Lecture 09
Analog Output

CE346 – Microprocessor System Design

Branden Ghena – Spring 2025

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

Northwestern

Administrivia

- Design presentations all next week!
  - Happy to discuss things before then via Piazza
  - I will provide individual group feedback as I get time to
- Drop deadline is Friday next week
  - I’m not worried about anyone in CE346
  - But if you’re worried, I’m happy to talk about it.

Today's Goals

- Explore common methods for generating analog signals

- Understand the role of Digital-to-Analog converters

- Discuss the concepts of Pulse-Width Modulation
  - And the nRF52 implementation of it

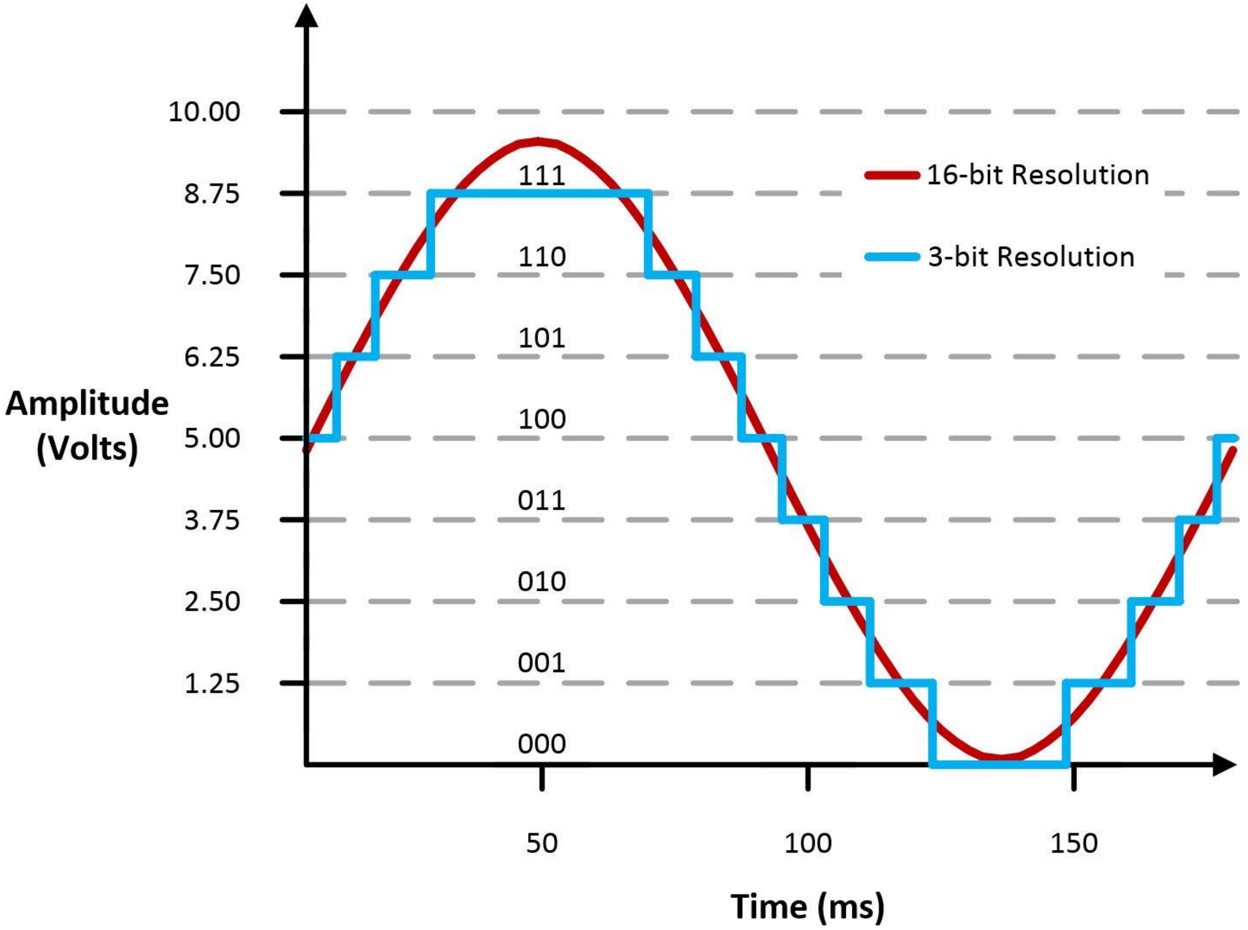
Outline

- **Digital-to-Analog Converters**
- Pulse-Width Modulation
- nRF52 PWM

Digital-to-Analog Converters

- Generates an analog voltage

- DACs are conceptually the inverse of ADCs
  - Number of bits of resolution choose analog step size
  - Frequency determines step duration



High resolution versus high frequency

- What role does each play in a DAC?
  Which is more important?

- High resolution can accurately represent a voltage

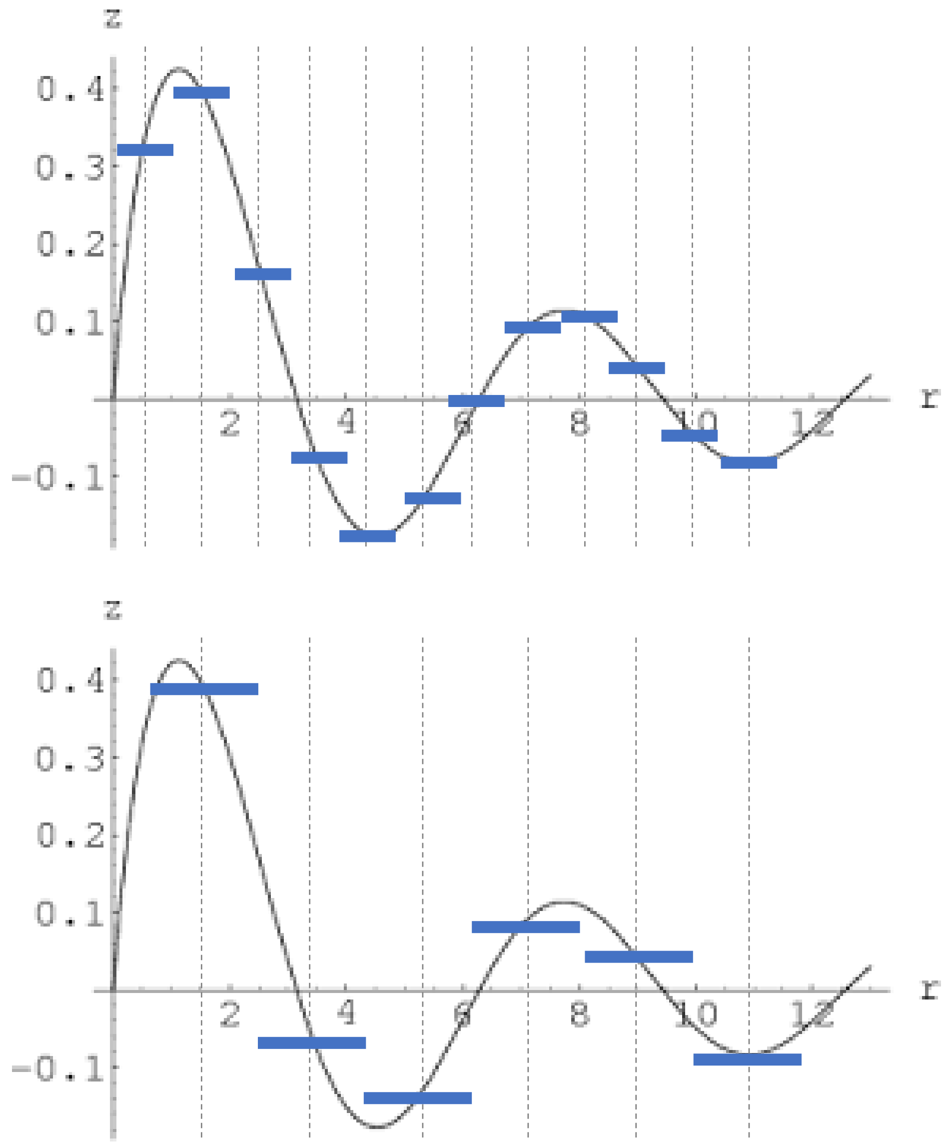
- High frequency can accurately represent a changing voltage

- In practice:
  - Need high *enough* resolution, then as high of frequency as possible

Infinite resolution is not sufficient

- DAC frequency corresponds to representable signal changes
  - Rise and fall times

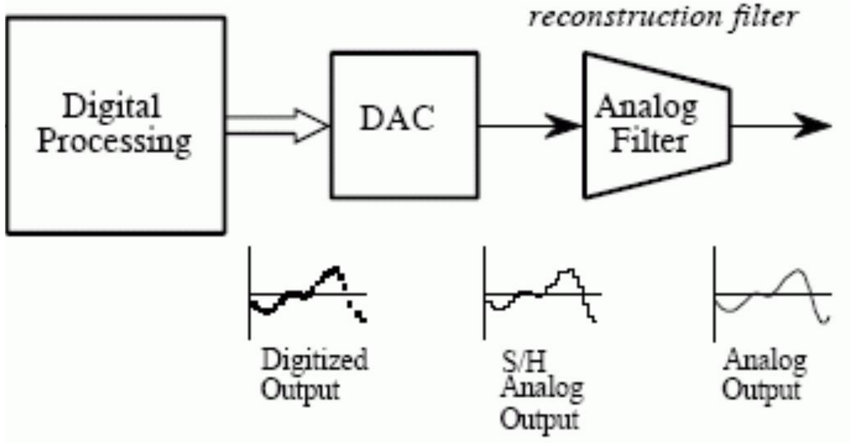
- Even an infinite resolution DAC cannot represent a signal if it is not fast enough

