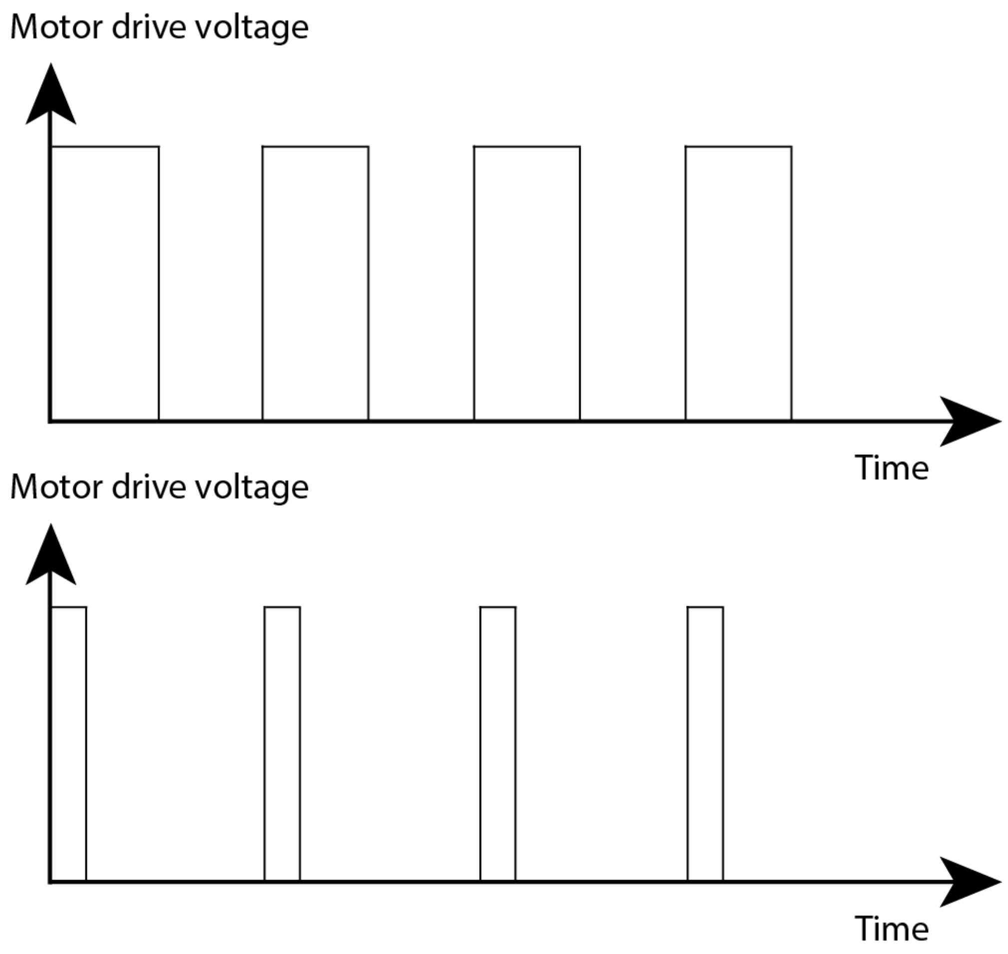
CC2511 Week 5: Lecture 2

Overview

- Pulse Width Modulation (PWM).
- Practical motor drive circuits using PWM.
- The H bridge circuit for controlling motor direction.

Pulse Width Modulation

- Vary the **duty cycle** of the drive voltage: “**Pulse Width Modulation**”
- Set the period fast enough that the motor inductance and mechanical inertia will smooth out the pulses.
- The result is an effective drive voltage proportional to the duty cycle.



PWM Ratio

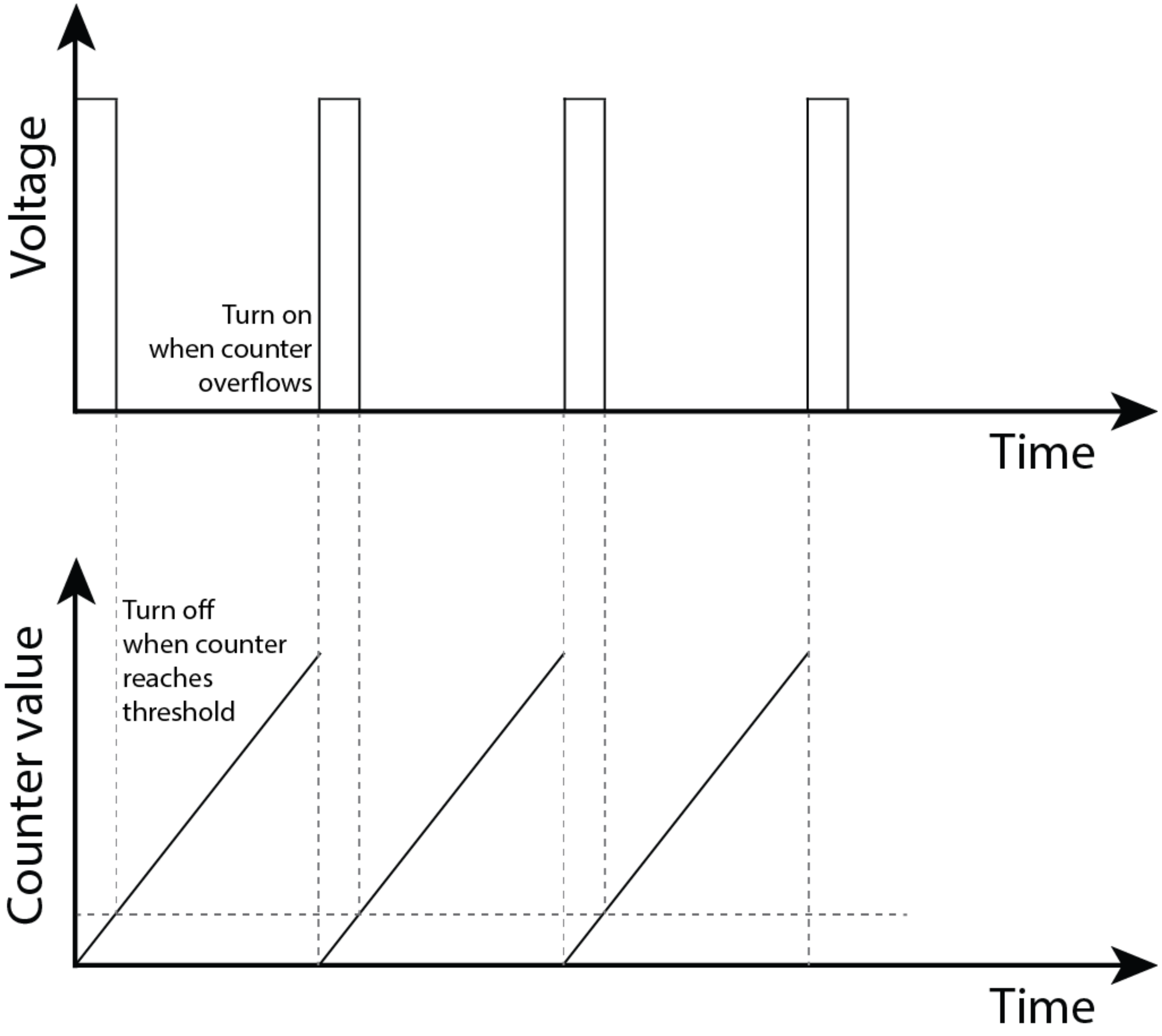
- Usually the PWM duty cycle is configured as

$$\text{Ratio} = \frac{\text{On time}}{\text{Period}}$$

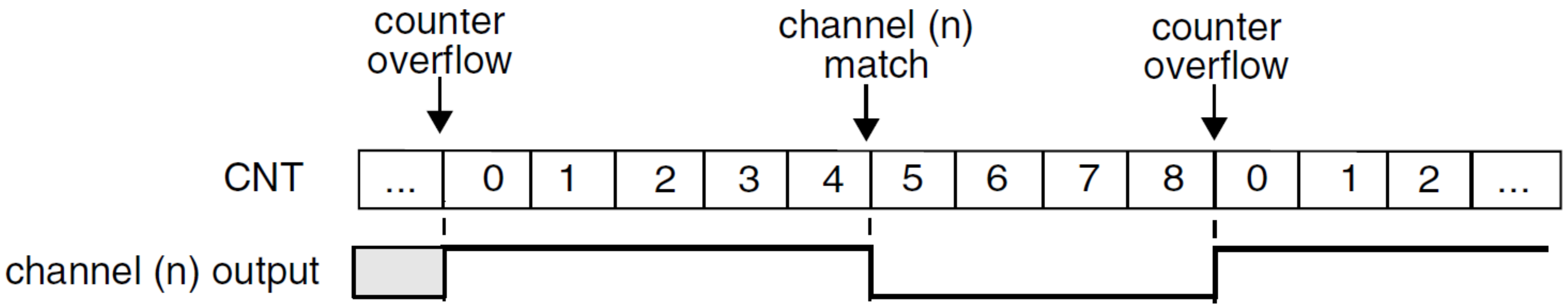
- A ratio of 0% has the device completely off.
- A ratio of 100% has the device completely on.

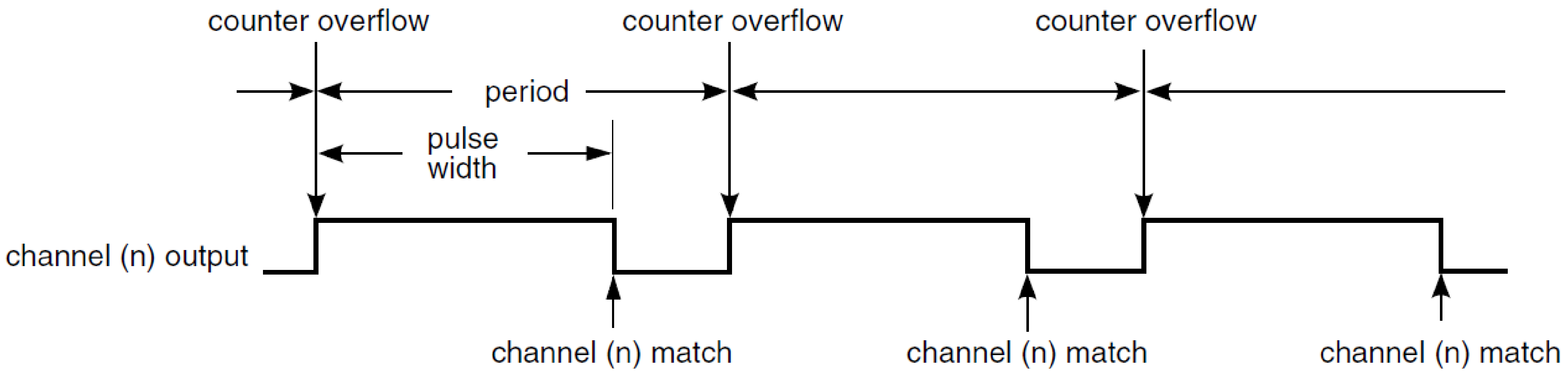
Implementation

- Use a counter that continuously increments at a known rate.
- When the counter resets to zero, turn the voltage on.
- When the counter reaches a specified value, turn the voltage on.



PWM operation





PWM implementation in the K20 family

Our boards implement PWM using the "**FlexTimer Module**" (FTM).
Each FTM maintains a running counter that can drive PWM.

K20:

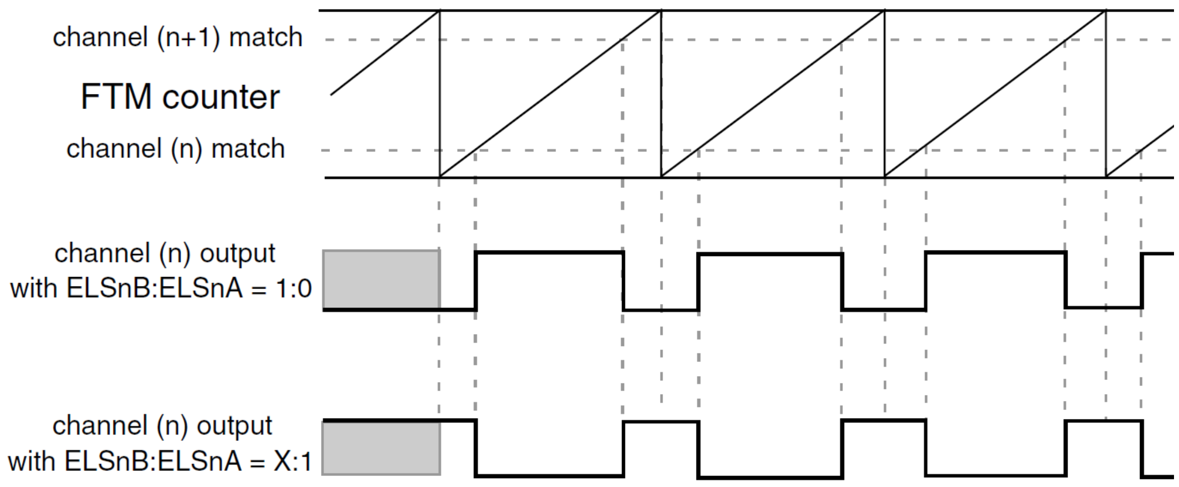
- Reference Manual Ch. 35.
- Two FTMs: FTM0 and FTM1.
- FTM0 has 8 channels (FTM0_C*n*V, *n*=0 to 7).
- FTM1 has 2 channels (FTM1_C0V and FTM1_C1V).

K22:

- Reference Manual Ch. 39.
- Four FTMs: FTM0 ... FTM3

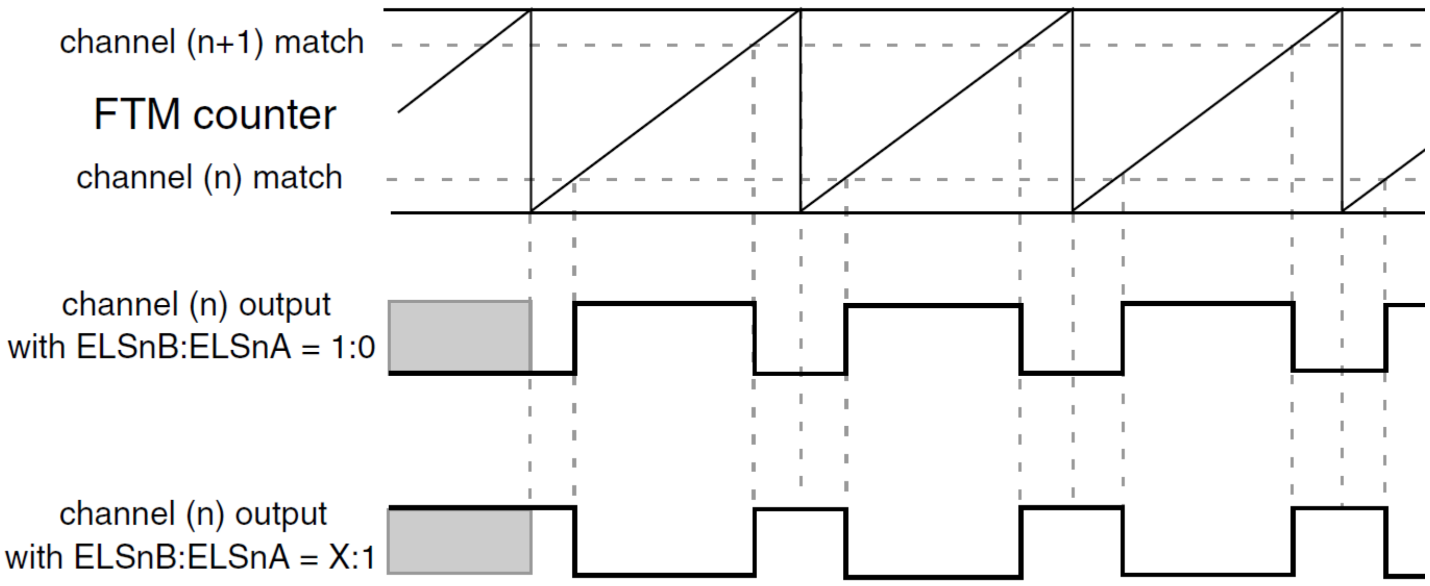
Consequences of this implementation

- Suppose that you drive PWM on three different pins from the same FTM.
- The FTM has a single running counter.
- What are the consequences of this implementation?



