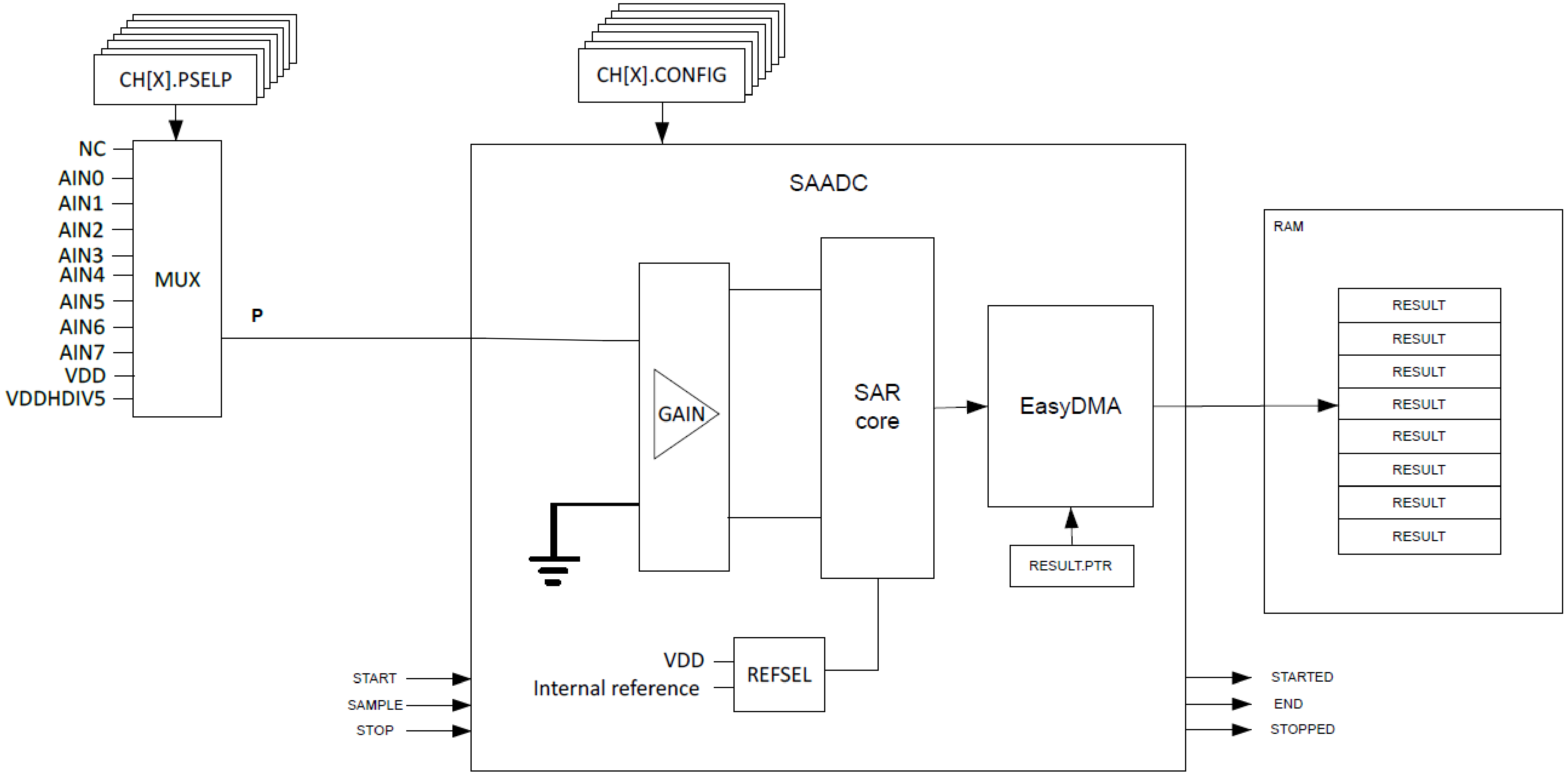
Outline

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

nRF SAADC (Successive Approximation ADC)