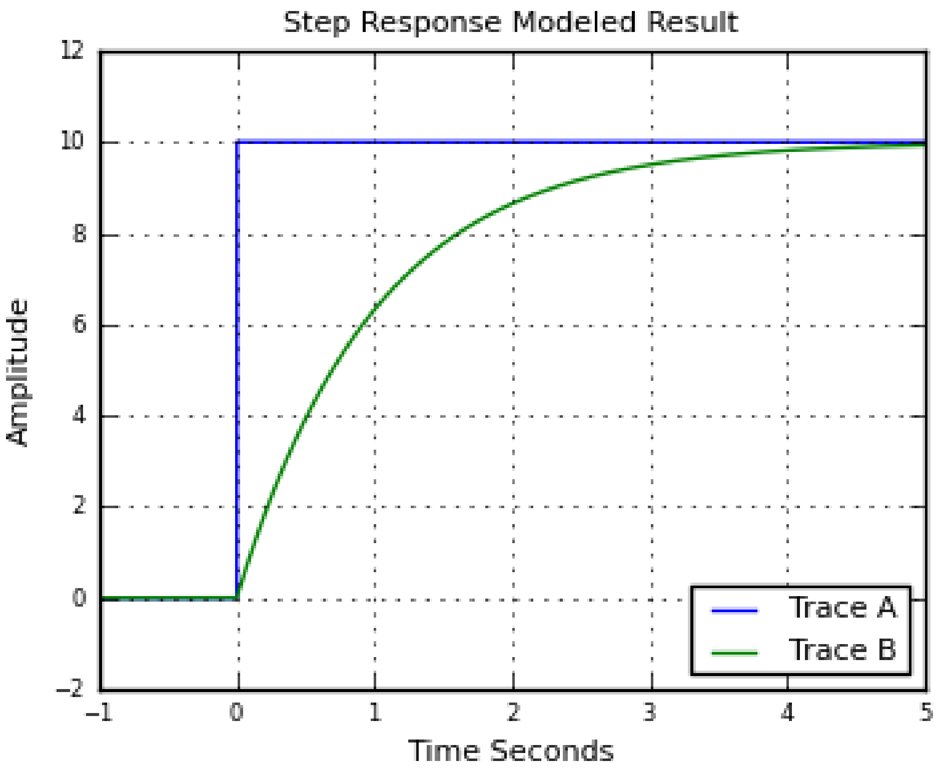


Low-pass filter smooths output

- Low-pass filter delays changes in voltage and smoothly transitions between them
  - Low-frequency signals stay
  - High-frequency are smoothed

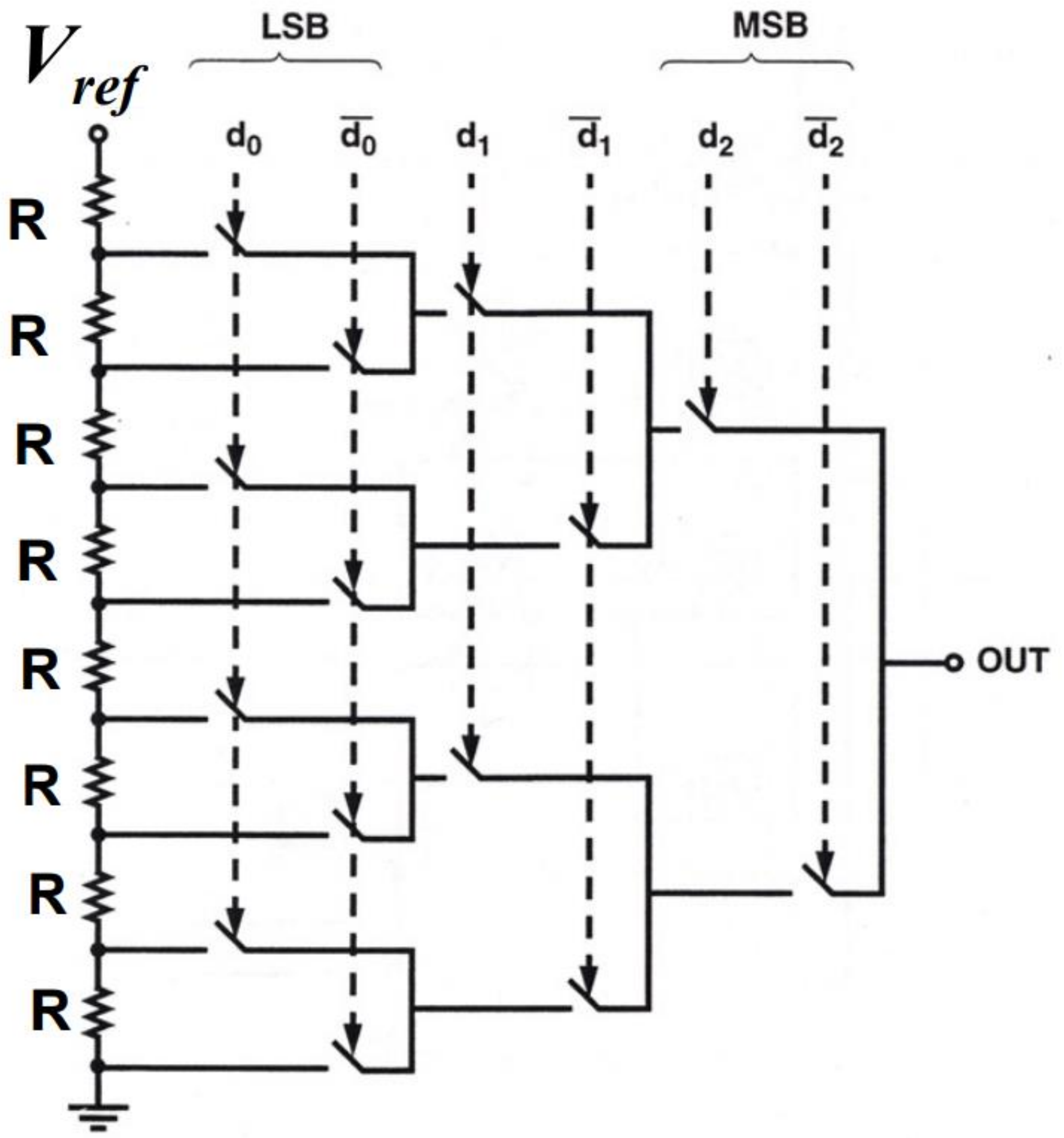
- Greatly improves quality of output but must be tuned to the desired signal frequency
  - Usually not included in microcontroller





Resistor string DAC

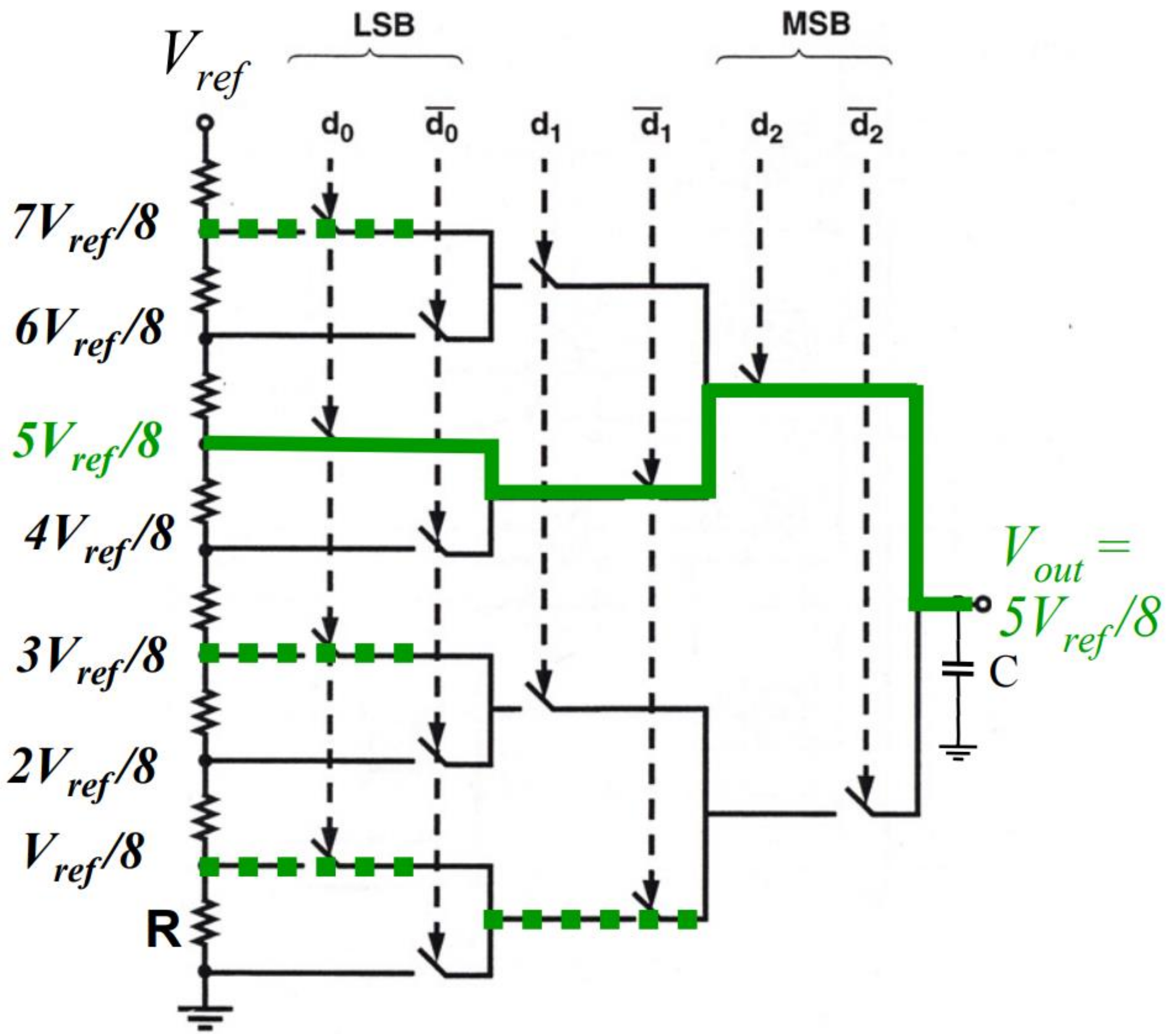
- Use series of voltage dividers and switches to set output voltage
  - Generates equally spaced voltages that can be selected between
- Needs output buffer to provide stable current
- Takes a lot of resistors
  - And resistors take a lot of silicon