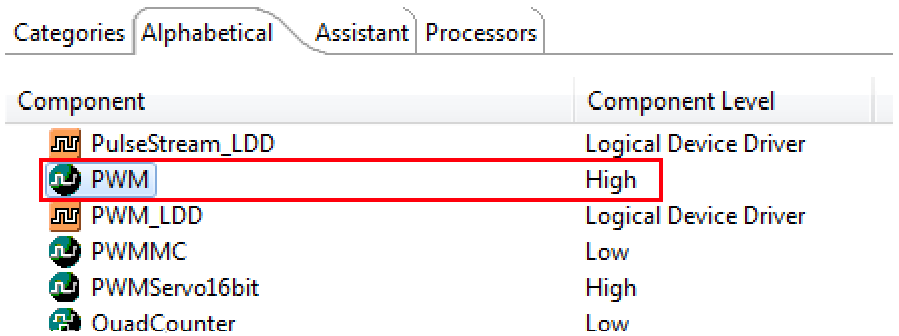
Each PWM must have the same period

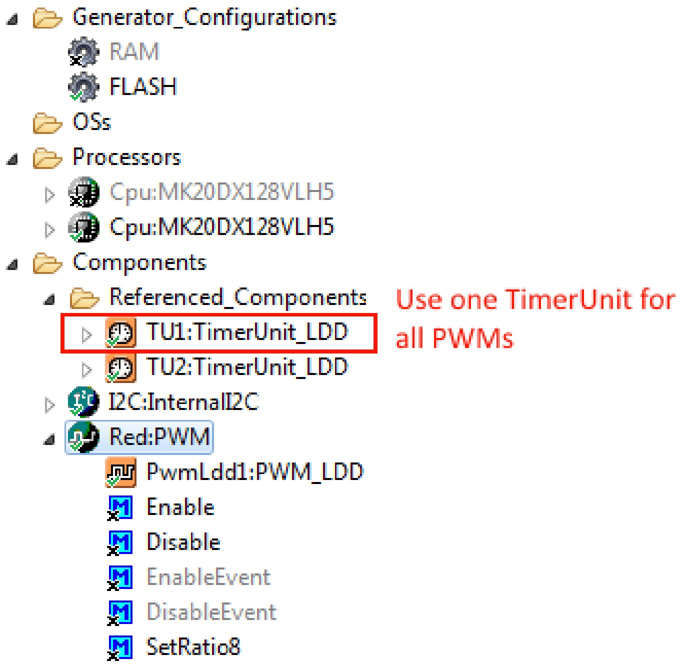
- **Each PWM channel must have the same period** because each channel is triggered from the same counter.

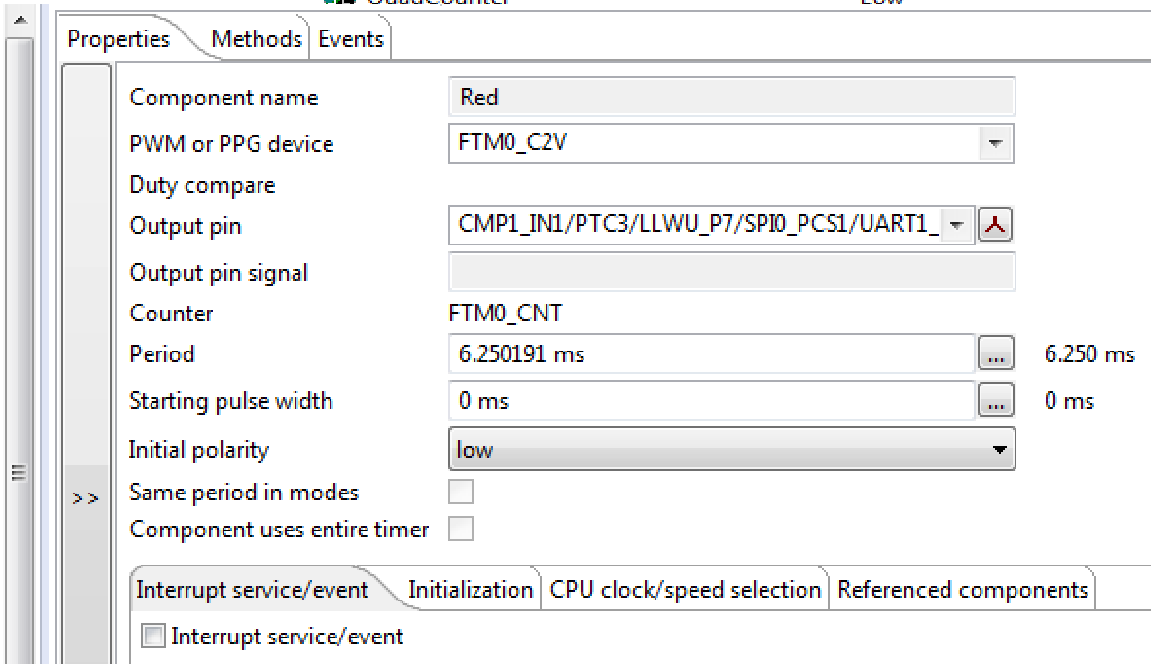


Configuring PWM through Processor Expert

- Use the **PWM** component.
- If you have multiple PWMs, set the same period.





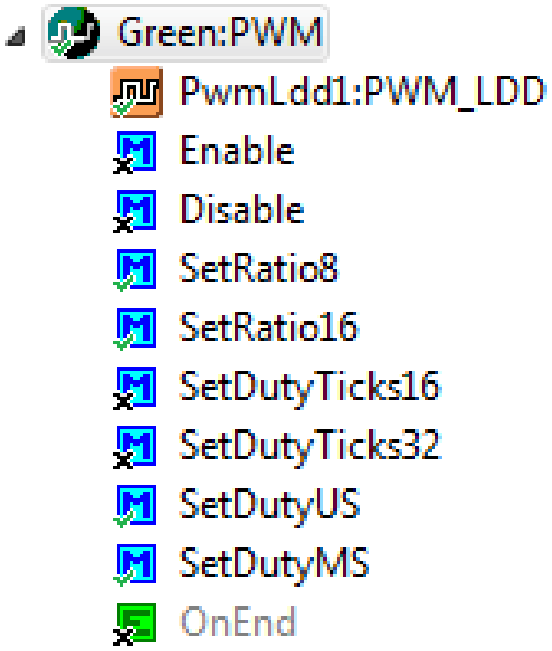


Processor Expert Methods

- Use SetRatio8 or SetRatio16 to set

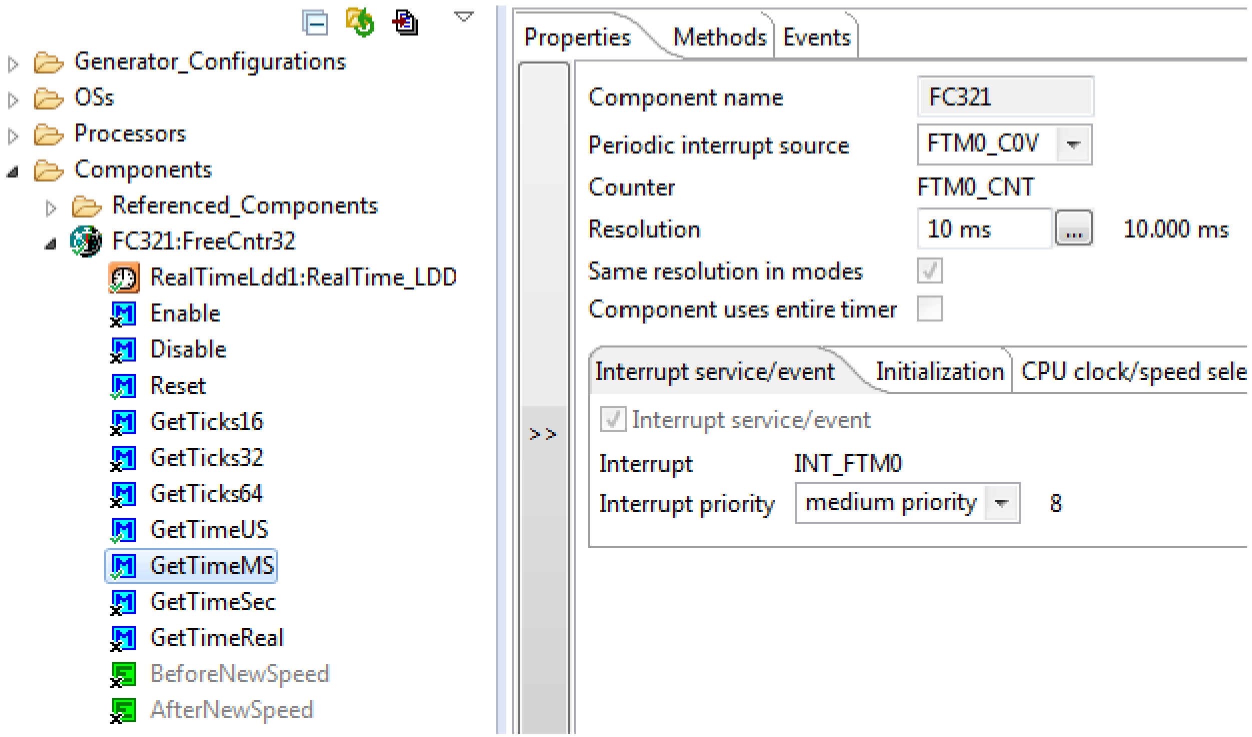
$$\text{Ratio} = \frac{\text{On time}}{\text{Period}}$$

- Example: SetRatio8(0) turns the device off, SetRatio8(128) is 50%.
- “On” is either of a high voltage or a low voltage according to the “Initial polarity” setting.
- Can also set the duty cycle in microseconds or milliseconds.



The FlexTimer module

- The FlexTimer hardware can also be used for timekeeping.
- Example: FreeCntr32 measures time in microseconds, milliseconds or seconds.



Using FreeCntr32

This method returns the time (as a 16-bit unsigned integer) in milliseconds since the last resetting after the last reset.

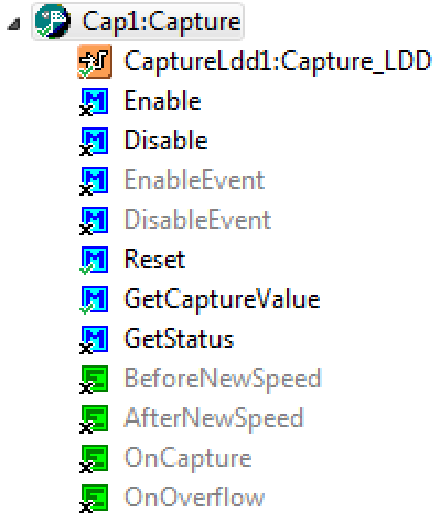
```
byte FC321_GetTimeMS(word *Time);
```

-Return value: Error code, possible codes:
ERR_OK - OK
ERR_SPEED - This device does not work in the active speed mode
ERR_OVERFLOW - Software counter overflow
ERR_MATH - Overflow during evaluation
-1. parameter: A pointer to the returned 16-bit value in milliseconds

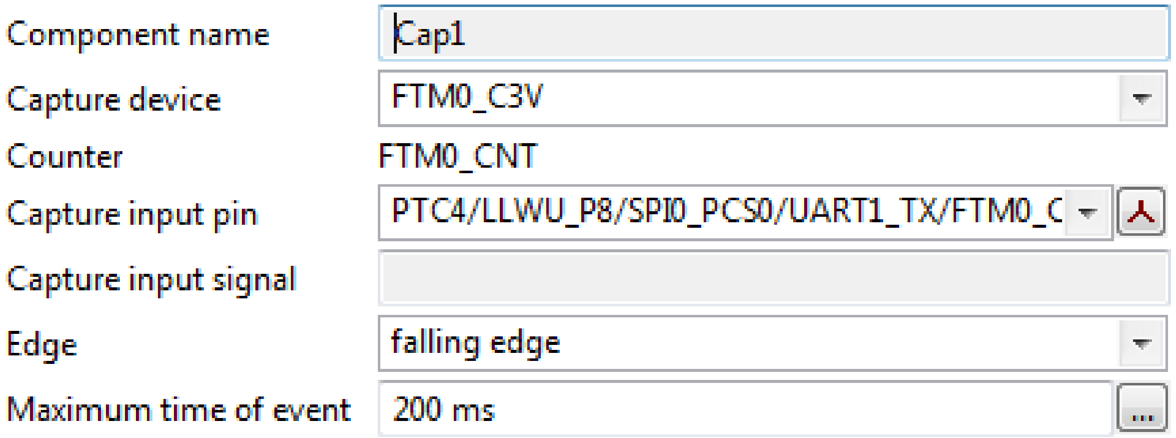
- Example code:

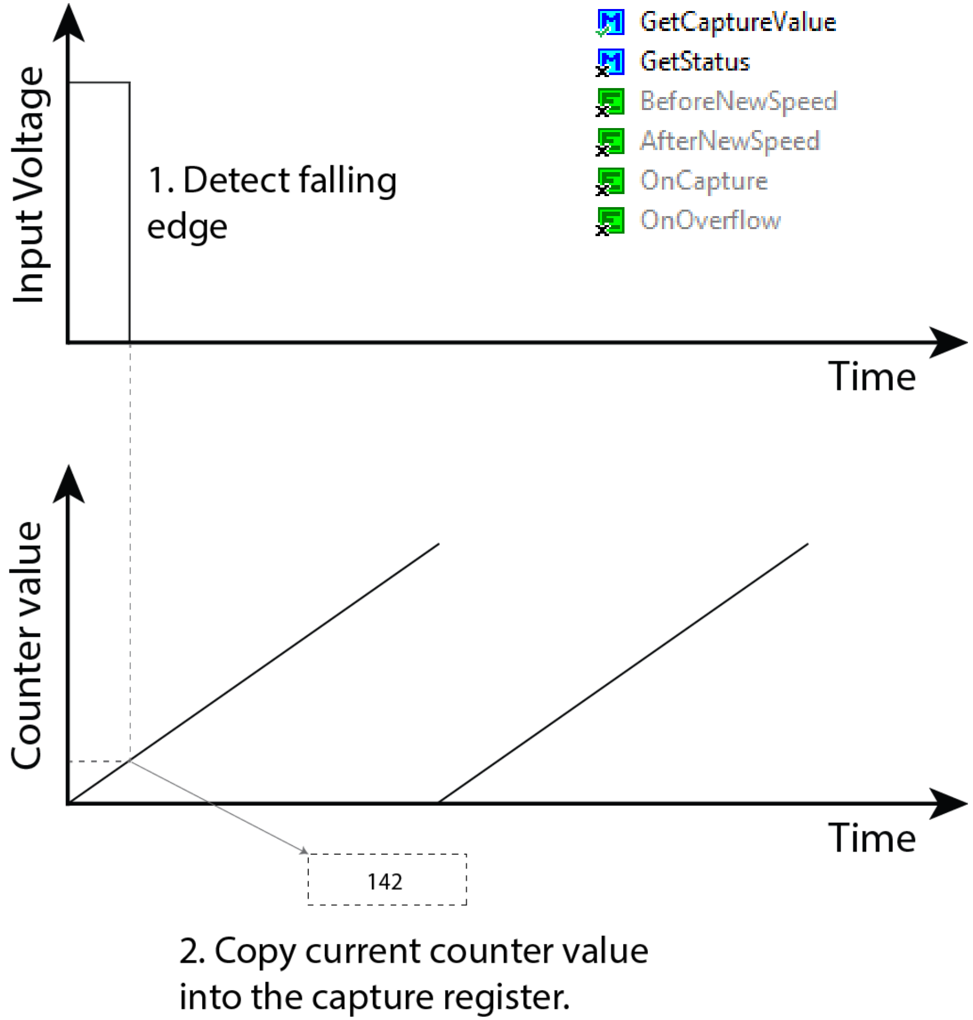
```
byte err;
word time;
FC321_Reset(); // Start measuring time here
// ...
err = FC321_GetTimeMS(&time);
if (err == ERR_OK) { /* time contains milliseconds since Reset */ }
else { /* an error occurred and time is not available */ }
```

Input capture: “PWM in reverse”



- The Capture component saves the FTM counter when a rising/falling edge is detected.