How most people use the SAADC



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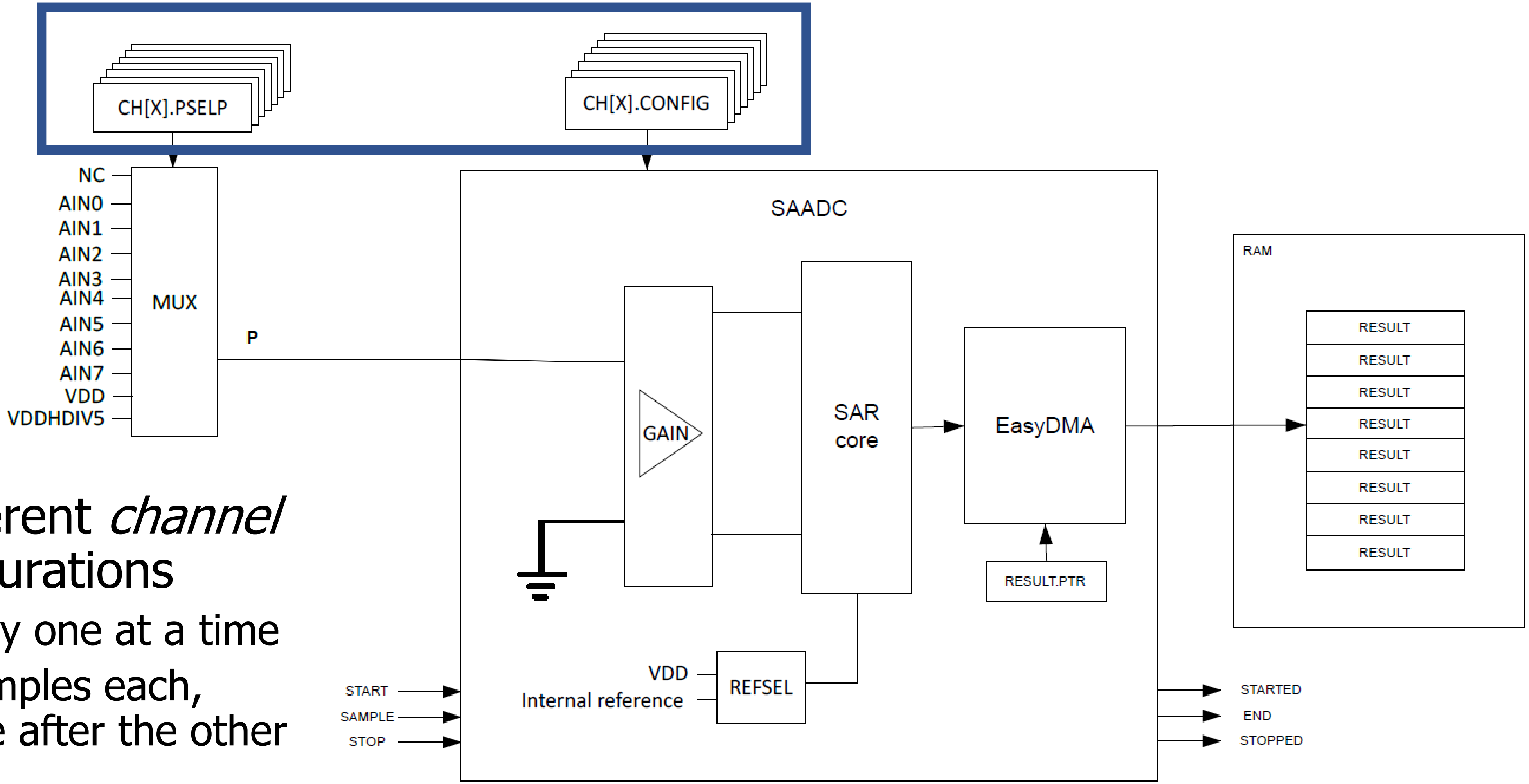
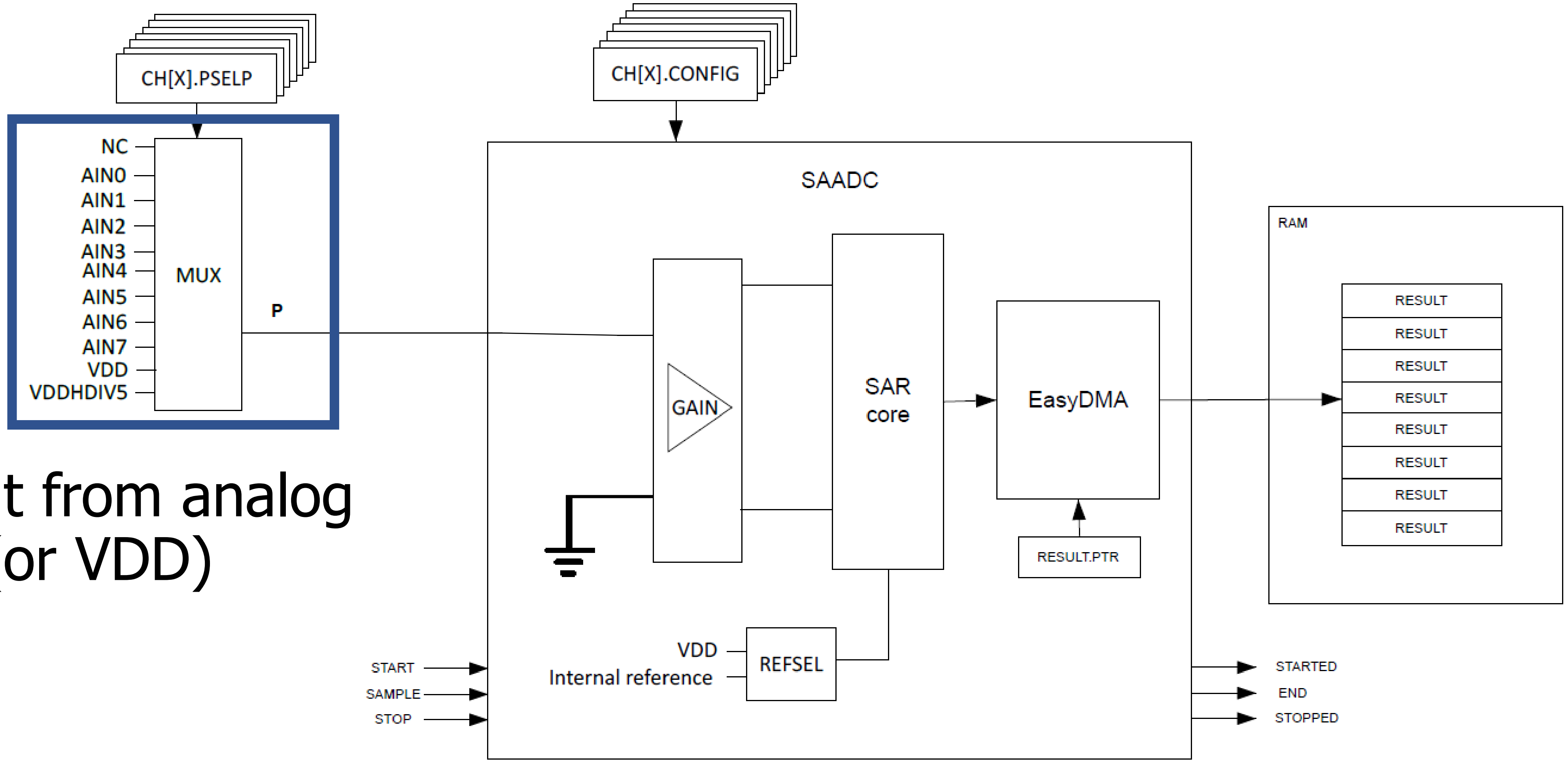