Resistor string example

- $V_{out} = code * \frac{V_{ref}}{2^{resolution}}$

- Input code is **101**
  - Selects switches such that $5/8*V_{ref}$ is connected to output



Break + DAC applications

- What do you use an analog output for?

Break + DAC applications

- What do you use an analog output for?

  - Audio output
    - But it needs to be high quality (resolution and speed)

  - Motors
    - But only with a controller that actually drives them with enough current

  - LED brightness

  - <u>Not Much</u>
    - And these last two can be done more easily with PWM

DACs are not in all microcontrollers

- Not rare, but not ubiquitous either
  - Every microcontroller has GPIO
  - Just about every microcontroller has an ADC
  - *Some* microcontrollers have DACs
    (the nRF52833 does not!)

- Reasons
  - Hardware is complicated (but we could fit it if we wanted)
  - Use cases are uncommon (and might need very high quality)
    - Many devices can be controller digitally

  - Pulse-Width Modulation (PWM) can emulate usably analog signals

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- **Pulse-Width Modulation**
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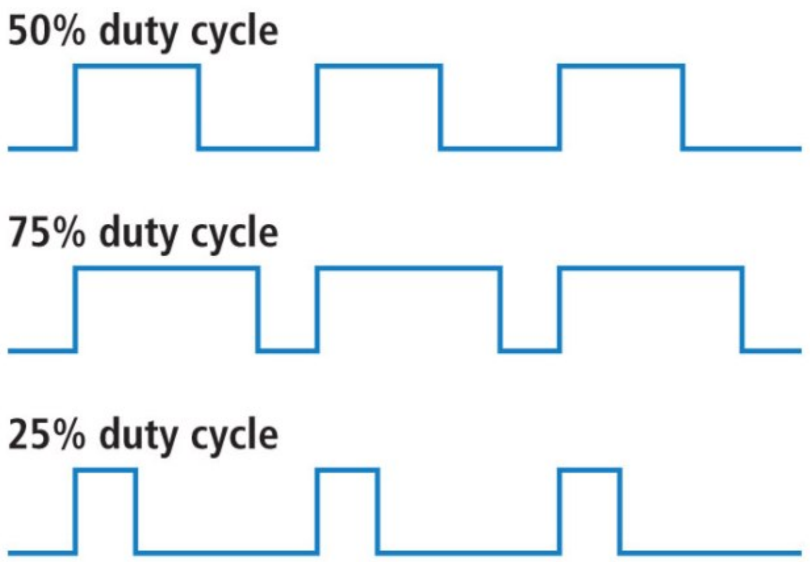
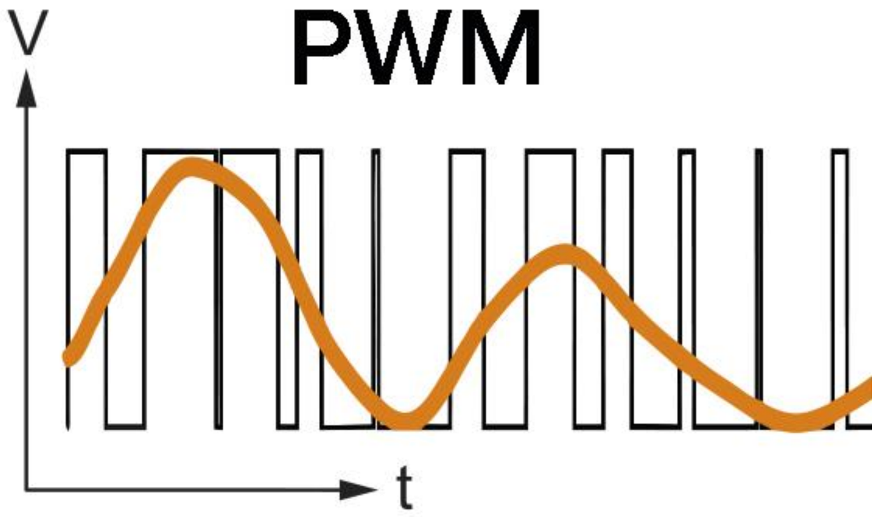
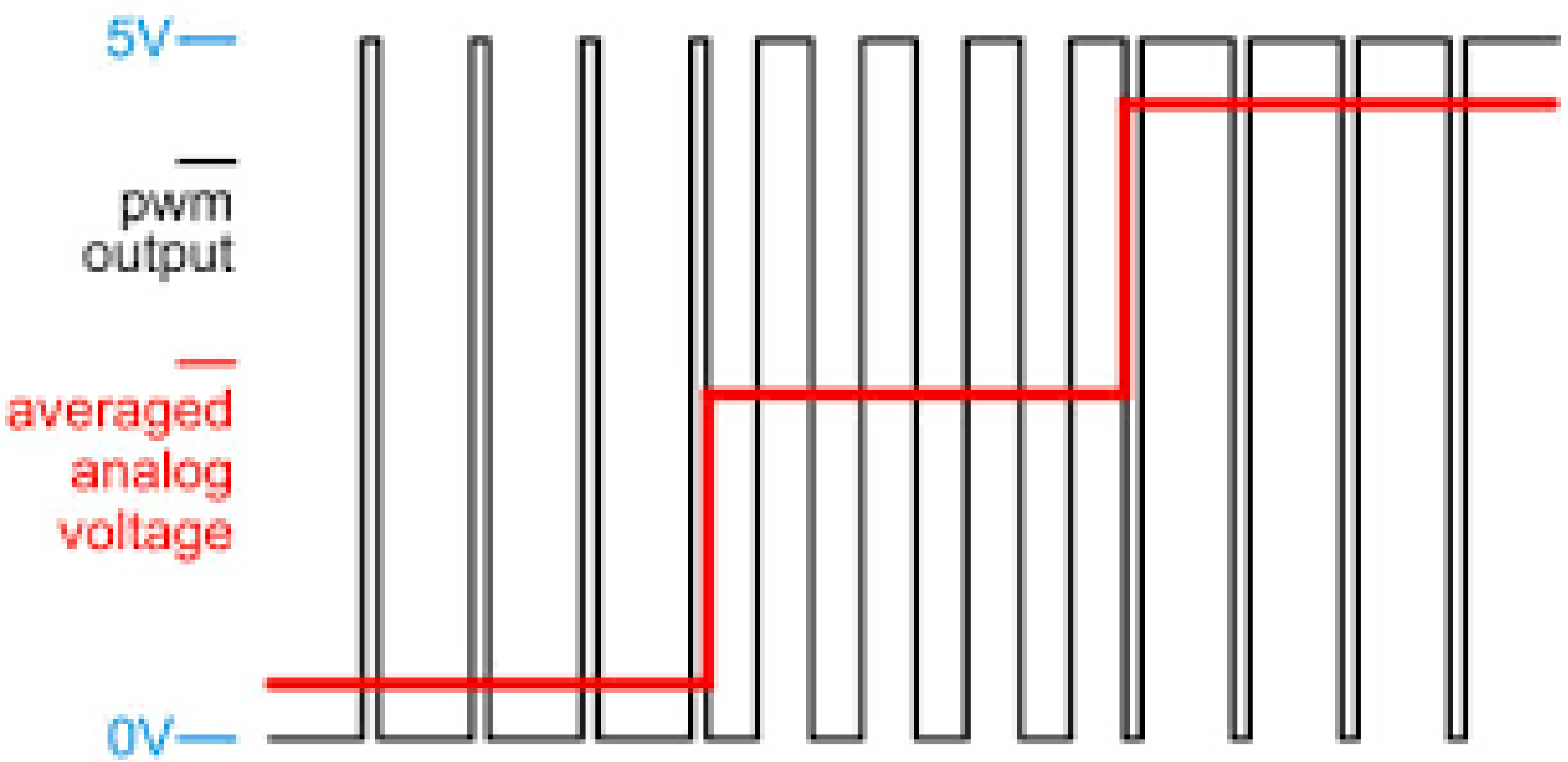
Pulse-Width Modulation

- Much easier to control high or low than an analog output
- Idea: modify how long a signal is high within some switching frequency, a.k.a duty cycle
  - On 50% of the time for half voltage
  - On 10% of the time for tenth voltage
- Duty cycle, not frequency!