Combining FlexTimer features

- The Processor Expert components assume they have free reign over the FlexTimer settings.
- Different components would try to set up the FlexTimer differently.
- You cannot combine (for example) a PWM and a FreeCntr32 on the same TimerUnit.

Errors (4 items)

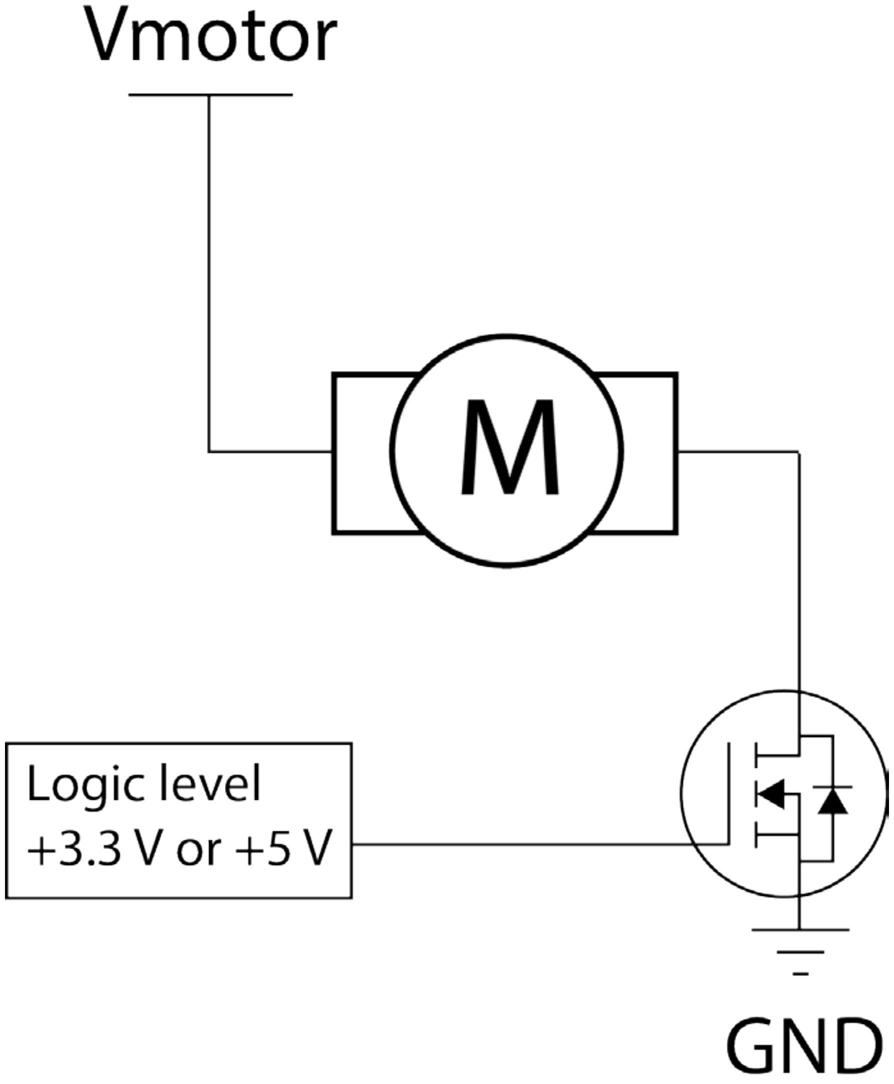
- Conflict in required values from components in the project (Counter restart)
- Error in the inherited component settings (PWM_LDD)
- Event is required by the interface, but is disabled by component settings or by template (OnEnd)
- Linked component TU1 is shared with another component of inadmissible type. (Linked component)

Using PWM for motor control

- A microcontroller generates PWM on a 3.3V logic pin.
- **Design problem: switch a 12 V DC motor.**
- How would you do this?

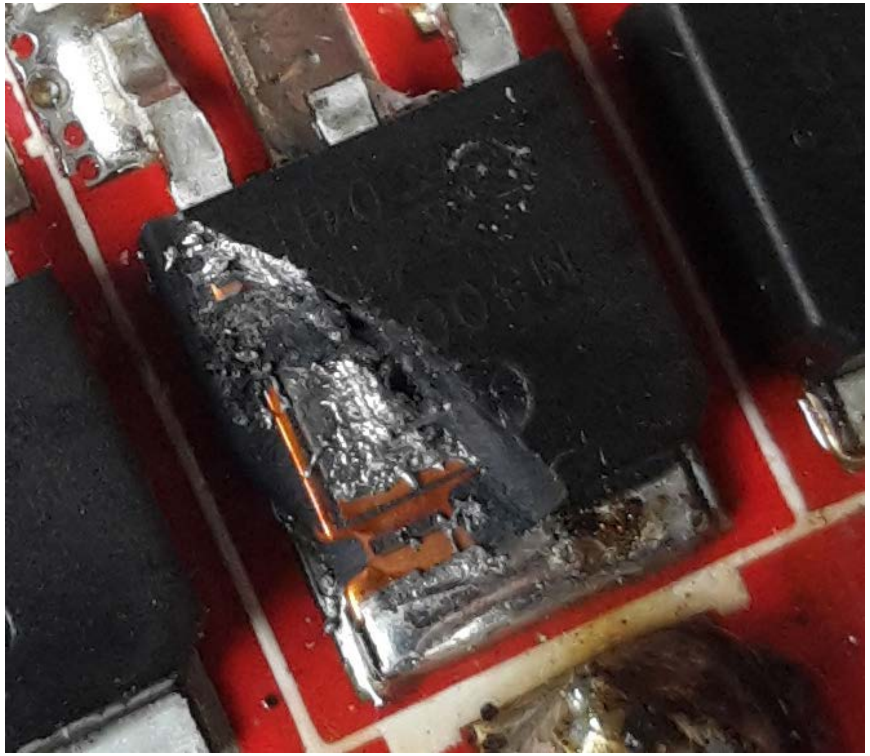
Using a MOSFET to switch a motor: Simple case

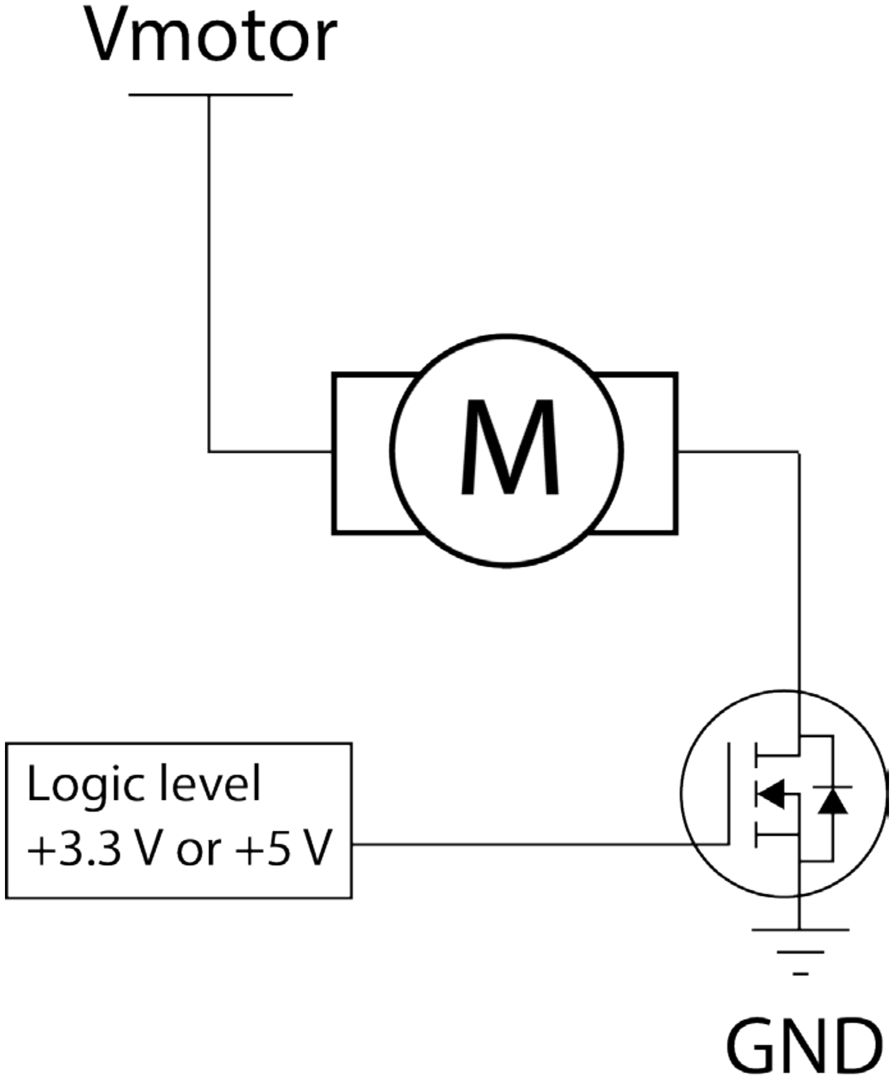
- Place the MOSFET on the low side (source terminal grounded) so that Vgs is independent of the motor current.
  - Vgs = voltage from gate to source
- The microcontroller can control the gate-source voltage directly.
- This works! The motor turns on.



Using a MOSFET to switch a motor: Simple case

- Then you switch the motor off and this happens:





Motors are inductors!

- A motor consists of coils of wire (with a large inductance).
- The voltage on an inductor is
$$v_L = L\frac{di}{dt}$$
- During switching, **di/dt is large** and the **voltage is large**, destroying the FET.

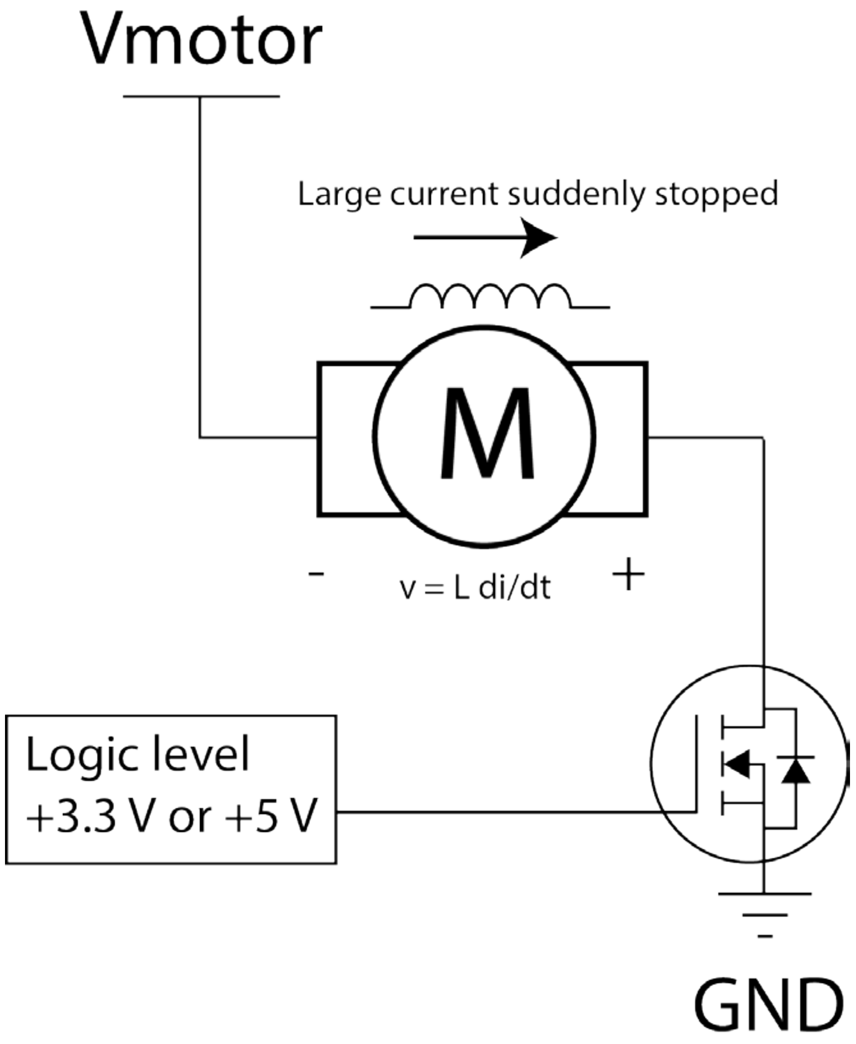
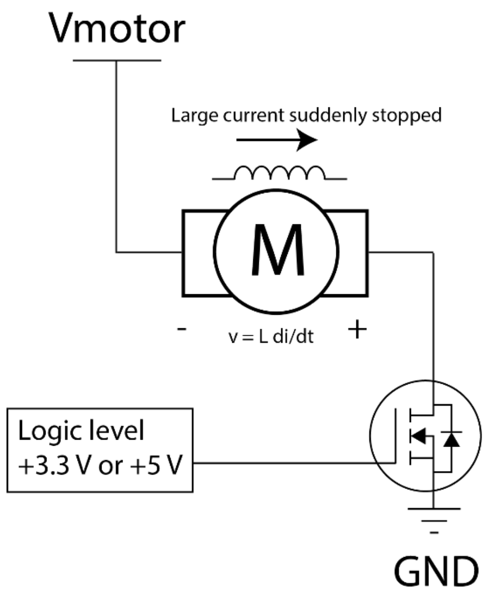


Table 2. Absolute maximum ratings

Symbol	Parameter	Value	Unit
V_{DS}	Drain-source voltage (V_{GS} = 0)	30	V
V_{DGR}	Drain-gate voltage (R_{GS} = 20 kΩ)	30	V
V_{GS}	Gate- source voltage	± 15	V

Table from STP22NF03L datasheet (22A power MOSFET)

Switch off voltage spike



Realistic values:

- Motor L = 0.5 mH
- FET turn off time = 20 ns (with resistive load!)
- Motor current = 0.5 A

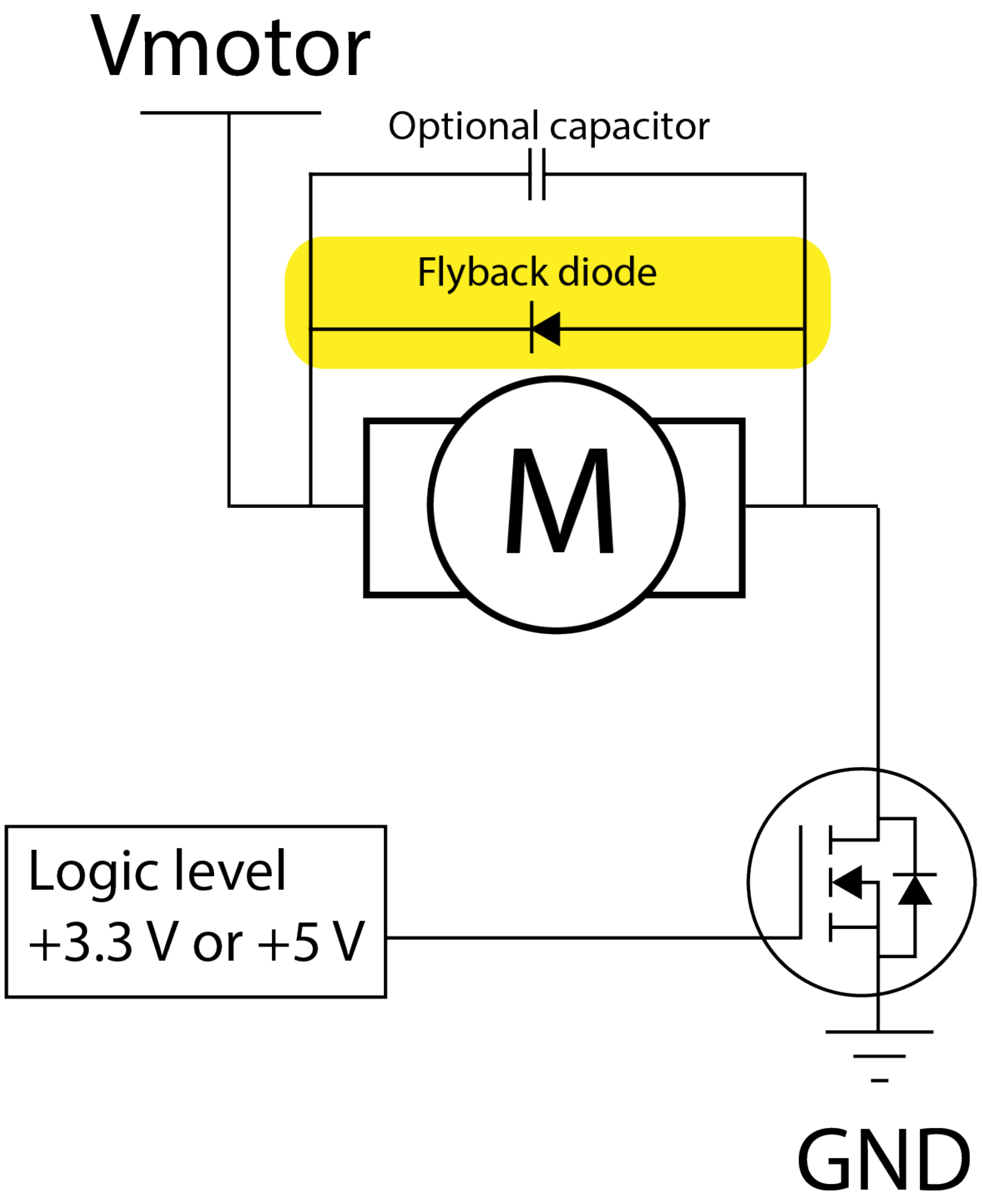
If we were able to stop the motor current in 20 ns, the average voltage on the motor would be approximately:

$$v = L\frac{di}{dt} = 0.5 \times 10^{-3} \times \frac{0.5}{20 \times 10^{-9}} = 12500\ \mathrm{V}$$

Clearly we have a problem.