- 8 different *channel* configurations
  - Only one at a time
  - Samples each, one after the other

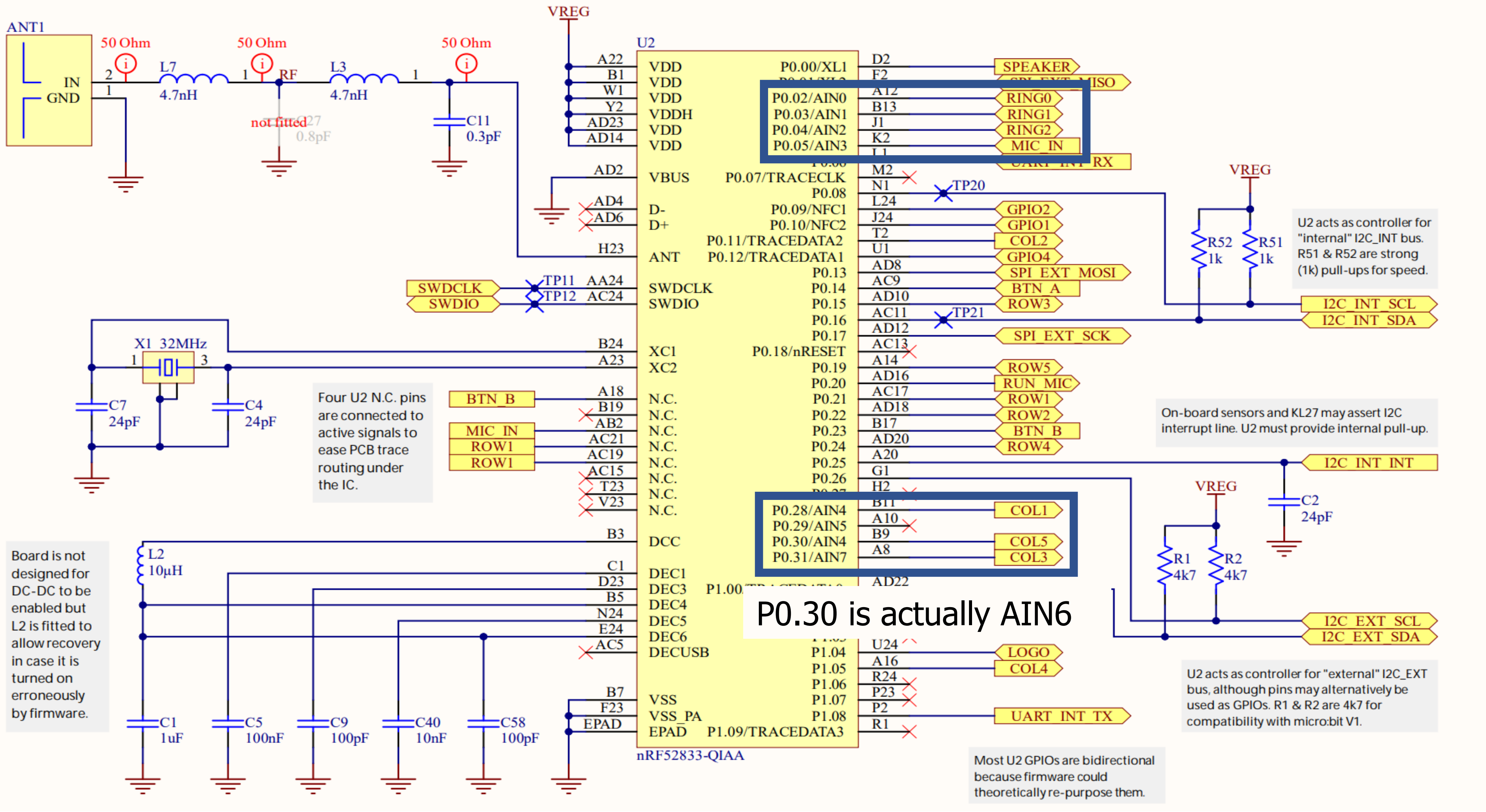
- Essentially virtualization in hardware!