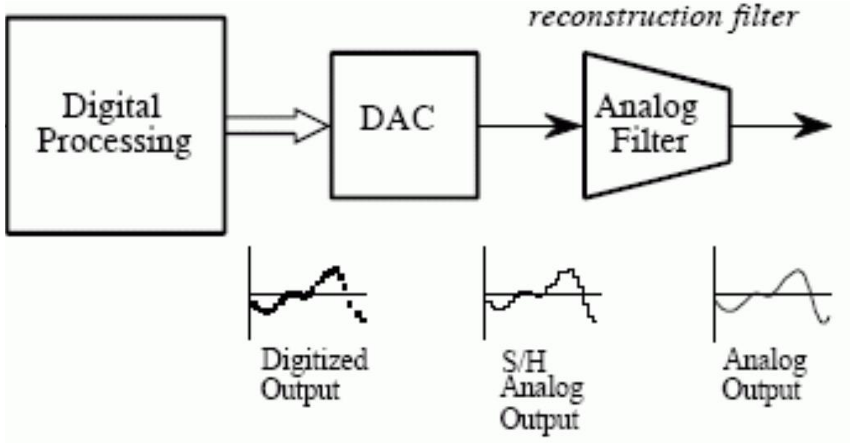
PWM to Analog Signal example

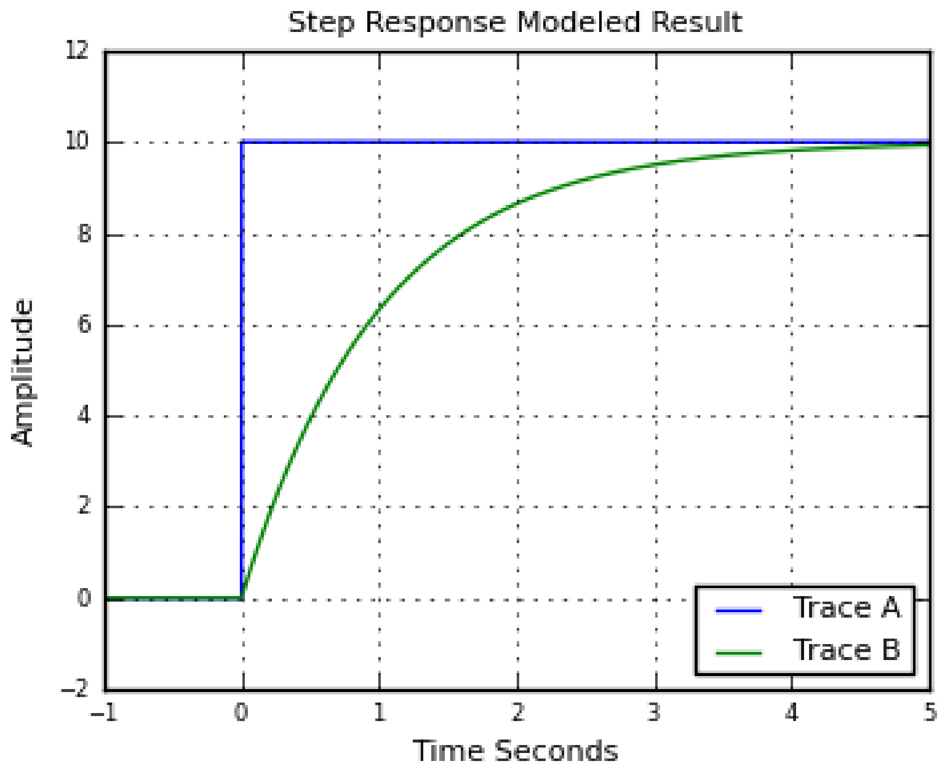


- PWM period should be much faster than the desired analog signal
  - PWM duty cycle represents the voltage along the way
  - Multiple duty cycles per output point makes it more accurate

Low-pass approach works here too

- Importantly, many devices are inherent low-pass filters
- Heaters, Motors
  - Low-pass by physical design
  - I.e., they can't start/stop quickly
- LEDs are not
  - But our eyes are!



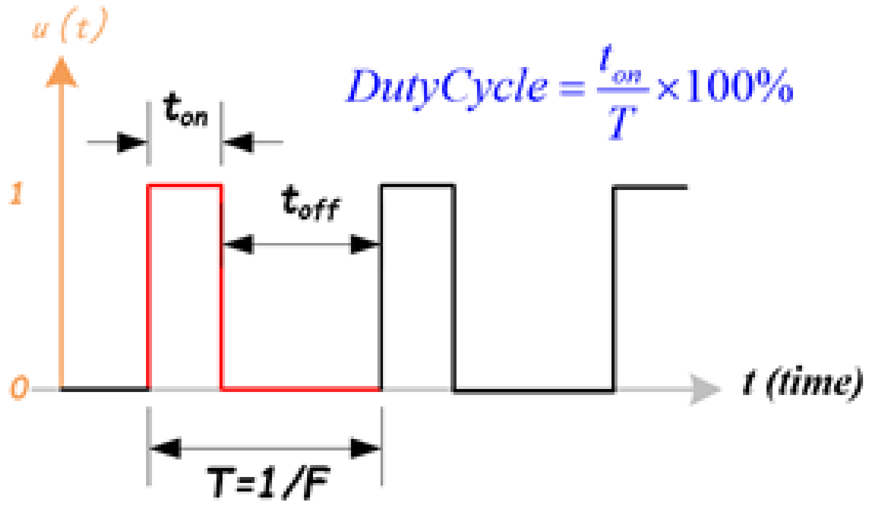


Controlling PWM

- Vary duty cycle by selecting transition points
  - Time when set
  - Time when unset

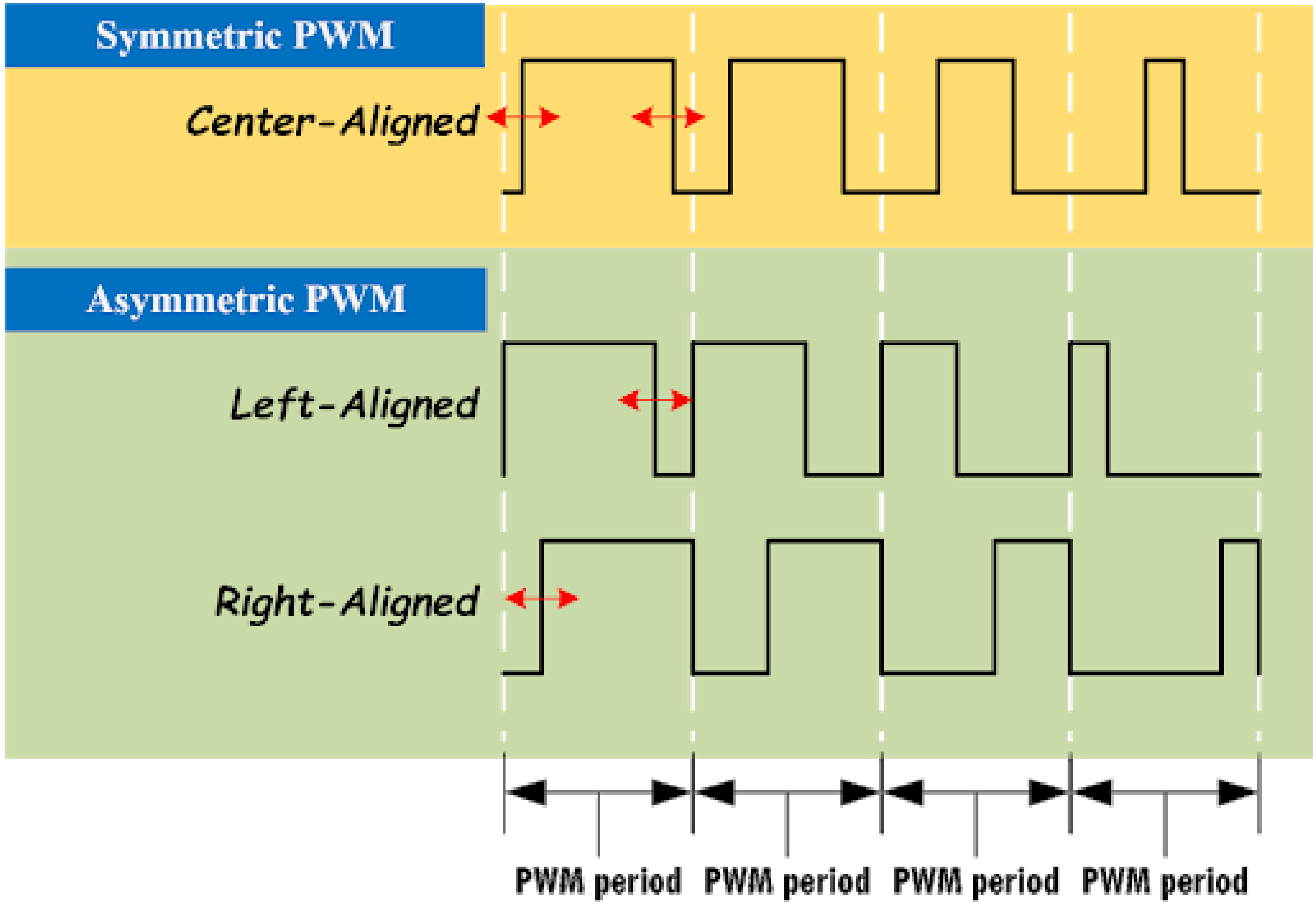
- Repeat every cycle
  - Period much faster than signal if possible
  - Makes analog approximation more accurate
    - The faster you run it, the less likely it matters that it is not actually analog
    - Example: LED switching frequency