Flyback diode

- A “flyback diode” is needed to give the motor’s inductance a pathway to dissipate energy when the motor is switched off.
- Diode selection requirements:
  - Reverse bias voltage >= Vmotor
  - Forward bias current >= motor drive current



Impact of diode on switching speed

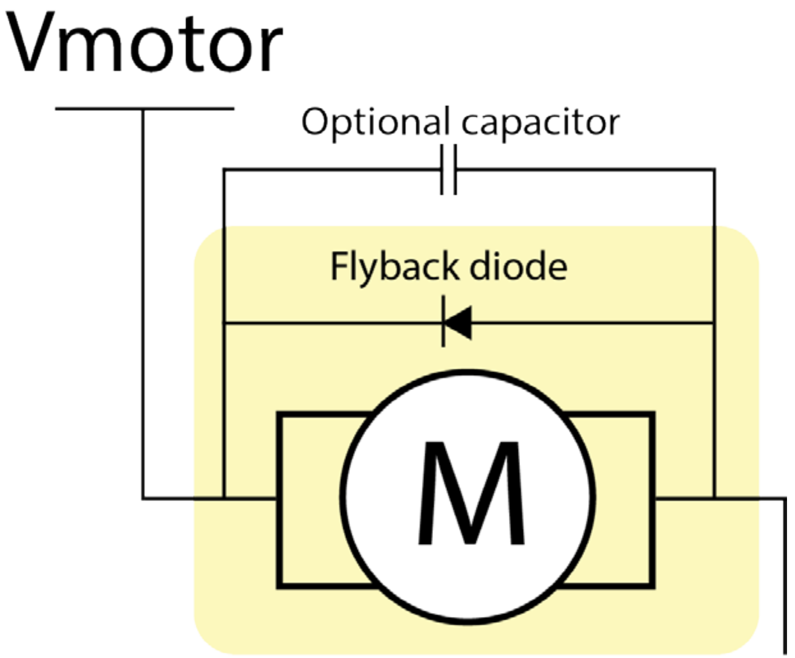
The motor voltage (neglecting back EMF due to rotational motion) is

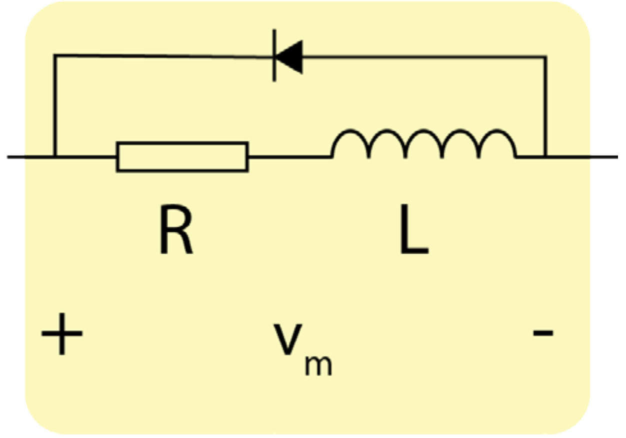
$$v_m = iR + L\frac{di}{dt}$$

If the diode conducts at 0.7 V (typical for Si diode), we have

$$-0.7 = iR + L\frac{di}{dt}$$

First order differential equation. Solve for $i(t)$.





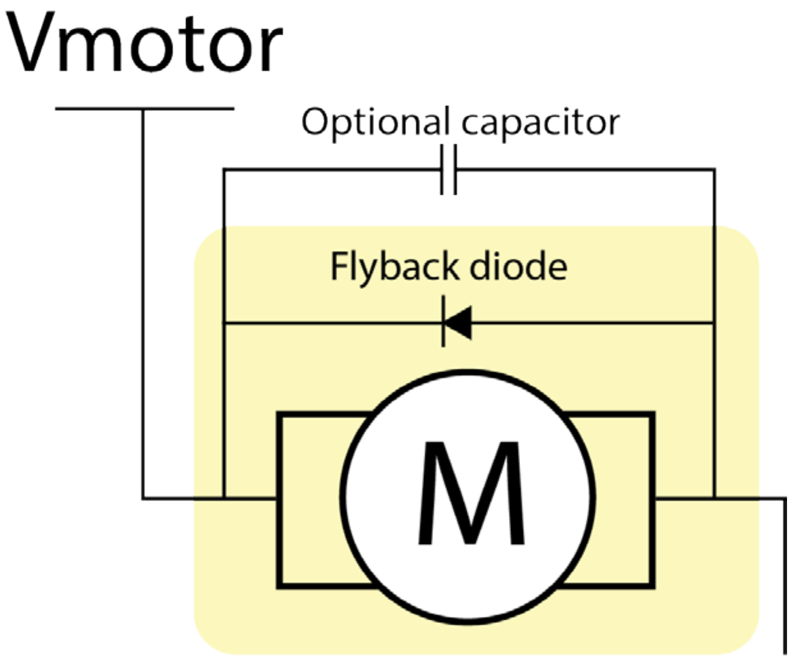
Impact of diode on switching speed

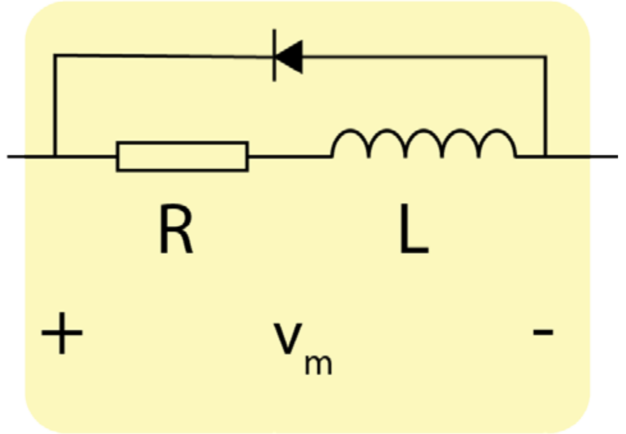
Solve for $i(t)$

$$i(t) = \frac{(0.7 + i_0 R)e^{-\frac{tR}{L}} - 0.7}{R}$$

The exponential time constant is L/R.

- Current in the motor windings decays with time constant L/R.

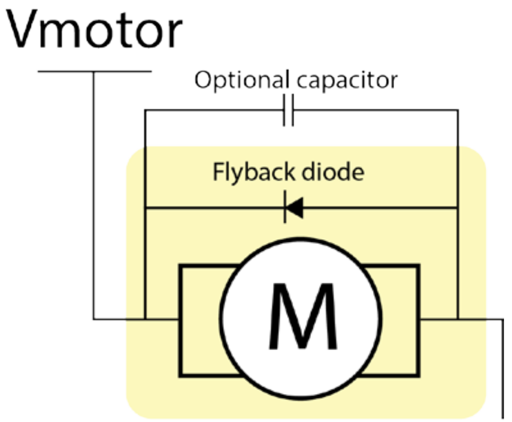


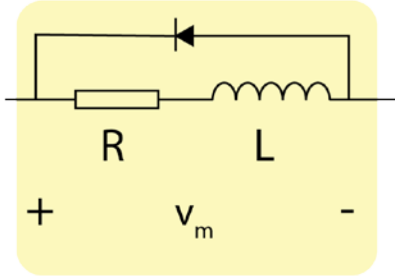


Choosing the PWM frequency

$$i(t) = \frac{(0.7 + i_0 R)e^{-\frac{tR}{L}} - 0.7}{R}$$

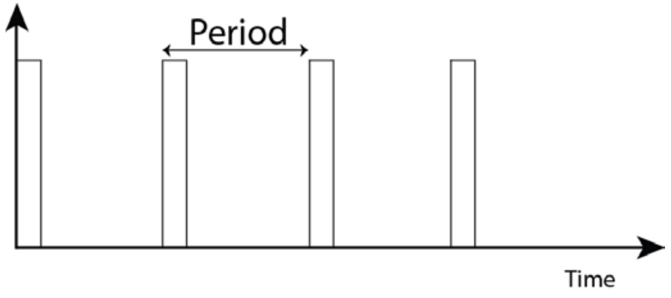
- Energy in the motor inductance decays with time constant $\sim L/R$.
- **Need the PWM period to be much shorter than L/R so that the motor windings remain energised and the torque output is maintained.**





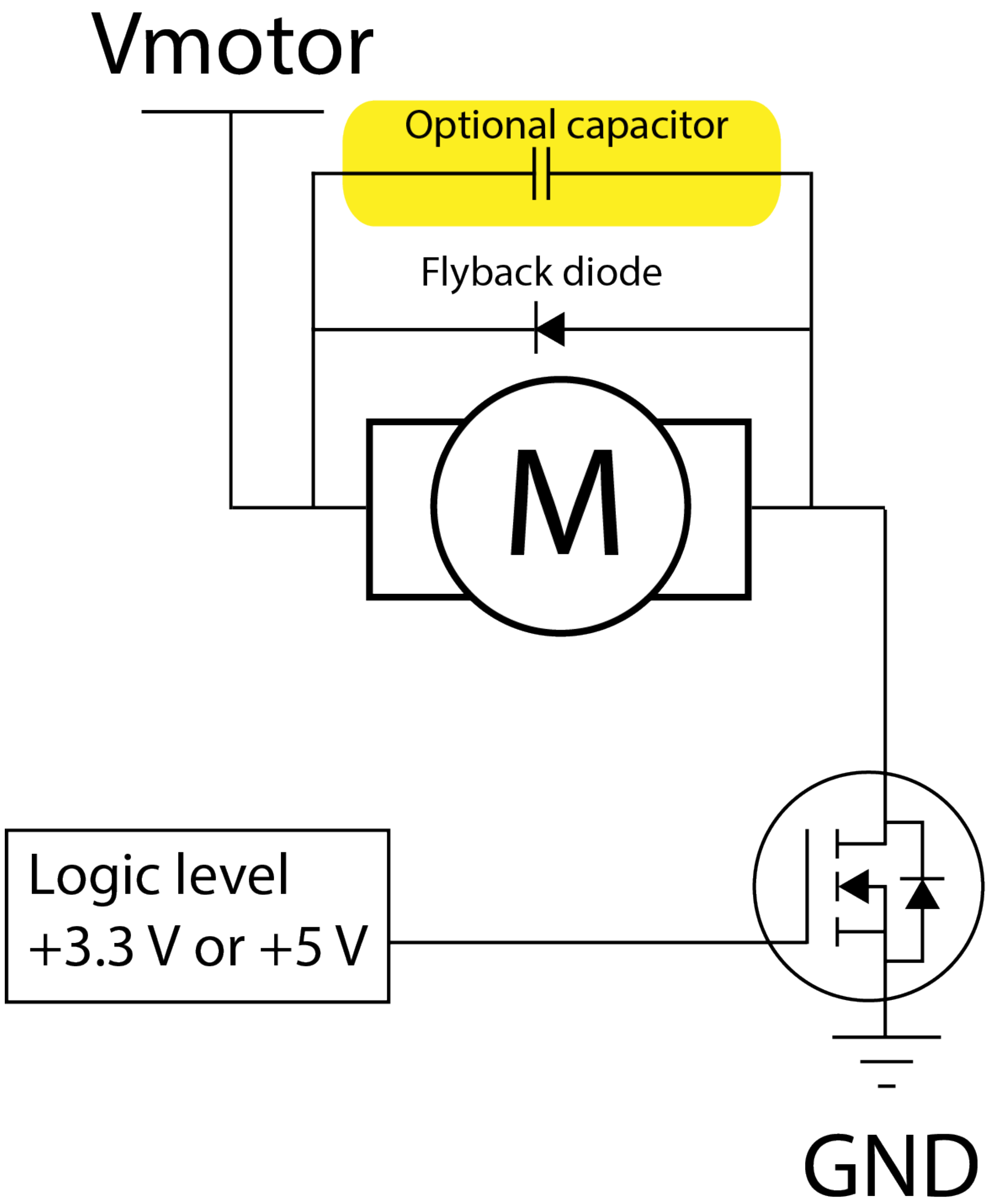
Choosing PWM frequency

- Example values for small DC motor:
  - L = 0.5 mH
  - R = 0.5 Ω
  - L/R = 1 ms.
  - R/L = 1 kHz.
  - PWM frequency must be at least several kHz.



Parallel capacitor

- A parallel capacitor acts to filter high frequency noise created by arcing as the motor brushes connect and disconnect.
- How to choose the capacitor?



Sizing the capacitor

- Typically done experimentally for a given motor drive system.
- Image shows ground plane noise for different values of parallel capacitance across a small vibration motor (e.g. as used in a smartphone).
- Place a small ceramic capacitor as close as possible to the motor terminals.
- Typical values 100 pF – 100 nF.