How most people use the SAADC

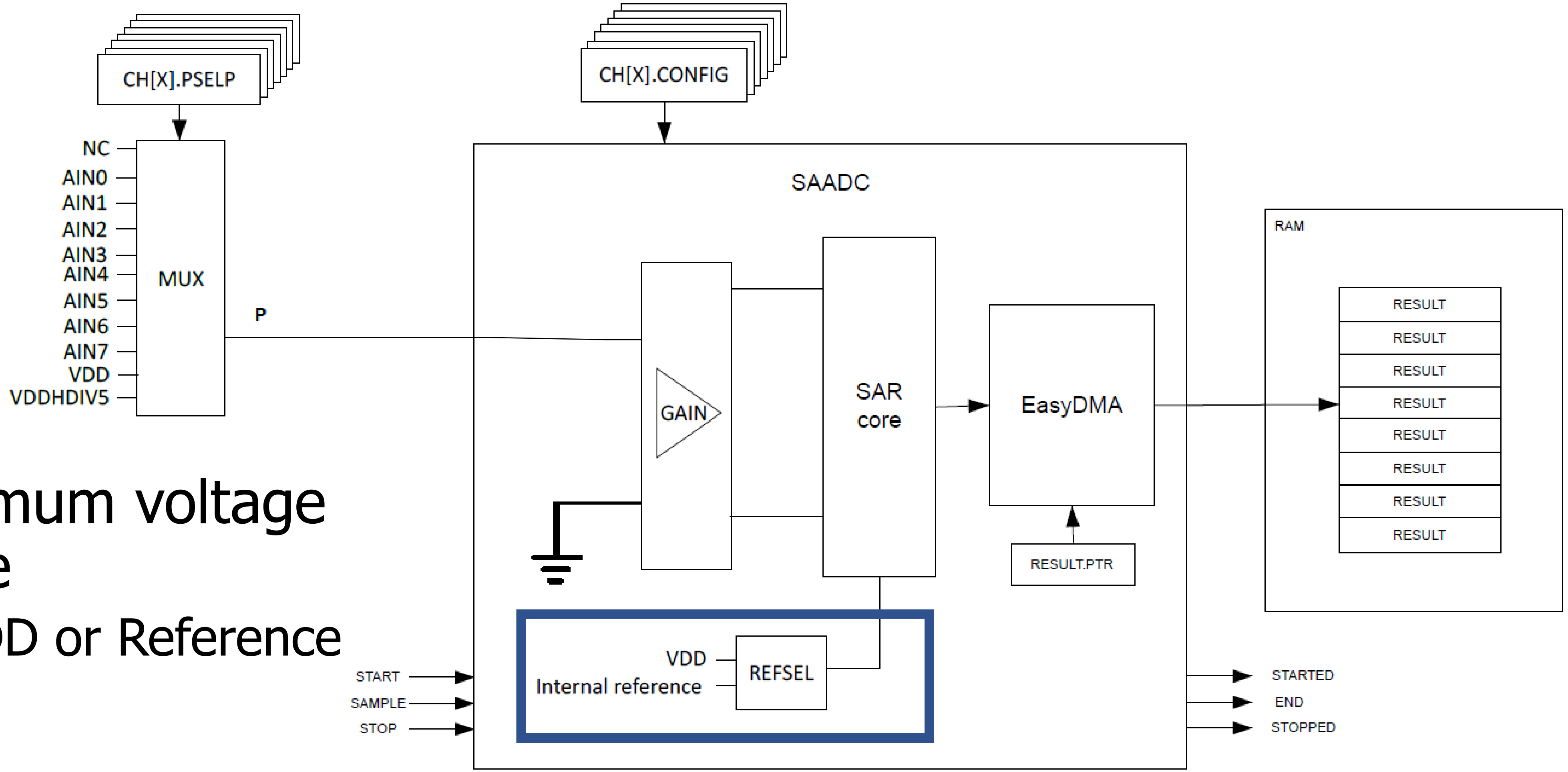


- Input from analog pin (or VDD)