- Duty cycle could vary cycle-by-cycle if it must



PWM alignment

- Can select alignment as well
  - Equivalent to a phase delay
- Centering produces cleaner analog output
  - Less harmonics
- Not relevant for most devices



Every microcontroller can do PWM

- Not every microcontroller has a PWM peripheral
- But every microcontroller has timers and digital outputs

- All that is needed is a GPIO and a Timer (or two)
  - Timer determines when to turn GPIO on and off
  - Often can be automated in hardware rather than using an interrupt
    - Connect timer expiration to GPIO toggling

PWM is an example of encoding data on a signal

- PWM is a pulse-width modulated signal

- There are many other ways to “modulate” a signal to transmit data
  - Amplitude, Frequency, and Phase are common
  - Layers data on top of an existing “carrier signal”

- Used especially for high-speed communication
  - Wired (cable lines) or Wireless (basically everything)

PWM applications

- Servos
  - Duty cycle chooses angle or rotation speed
- Motor controllers
  - Duty cycle chooses current and therefore speed
- LED brightness
  - And “breathing” effect
- Audio
  - Can sound okay if frequency is high enough

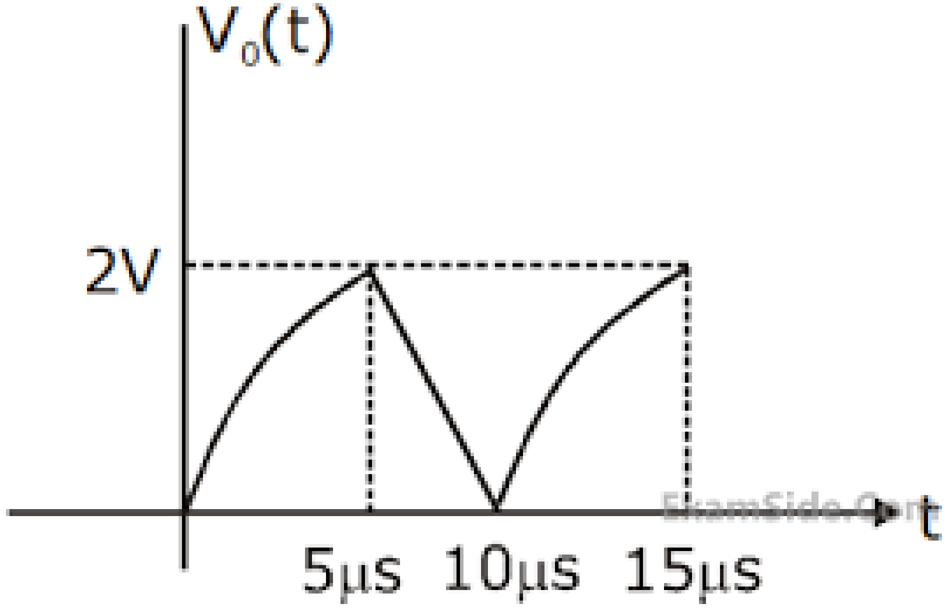
Controlling LED Matrix brightness

- Option 1: PWM peripheral
  - Need to use multiple PWM peripherals to get 5 pins to control each LED
  - Alternatively, could only control brightness for the entire matrix
    - Then use a single PWM output to control the row
    - When timer fires, change which row pin is used for PWM
    - PWM frequency should be much faster than row change frequency

- Option 2: do it manually (instead of PWM peripheral)
  - Need to apply duty cycle on top of the existing stepping through rows
  - Add 5 new one-shot app timers, one for each column
    - Fire some percentage into the time the LED is active (within the 2 ms)
    - Use to toggle individual column LED back to off
    - Result: the LED is on for some portion of the time it should be active

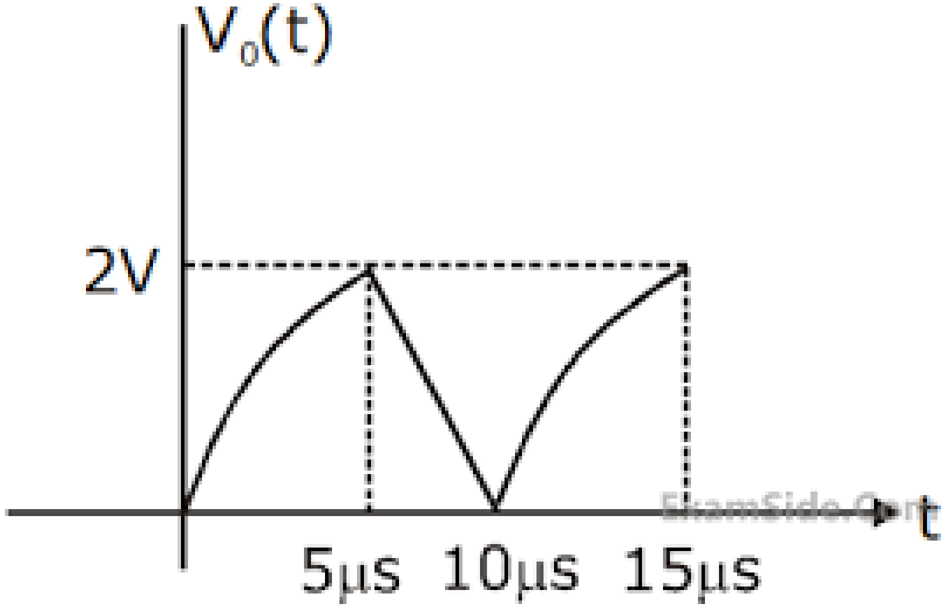
Break + Open Question

- Imagine you want to represent the following signal with PWM
  - **What should the PWM period be?**



  - **What kinds of duty cycle values would you use?** (3.3v is 100%)

Break + Open Question



- Imagine you want to represent the following signal with PWM
  - **What should the PWM period be?**
    - Signal period is ~10 μs
    - PWM period should be at least 2x that
      - 10x faster seems like a good start
      - Then if we want multiple PWM outputs per sample, that's ~20-40x faster
  - **What kinds of duty cycle values would you use?** (3.3v is 100%)
    - 2/3.3 = 61% duty cycle max
    - 0/3.3 = 0% duty cycle min

Outline

- Digital-to-Analog Converters
- Pulse-Width Modulation
- **nRF52 PWM**

nRF52 PWM – theory of operation

- A clock continuously adds to a counter value
    - (just like the Timer peripheral does)

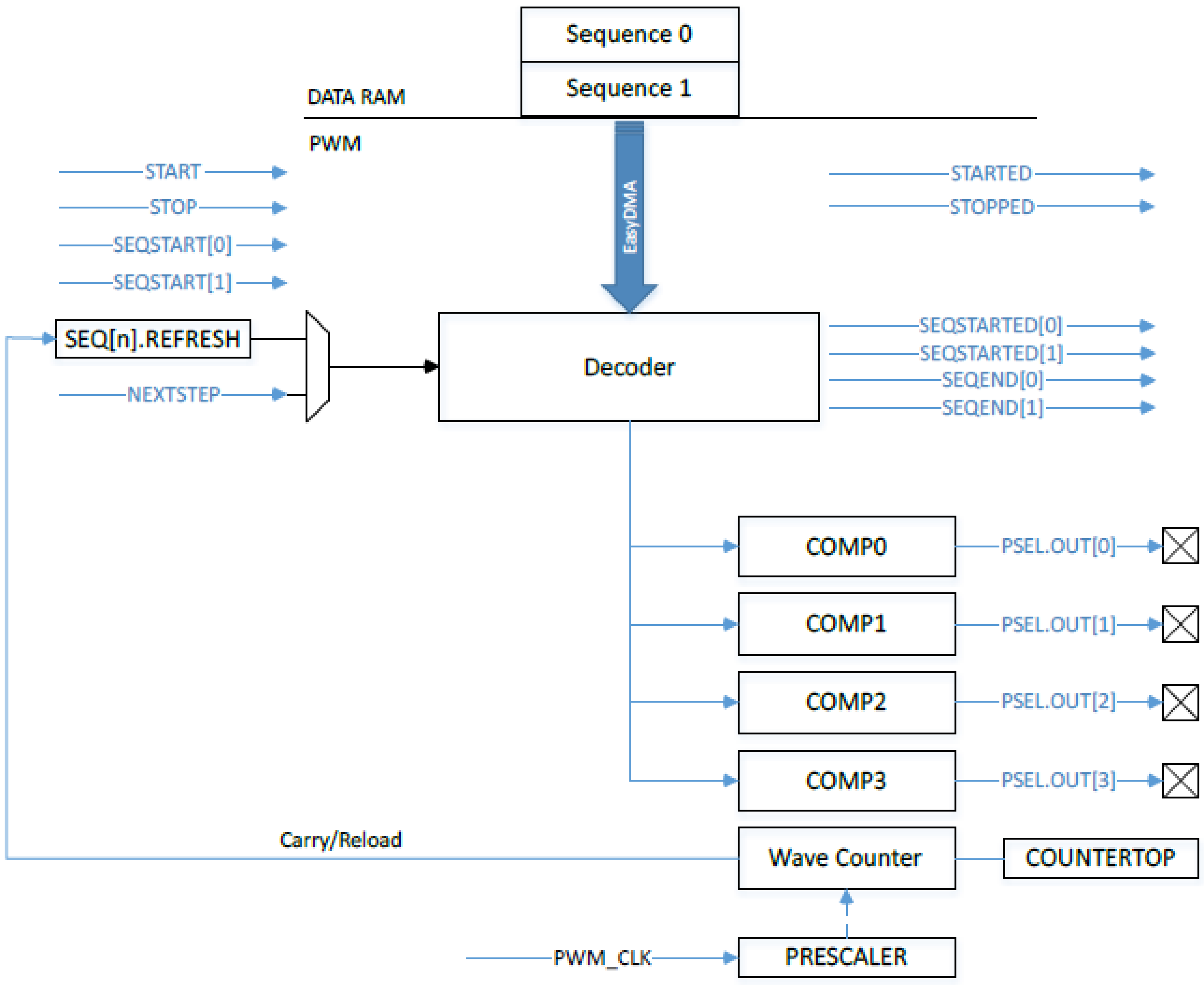
- When the counter value reaches COMP[n], the GPIO value on channel **n** changes from high to low (or vice-versa)