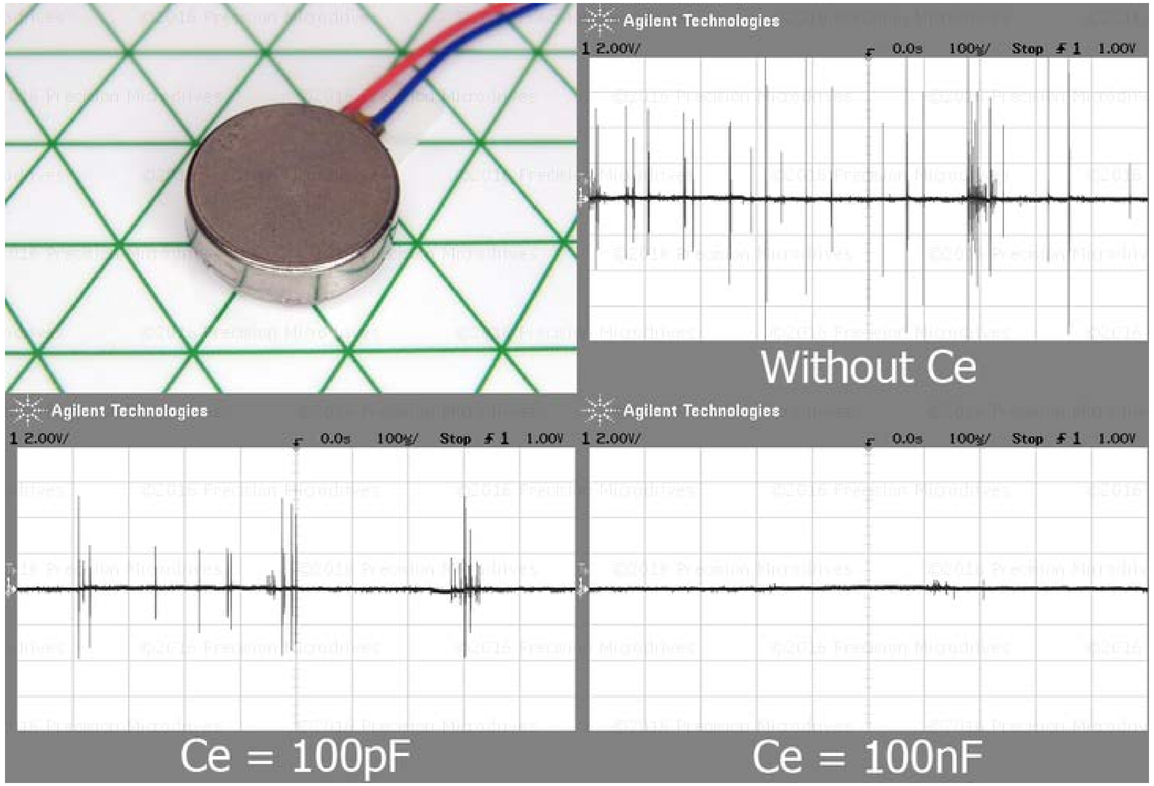
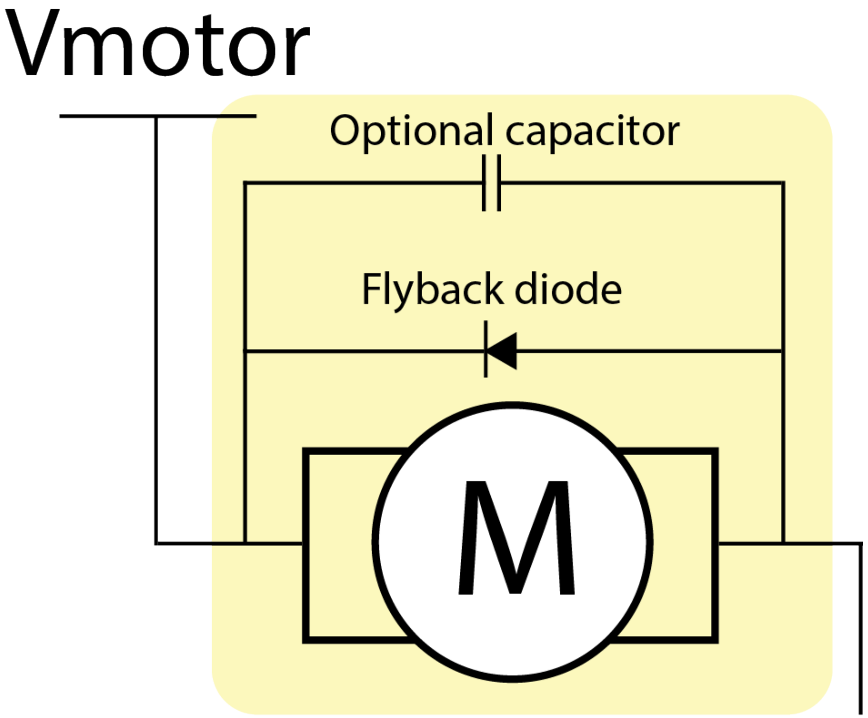


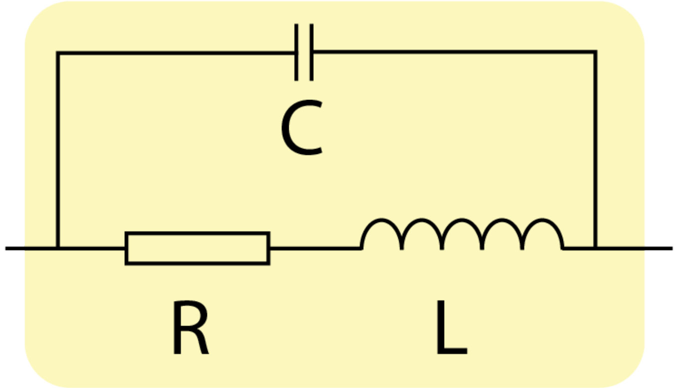
Image from Precision Microdrives Application Note AB-005

Avoiding resonance

- With a capacitor across the motor, we have an LC resonant circuit.
- The resonant frequency is the frequency that minimises the magnitude of the total impedance.
- Assuming small R:

$$\omega = 2\pi f \approx \frac{1}{\sqrt{LC}}$$





Resonance example

- Example: a motor has an inductance of 1 mH and has a parallel capacitor of 100 nF.

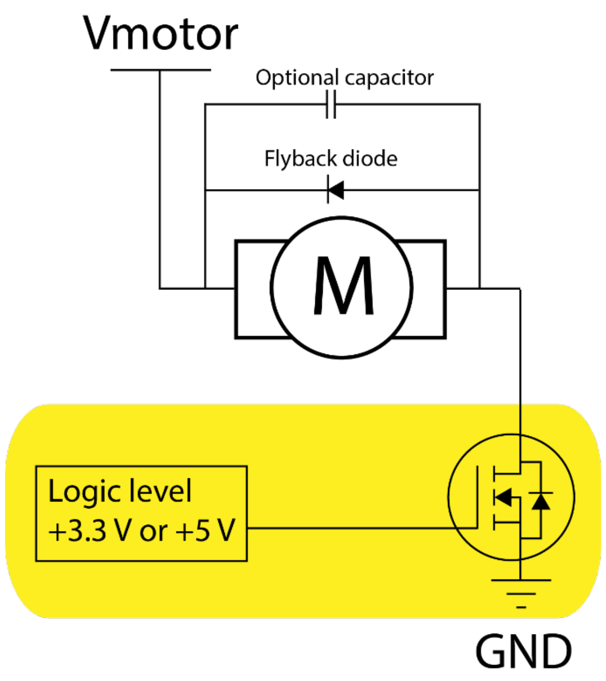
$$f_{resonant} \approx \frac{1}{2\pi\sqrt{LC}} = 16\ \mathrm{kHz}$$

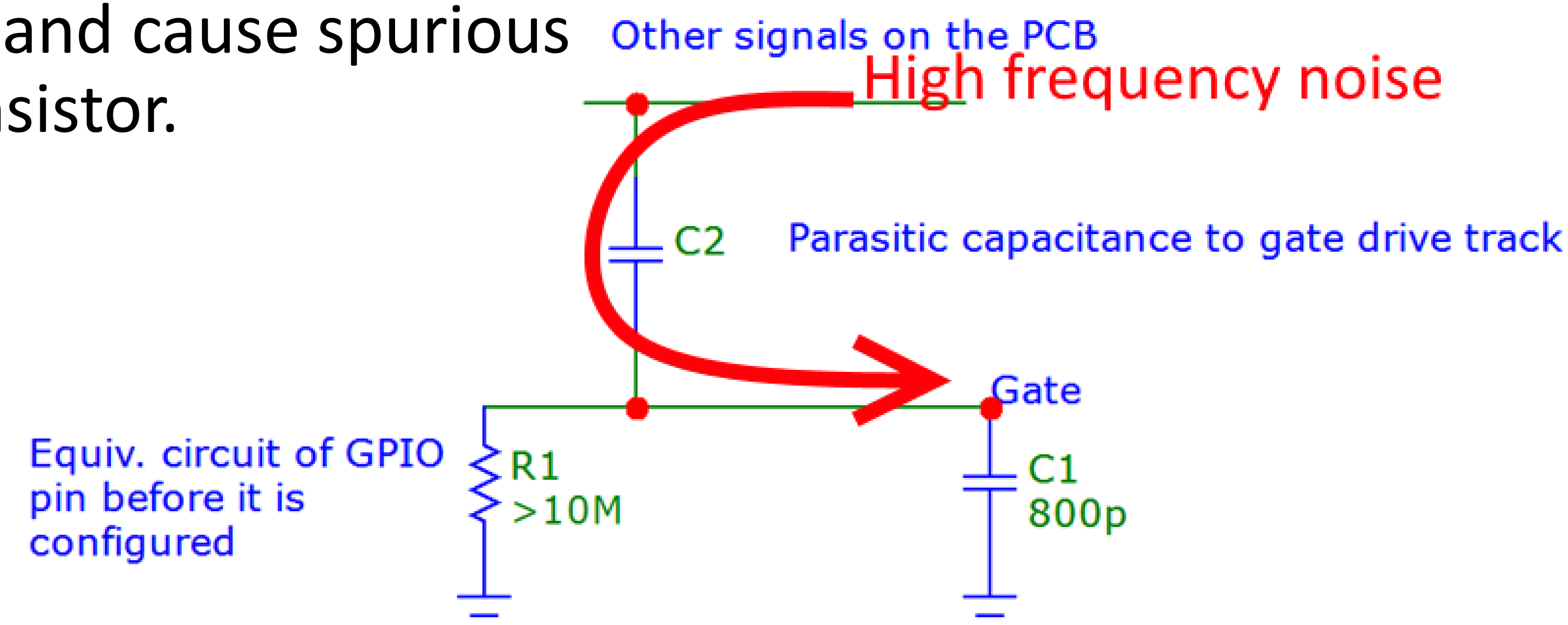
Avoid frequencies near this.

- A plausible “rule of thumb” might be to switch at less than half the resonant frequency, i.e. 8 kHz.

Another point: robust gate driver circuitry

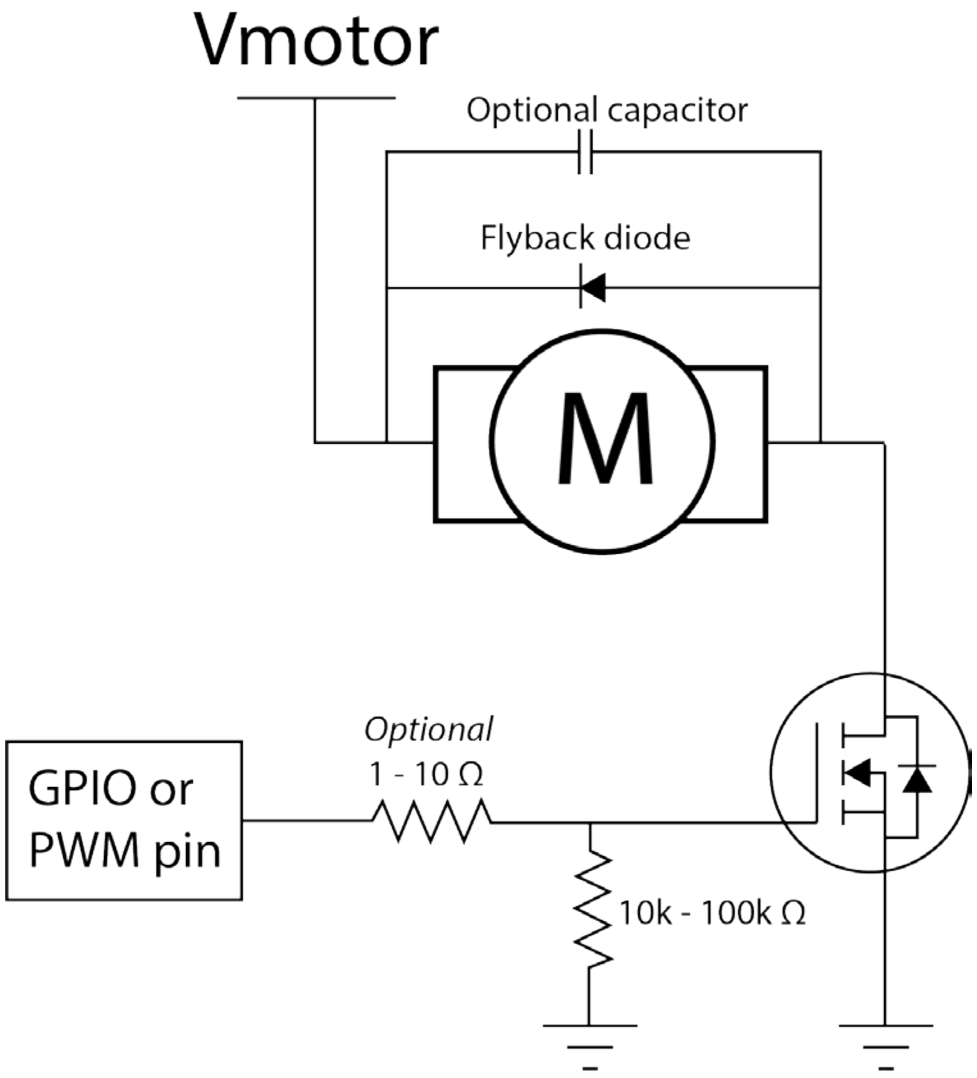
- The equivalent circuit looking into the gate is a capacitor (typically hundreds of pF for a power MOSFET).
- Parasitic capacitance could couple AC signals into the gate and cause spurious switching of the transistor.





Final motor drive circuit

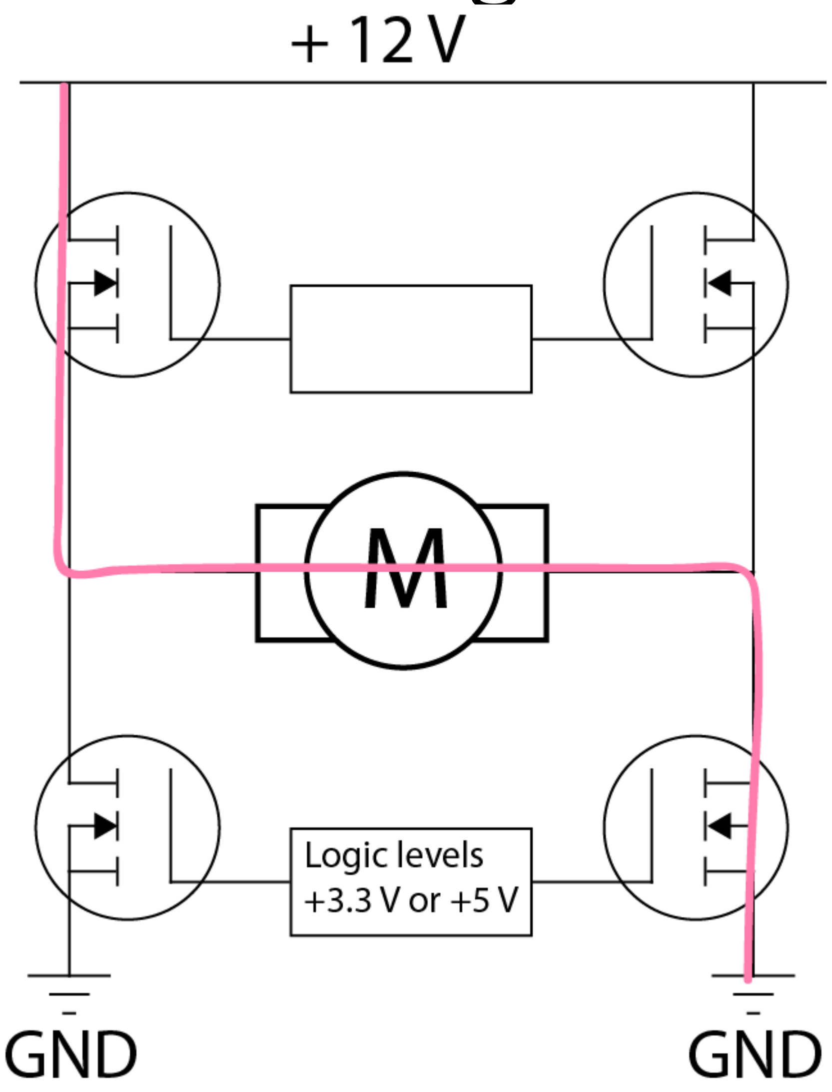
- Use a weak pulldown (>= 10k) to short out high frequency noise.
- Optionally, isolate the GPIO pin from the gate terminal by a small resistance.
  - This slows switching (to ~ RC time) but reduces the instantaneous current demanded of the GPIO driver when switching a capacitive load.