Analog inputs on the Microbit

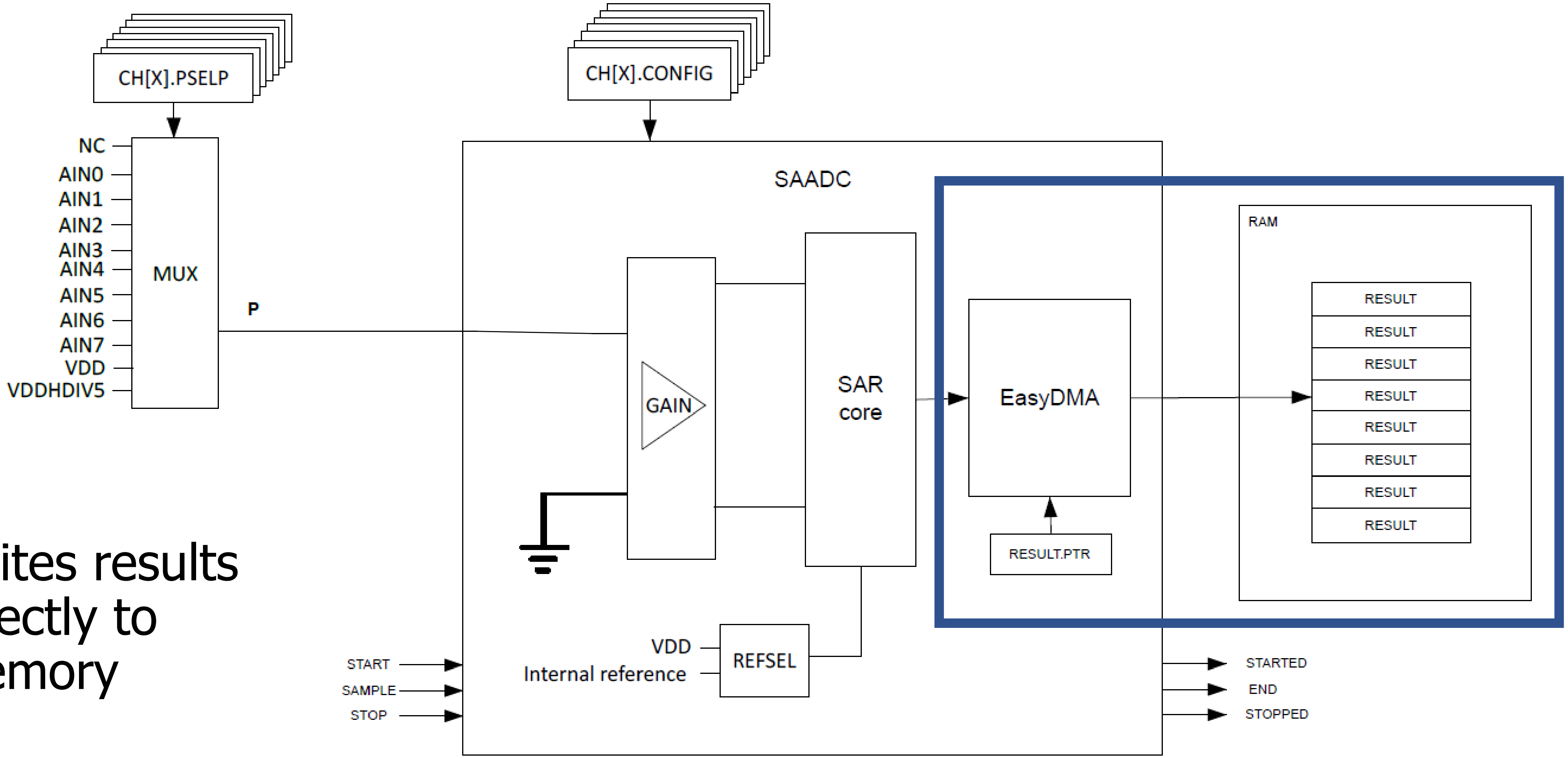


How most people use the SAADC



- Maximum voltage range
  - VDD or Reference

How most people use the SAADC

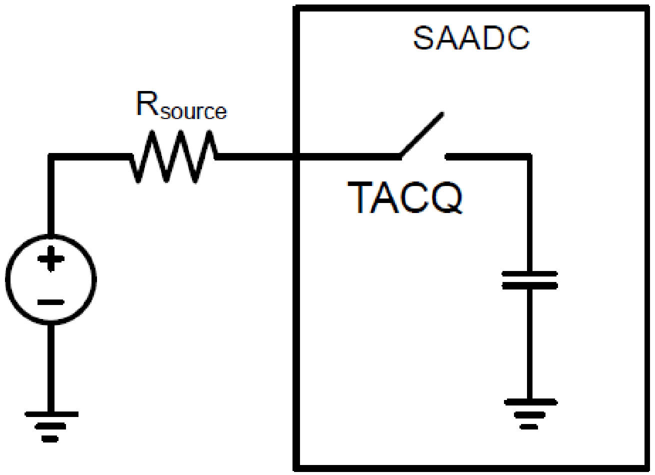


- DMA
  - Writes results directly to memory

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



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

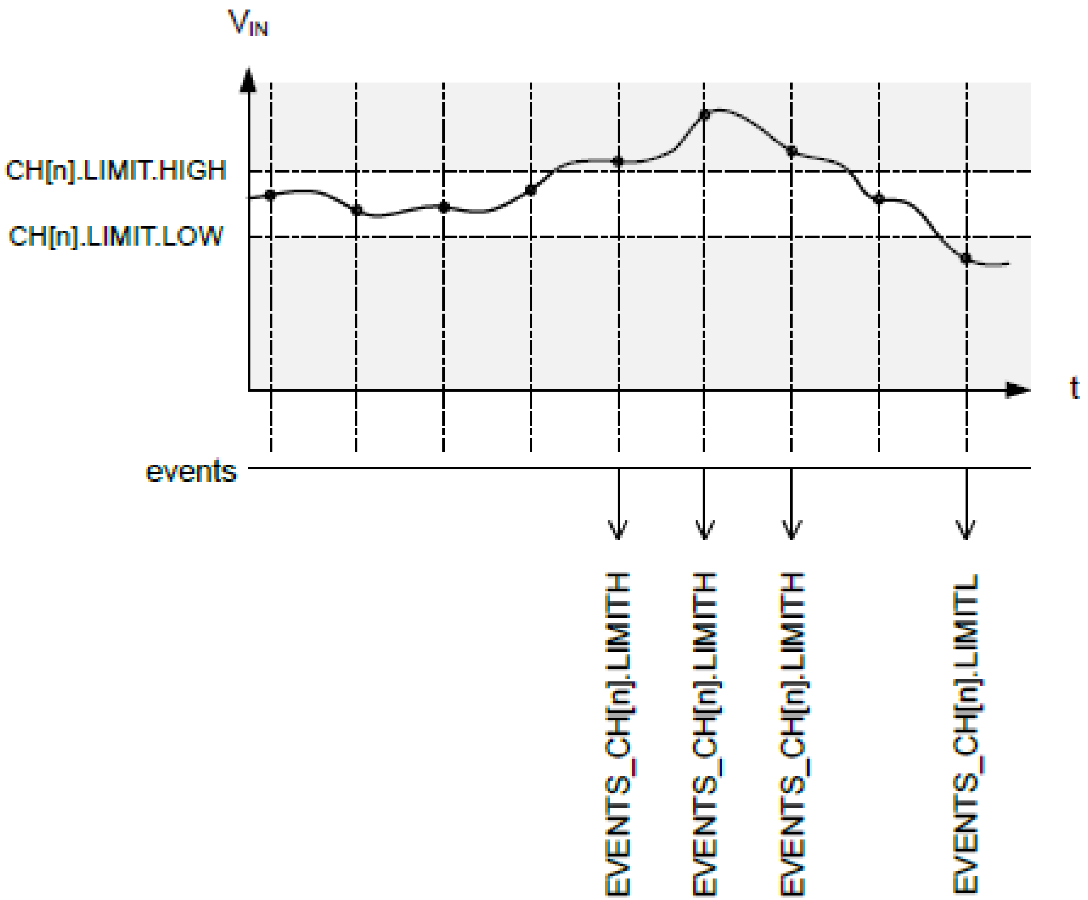
- There is no register to read ADC results from

- 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

Event limit monitoring

- Includes two comparators for each channel
  - High and Low limits
- Generates events whenever transitioning to above High or below Low
  - Events can be ignored if unnecessary



Temperature sensitivity

- ADCs are often temperature sensitive
  - nRF SAADC: 0.02% per degree C
- Recommends recalibrating every change of 10 degrees C or more
  - Automatic task for calibration
  - Real concern for deployed devices
    - Outdoors
    - Wearable

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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- General ADC Design
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