- When the counter value reaches COUNTERTOP, the GPIO value on channel **n** changes from low to high (or vice-versa)
    - AND the counter value resets to zero

nRF52 PWM peripheral

- Uses internal timer to create PWM output on up to 4 pins
  - 4 peripheral instances, so up to 16 pins total

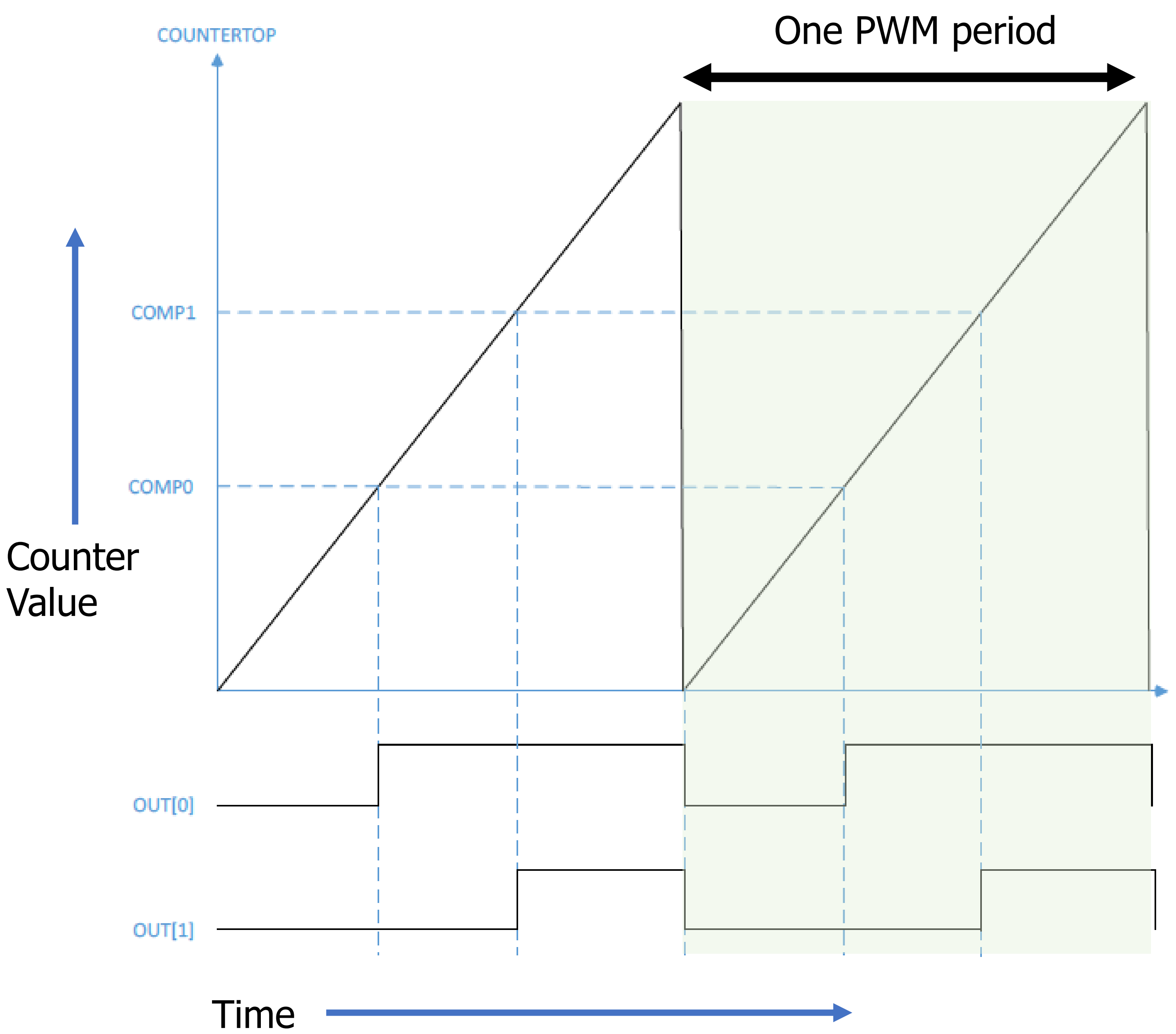
- Loads compare values via DMA to rapidly vary "analog" signal



PWM example

- Counter increments up to COUNTERTOP, resets and continues

- Period/Frequency
  - Chosen by COUNTEROP and timer PRESCALER

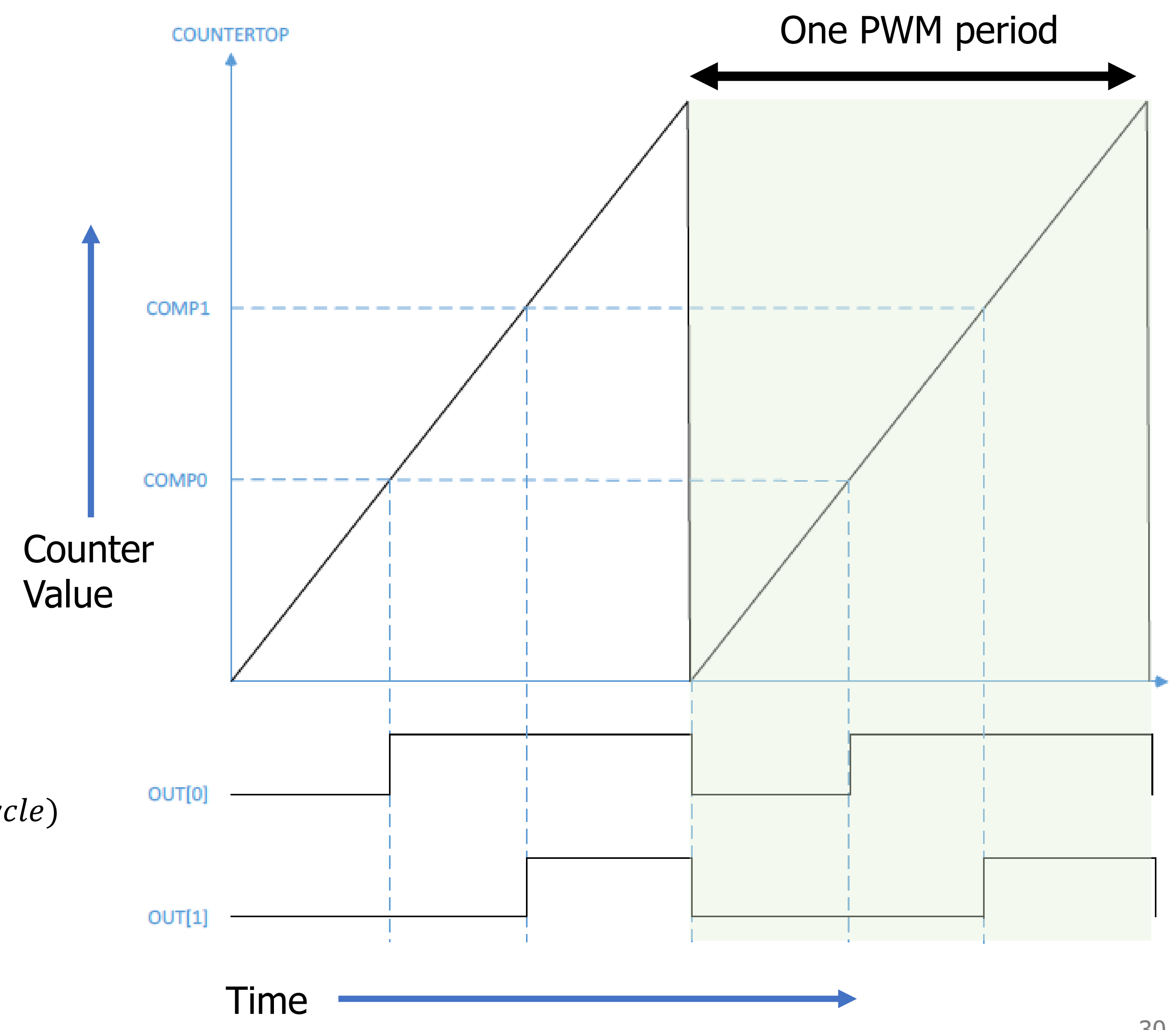


PWM example

- Counter increments up to COUNTERTOP, resets and continues
- Duty Cycle
  - COMP0 chooses first toggle point for OUT[0]
  - Second toggle point is when the timer resets