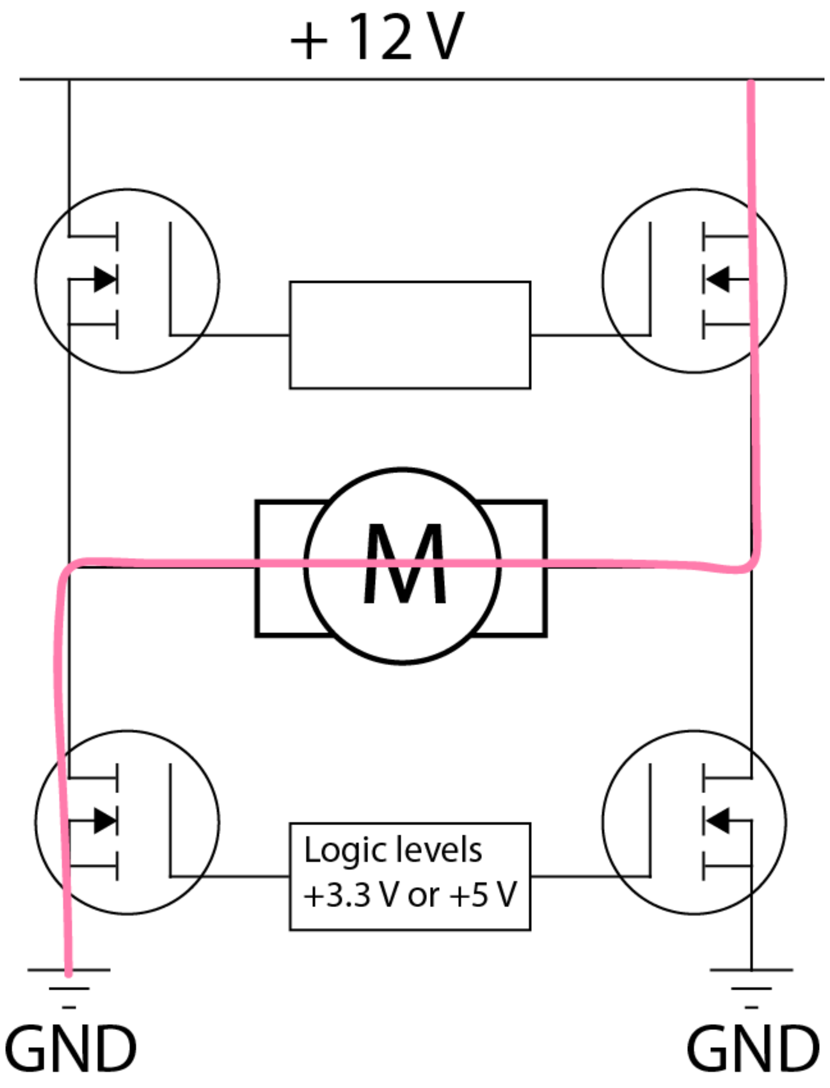


Other motor drive requirements

- So far we can turn a motor on or off.
- What about changing its direction?
- **A DC motor will run in reverse if we connect an opposite polarity voltage across its terminals.**

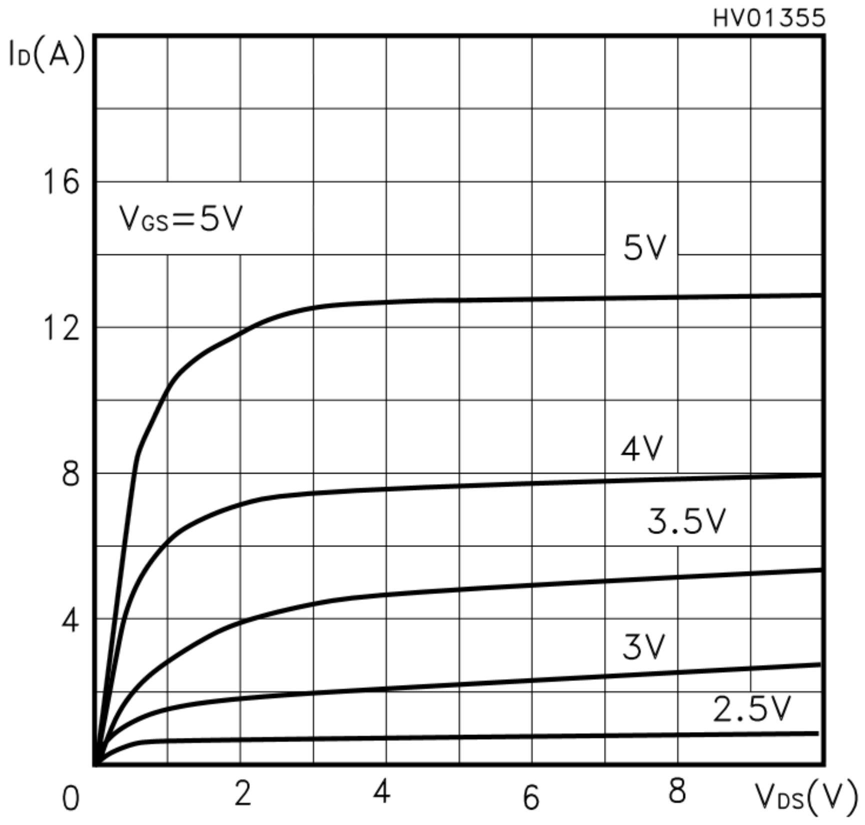
Basic H bridge

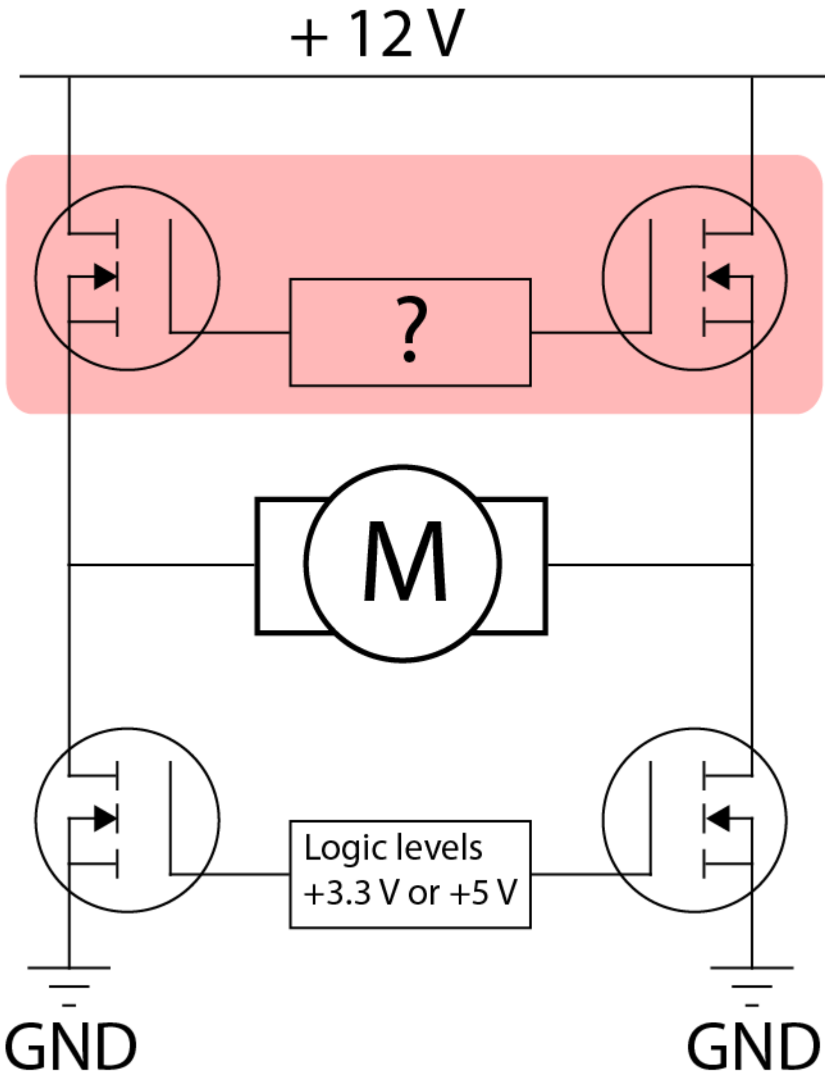




Basic H bridge: how to drive the high side?

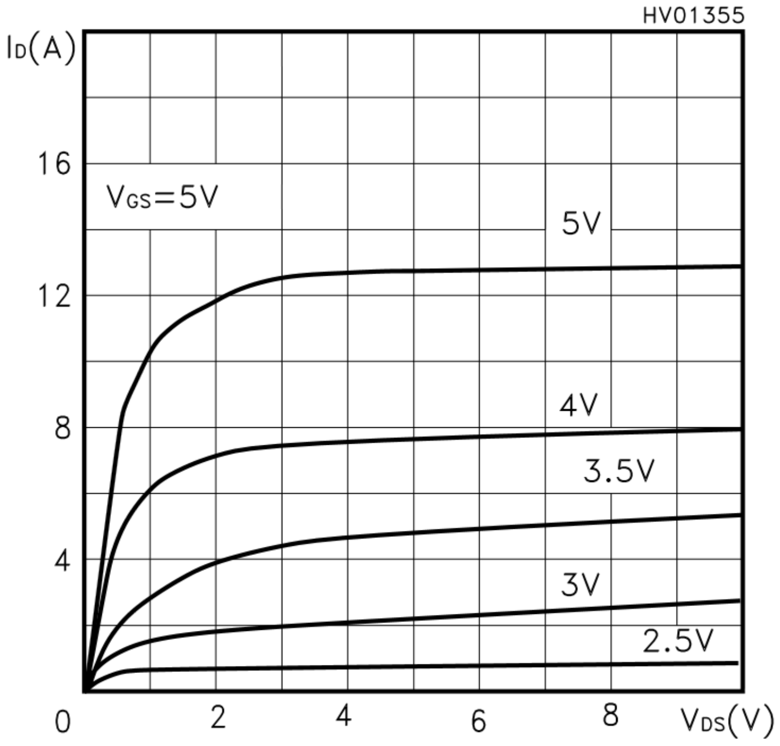
- Can you see the problem?

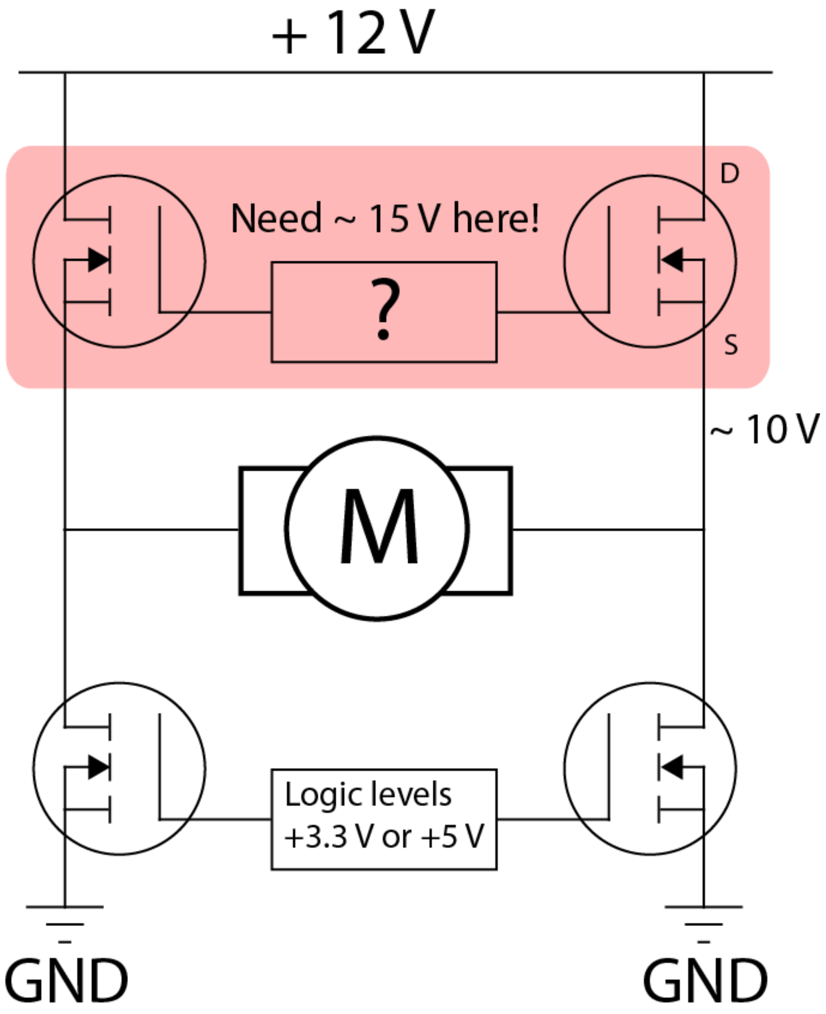




Basic H bridge: how to drive the high side?

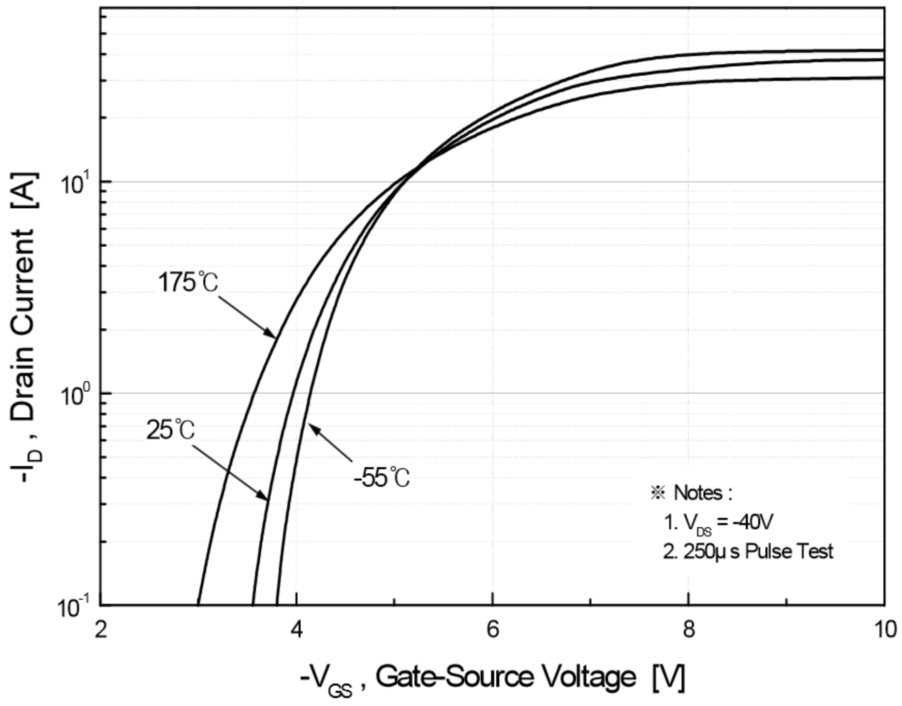
- A gate voltage higher than the supply is needed!

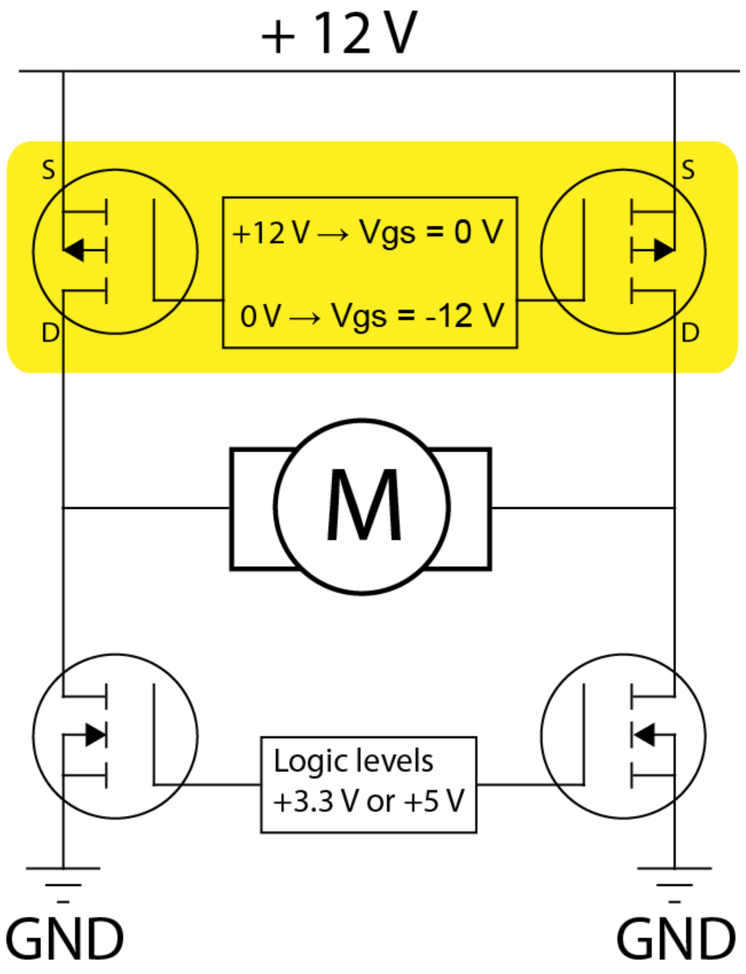




Solution: use P channel FETs!

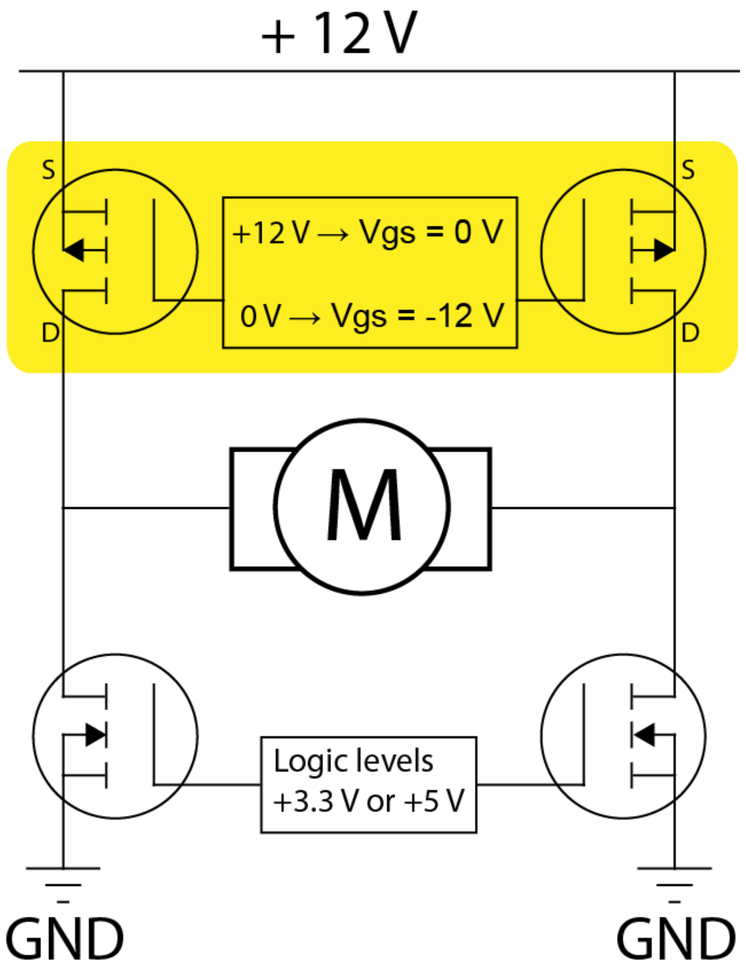
- With P channel FETs, the gate voltage is now inside the range of the supply!





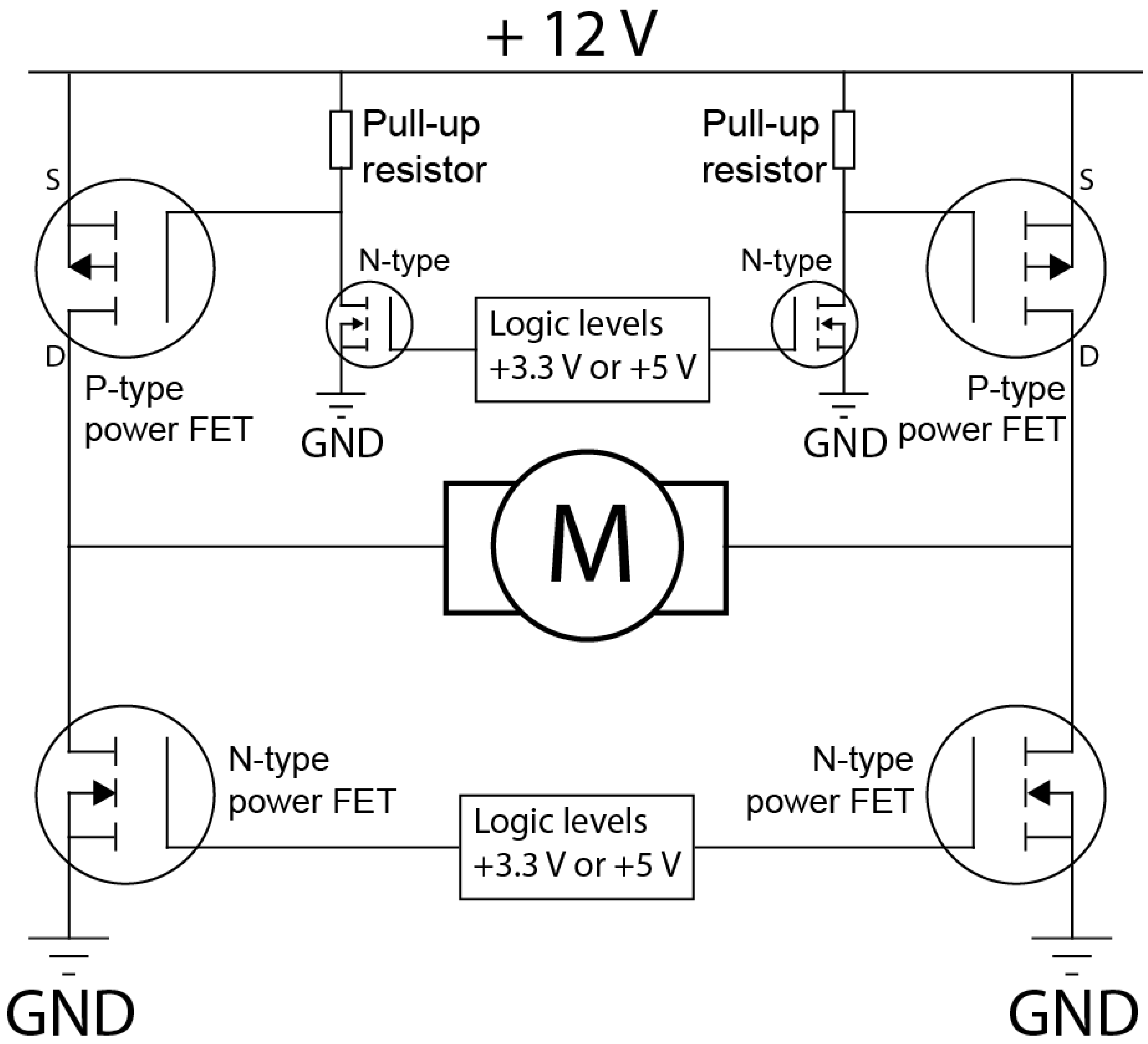
High side MOSFET driver

- How to drive + 12 V to the high side gates?



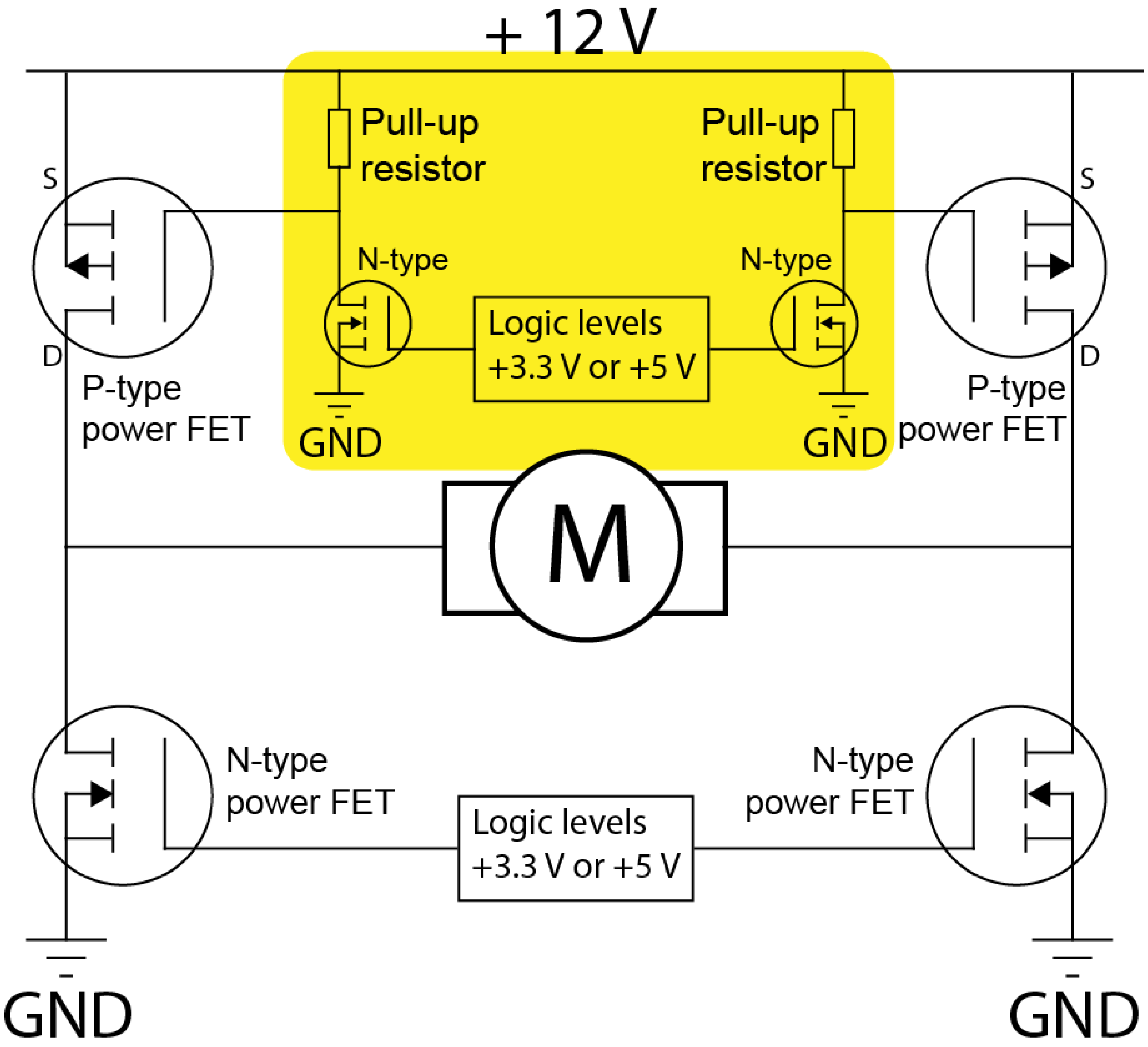
Complete H bridge

- Simplest high side driver: a pull-up resistor and an N-type FET.



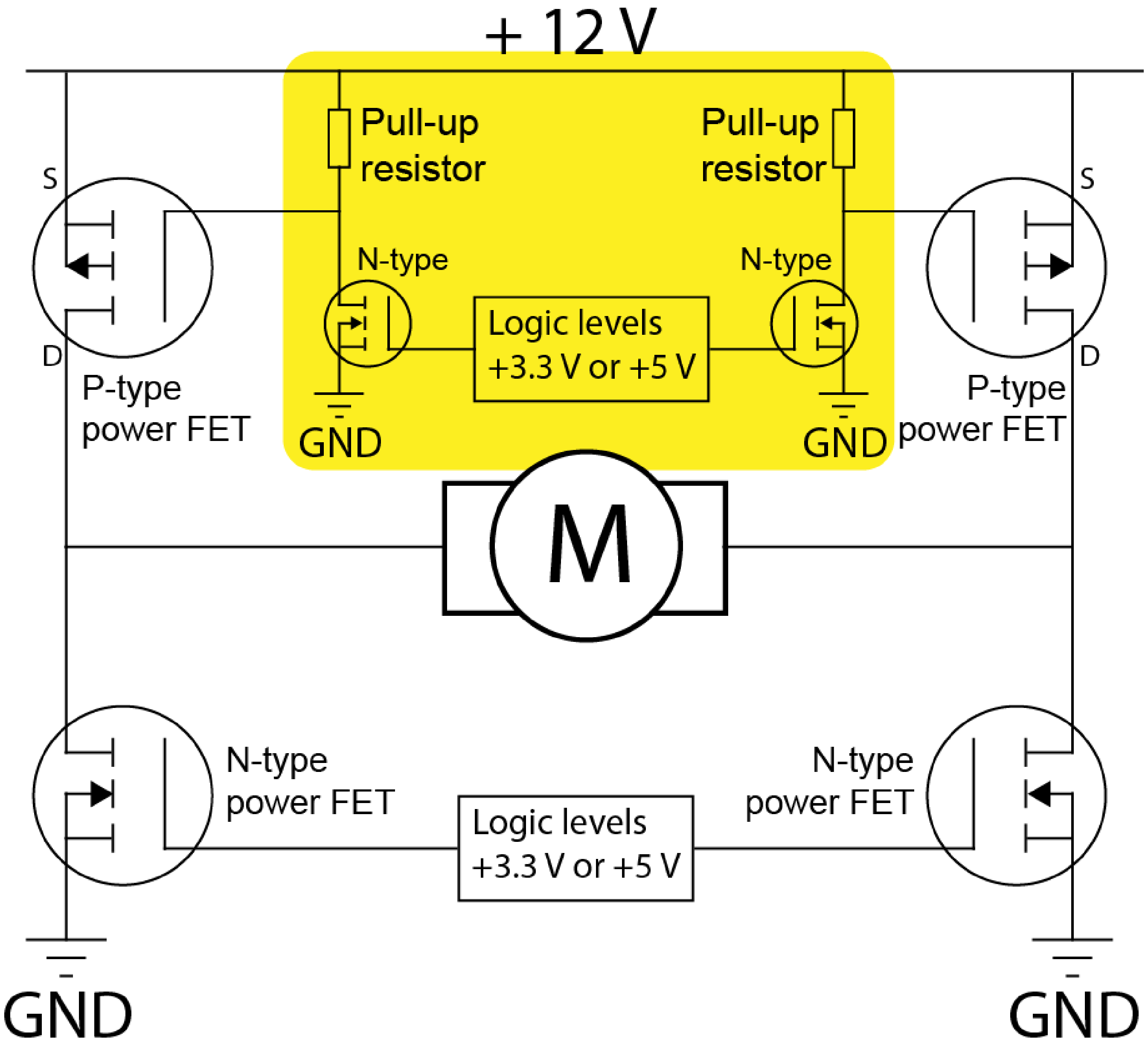
Weaknesses of this design

- What are the weaknesses of the P-type driver circuit?



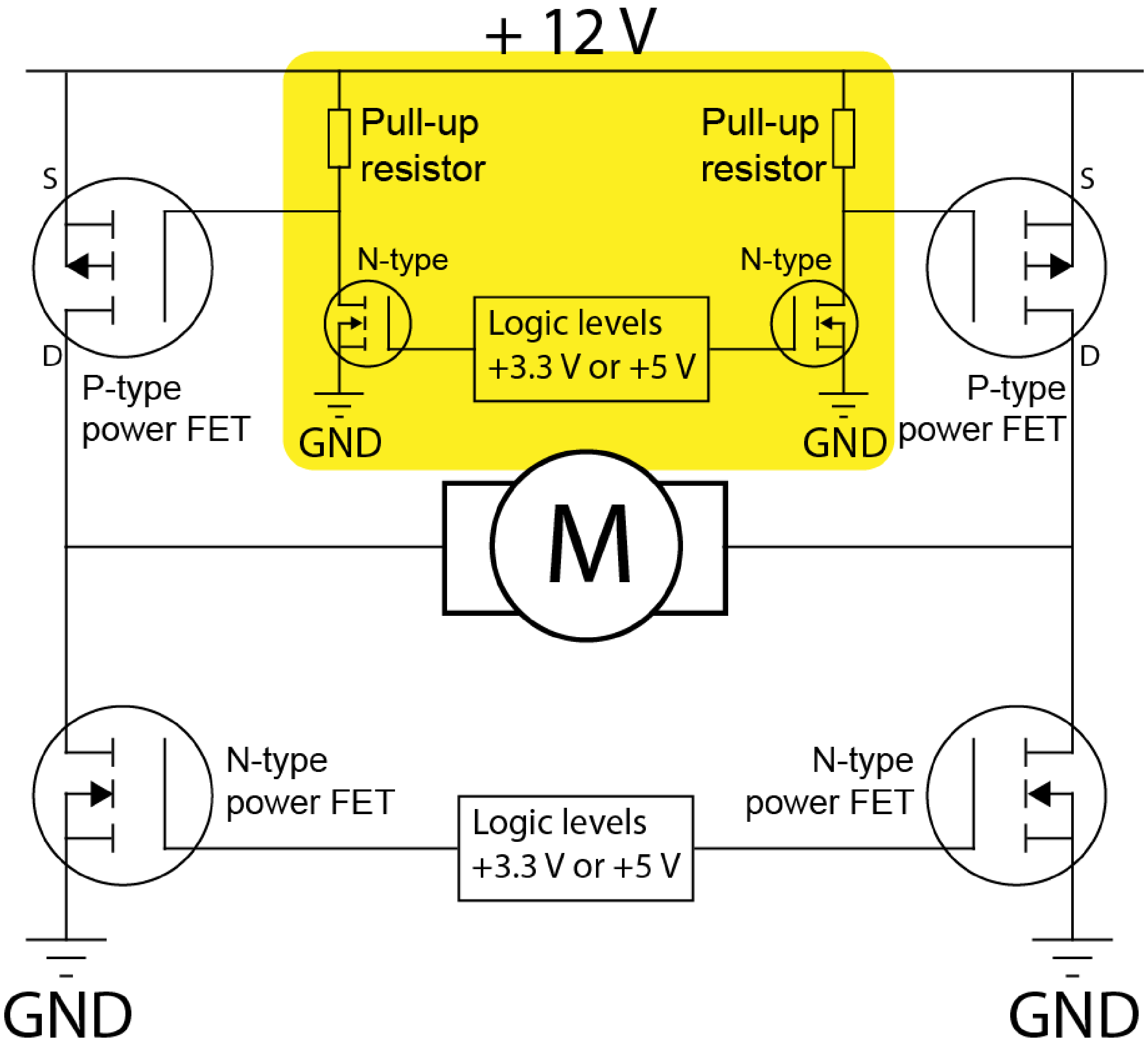
Weaknesses of this design

- Timing asymmetry:
  - Vg to ground is fast
  - Vg to +12V is RC limited.
- The low side switches much more quickly than the high side.