(right-aligned) $COMP = COUNTERTOP - (COUNTERTOP * DutyCycle)$

(left-aligned) $COMP = COUNTERTOP * DutyCycle$

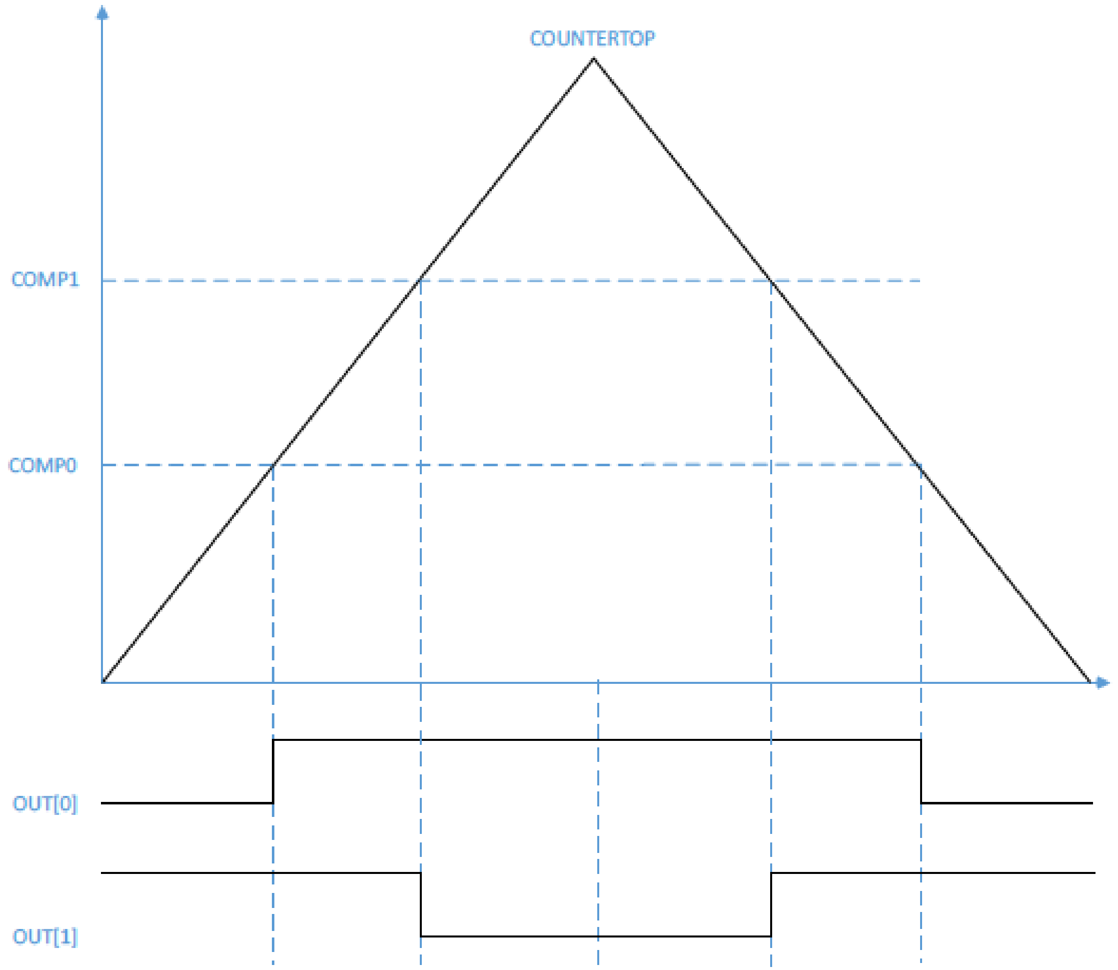


Center-aligned PWM

- Up-and-down mode enables center-aligned PWM

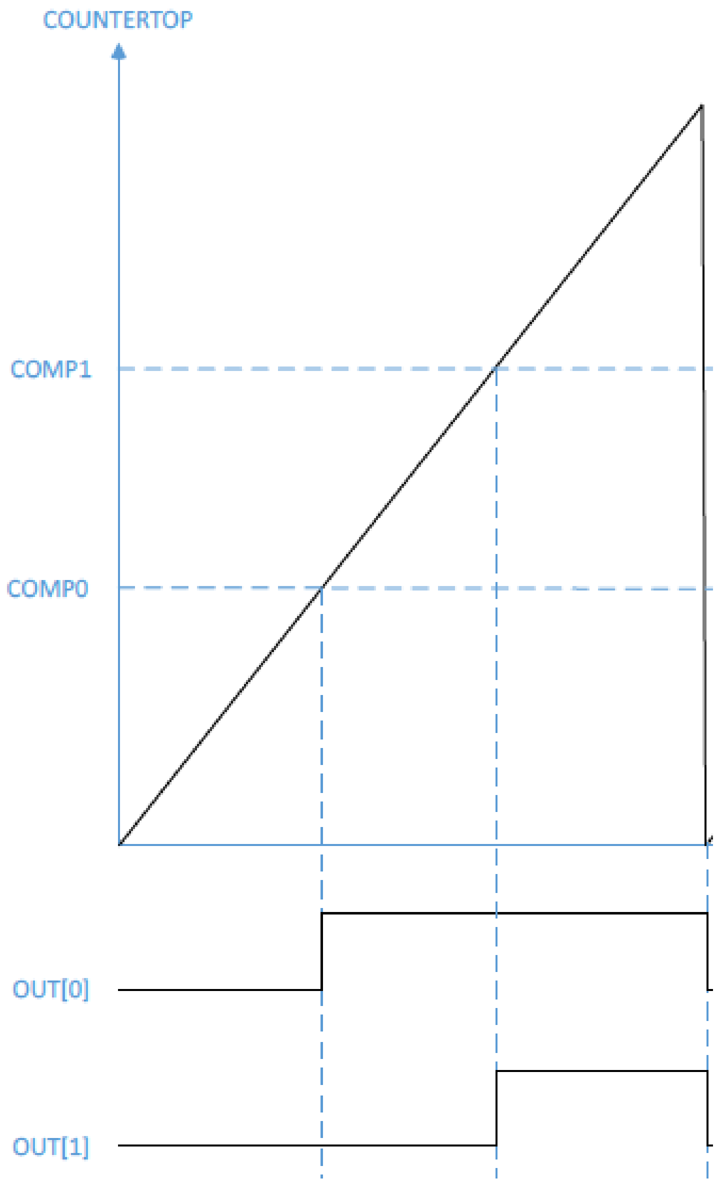
- Duty Cycle
  - Comp triggers toggle on rise
  - Comp triggers toggle again on fall

$$COMP = COUNTERTOP - (COUNTERTOP * 0.5 * DutyCycle)$$



Trading speed and accuracy

- How do you get the most accurate PWM values?
  - Select the largest COUNTERTOP possible
    - Most possible COMP values
    - Up to 15-bit resolution (32767 max)
- How do you get the fastest PWM frequency?
  - Select the smallest COUNTERTOP possible
  - PRESCALER also affects this
    - 16 MHz – 128 kHz (8 possible values)
- Fastest PRESCALER + largest COUNTERTOP equals 488 Hz
  - Likely need to sacrifice resolution for speed

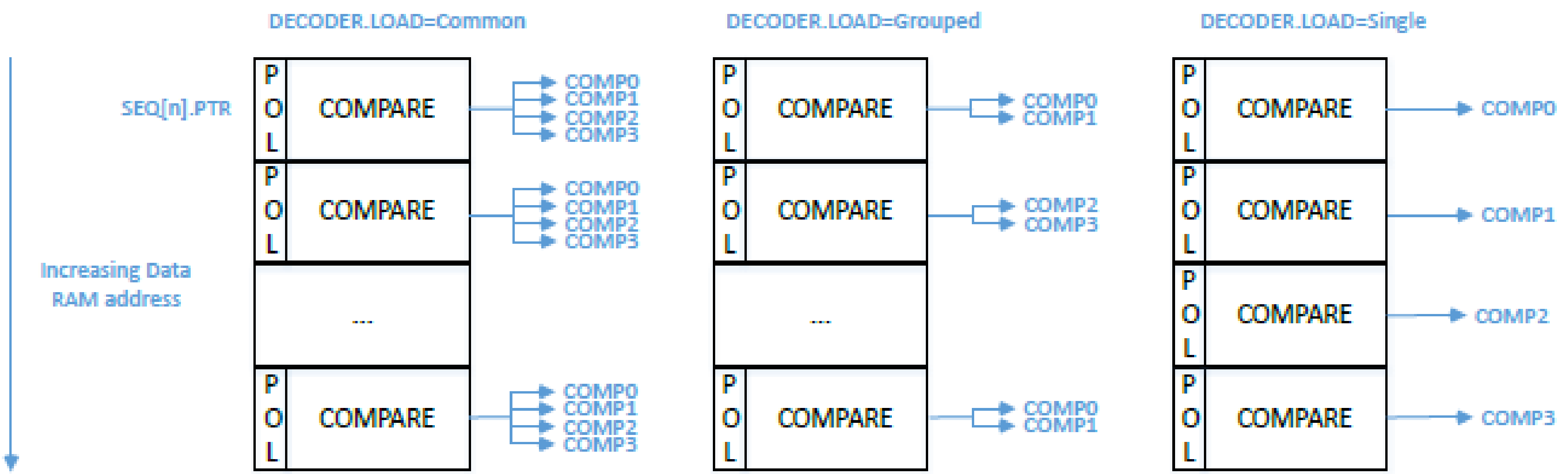


DMA with PWM

- Every *N* periods it loads a new configuration from RAM
  - *N* combined with PRESCALER and COUNTERTOP chooses “analog signal” period

- Configuration sets COMP values for each output channel
  - Also sets polarity (starting value: low or high)

- Application of memory loads to channels is configurable

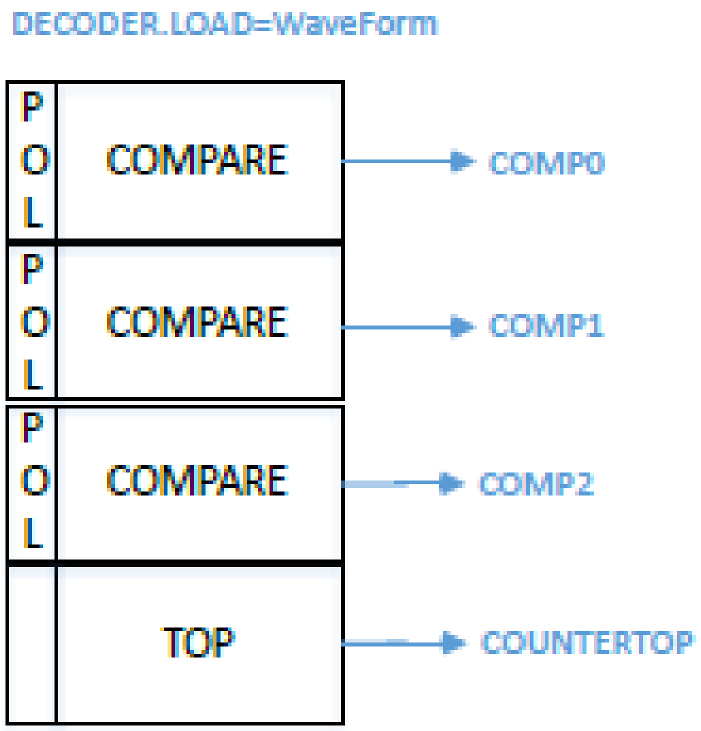


Waveform mode

- Also has the option to change COUNTERTOP every N PWM periods

- Allows arbitrary waveforms to be created
  - Frequency changes every period
  - Duty cycle can also change each period

- We don't normally need this, as a constant frequency with changing duty cycle should be fine



Other configurations

- How many times the entire DMA sequence repeats
  - 0 to large number, infinite with a configuration in SHORTS

- How long to delay between repeating sequence cycles
  - Repeats last PWM configuration

- Two DMA sequence configurations (0 and 1)
  - Can modify one while the other is playing - “Double Buffering”
  - Allows continuous signal (for example, music)

nRF SDK PWM driver

https://infocenter.nordicsemi.com/index.jsp?topic=%2Fsdk_nrf5_v16.0.0%2Fgroup__nrfx__pwm.html

- Initialize PWM with base configuration
  - Output pins, Clock frequency, COUNTERTOP, DMA grouping mode
  - Handler for events from peripheral

- nrfx_pwm_simple_playback(instance, sequence, count, flags)
  - Instance: pointer to global variable with registers
  - Sequence: struct containing sequence to be played (see next slide)
  - Count: number of times (1 or more) to repeat sequence
  - Flags: stop peripheral when done, loop forever, various events

Sequence struct

Data Fields

nrf_pwm_values_t values
Pointer to an array with duty cycle values. This array must be in Data RAM. More...

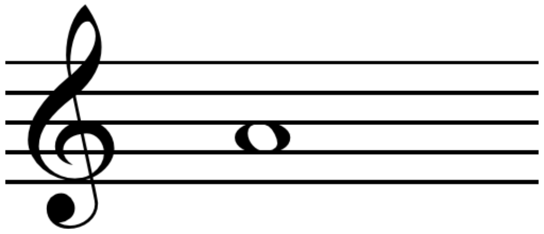
uint16_t length
Number of 16-bit values in the array pointed by `values`.

uint32_t repeats
Number of times that each duty cycle is to be repeated (after being played once). Ignored in NRF_PWM_STEP_TRIGGERED mode.

uint32_t end_delay
Additional time (in PWM periods) that the last duty cycle is to be kept after the sequence is played. Ignored in NRF_PWM_STEP_TRIGGERED mode.

- values: pointer to array of uint16_t values (union of types)
- length: length of array
- repeats: number of times to repeat each individual value
  - Sets period for "analog value" changing

Example, playing a note with a square wave



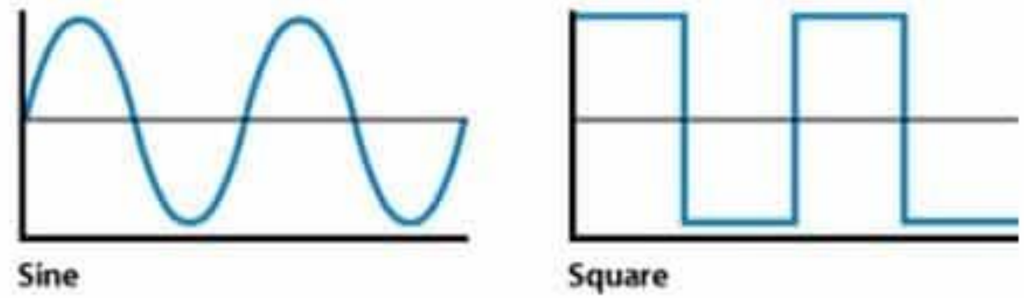
- Pick PWM frequency to match note frequency
  - Combination of PRESCALER, COUNTERTOP, and repeats
  - 440 Hz for the note A
    - PRESCALER 1 MHz, COUNTERTOP 2273 -> 440 Hz

- Set duty cycle of PWM to control volume
  - 50% duty cycle -> COMP value of 1137

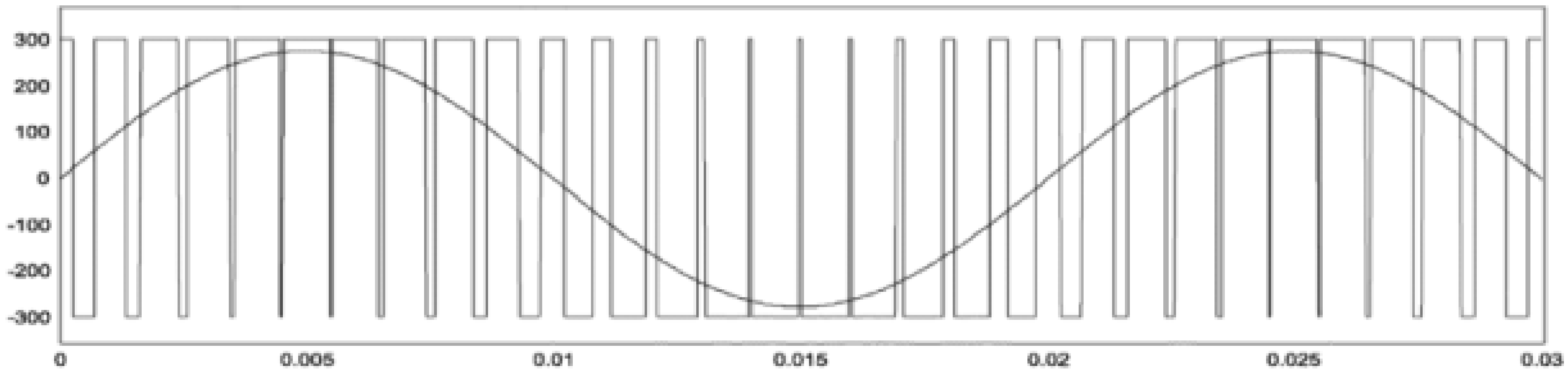
- Set sequence with an array of length 1, content is {1137} (polarity 0)
  - Repeats 0, end_delay 0
- Set playback_count to 1 and flags to NRFX_PWM_FLAG_LOOP

Playing sine waves instead of square waves

- Sine waves sound different than square waves
  - Sine is more smooth
  - Square is more harsh and buzzy



- For better sound quality, we can play sine waves via PWM



Steps to playing a note with a sine wave

1. Calculate sine wave values for some amount of duration
   - Reasonable to calculate one second of data at a time
   - `sin()` function might be too slow here
     - Instead calculate sine values in advance and interpolate into an array based on frequency

2. Translate sine wave values into duty cycle values
   - Fill an array with these duty cycle values

3. Play the array of duty cycle values
   - That gets one second of audio
   - For music, might change schedule a timer for when to stop current playback and play the next note instead

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