Weaknesses of this design

- **Large gate-source voltage**: the full motor supply is taken across Vgs when turned on.
- Too large a Vgs is a fast way to kill a MOSFET.
- Maximum Vgs for the STP22NF03L is 15 V.
- This circuit wouldn't work if the motor supply was > 15 V.

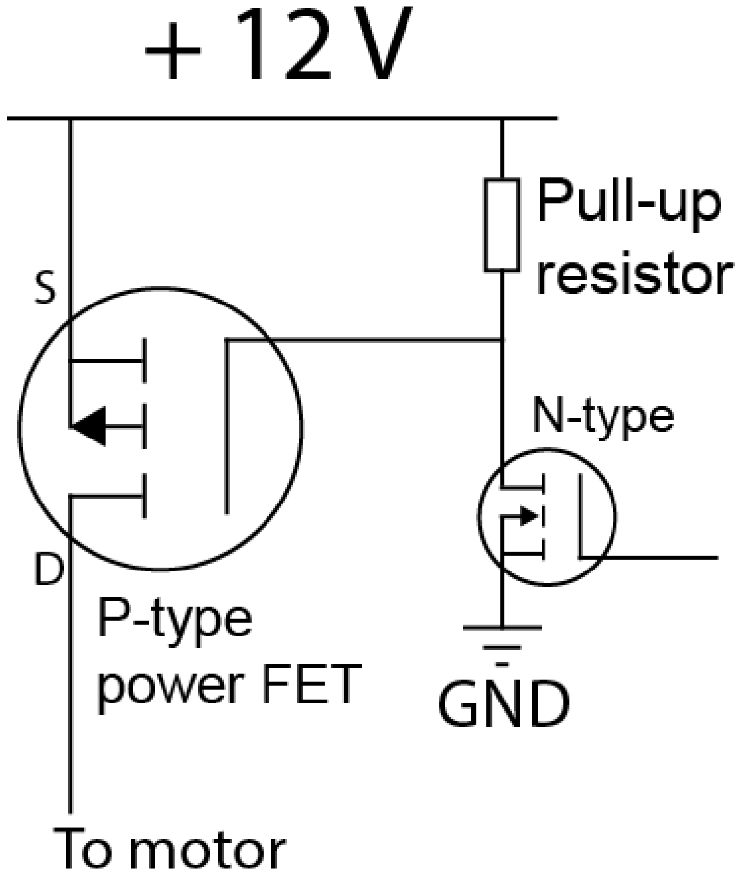


Sizing the pull-up resistors

- How to size the pull-up resistors?
- What is the trade-off?

Sizing the pull-up resistors

- Want a small resistance to reduce the RC time.
  - Look up the gate capacitance of your power FET and calculate your RC time.
  - Smaller resistance = faster switching.
- Want a large resistance to minimise the power dissipated in the pull-up resistor.



Example

- Consider a gate capacitance of 850 pF with a pull-up of 4.7 kΩ.
- RC = 4 μs.
- Allowing 2RC rise time, maximum switching frequency ~ 125 kHz.
- If the supply is 12 V then the power dissipated in the pull-up resistor is 30 mW.

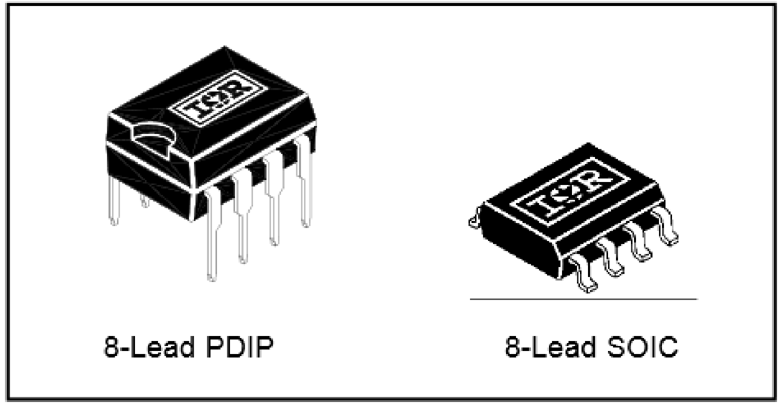
Alternative design

- **Use N channel FETs on both sides!**
- Use a charge pump to generate Vg > Vmotor

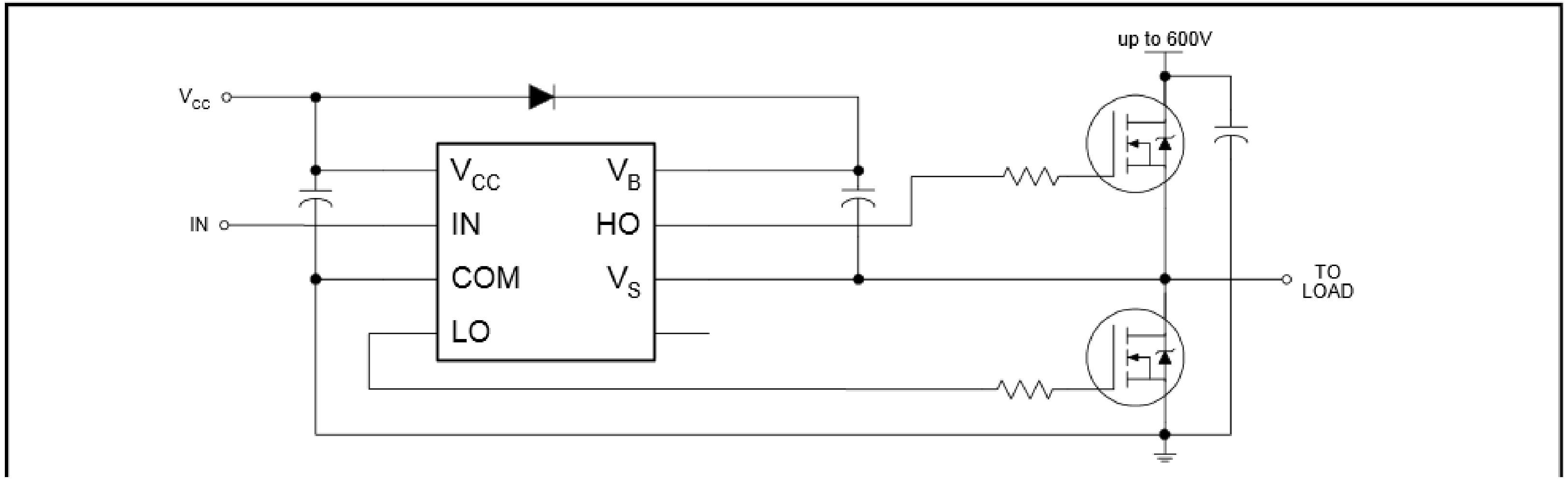
Description

The IR2111(S) is a high voltage, high speed power MOSFET and IGBT driver with dependent high and low side referenced output channels designed for half-bridge applications. Proprietary HVIC and latch immune CMOS technologies enable ruggedized monolithic construction. Logic input is compatible with standard CMOS outputs. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. Internal deadtime is provided to avoid shoot-through in the output half-bridge. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 600 volts.

Packages

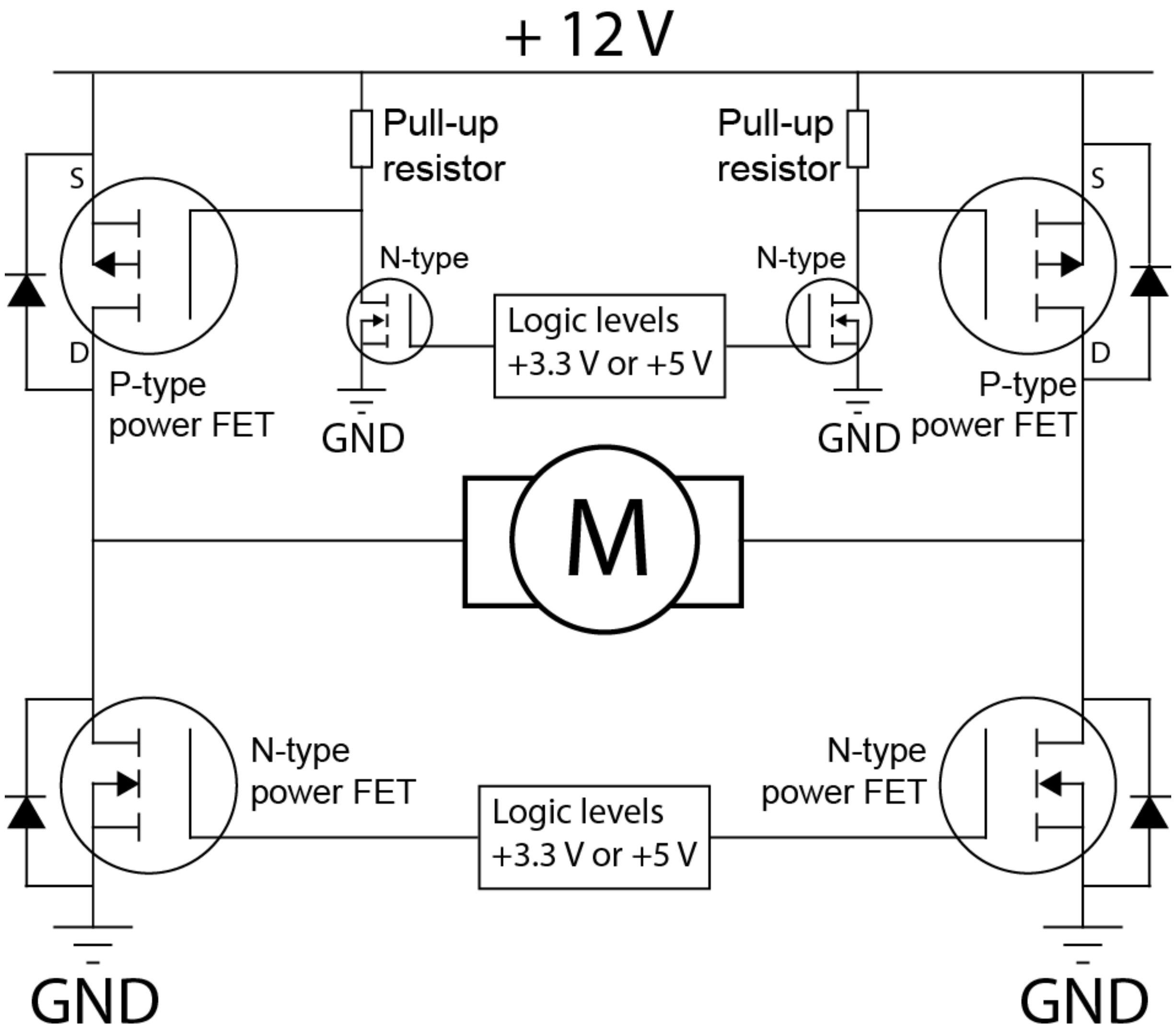


Typical Connection



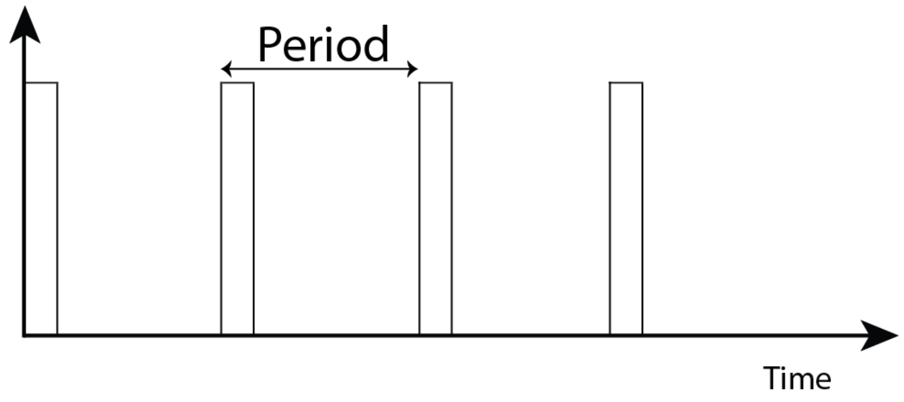
Protection considerations

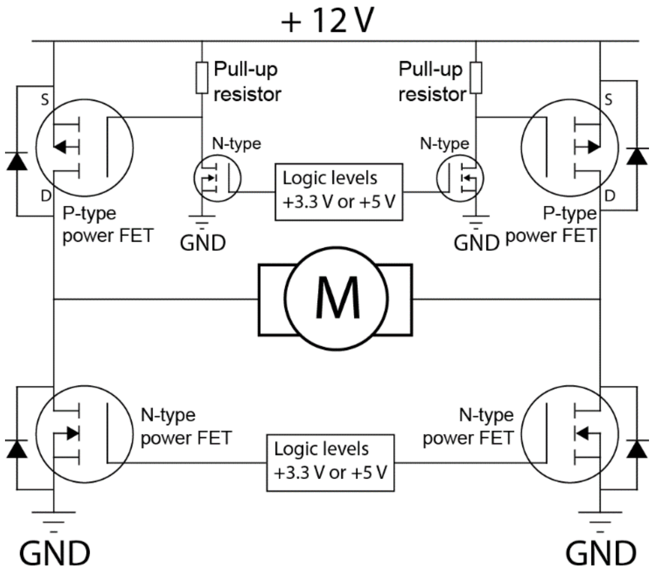
- The motor is an inductive load that produces large voltage spikes when switched off.
- There **must** be a mechanism to dissipate this voltage spike.
- Fortunately the body diode of the FETs will conduct any voltage outside [0, Vmotor].



Choosing the PWM period for H bridge designs

- For the H bridge design shown, the slowest switching path will be the RC time of the high side driver.
- Example: gate capacitance = 850 pF and R = 4.7 kΩ gives RC = 4 µs.
  - This is quite fast and not likely to be a problem.





Choosing the PWM period: summary

1. Motor windings should remain energised during each PWM period:

   Period much shorter than L_{motor}/R_{motor}.

2. Frequency far from any resonant frequencies (if a parallel capacitor is used)

$$f_{resonant} \approx \frac{1}{2\pi\sqrt{L_{motor}C_{parallel}}}$$

3. The MOSFETs need to be able to keep up with the PWM.

   PWM period much longer than the MOSFET switching time. Calculate switching times using the RC time constant of the gate driver circuit plus the dynamic rise/fall times from the MOSFET data sheet.

Summary

- Pulse Width Modulation (PWM) varies the duty cycle of a square wave. It can be used to control the speed of a motor.
- Inductive loads need special consideration (e.g. flyback diodes).
- A H-bridge circuit allows a motor to be run in forward and reverse directions.