Effective Application of Analog Comparators

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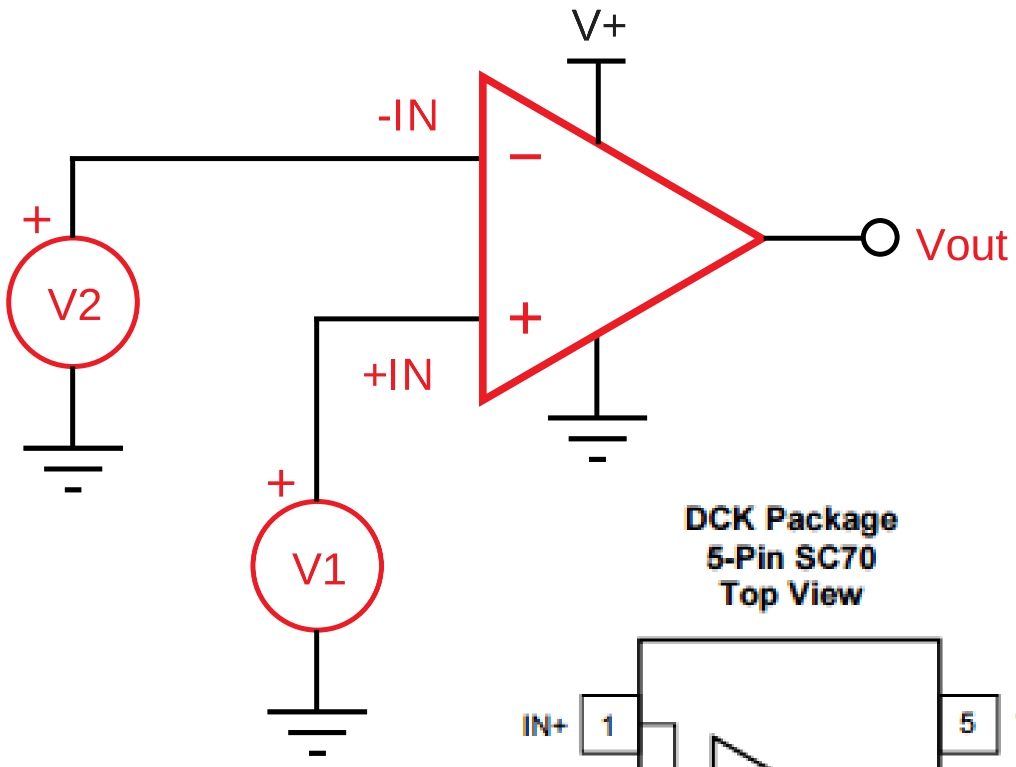
Effective Application of Analog Comparators

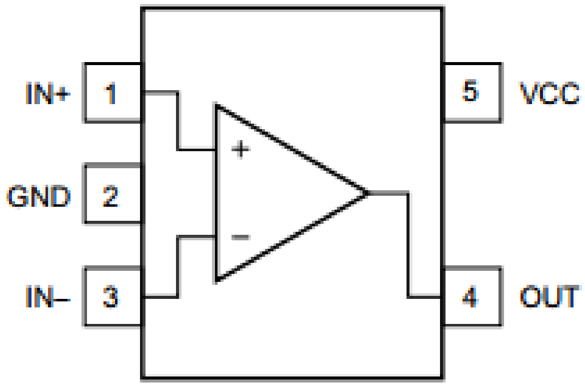
Session Subjects

- Comparator function
- Inside the comparator
- Comparator outputs
- Dc parameters
- Voltage offset
- Noise effects
- Hysteresis
- Single and dual supplies
- Common-mode voltage
- Start-up uncertainty
- Some ac parameters
- Additional features
- Op amps as comparators
- TIPD resources

The Comparator function



DCK Package
5-Pin SC70
Top View

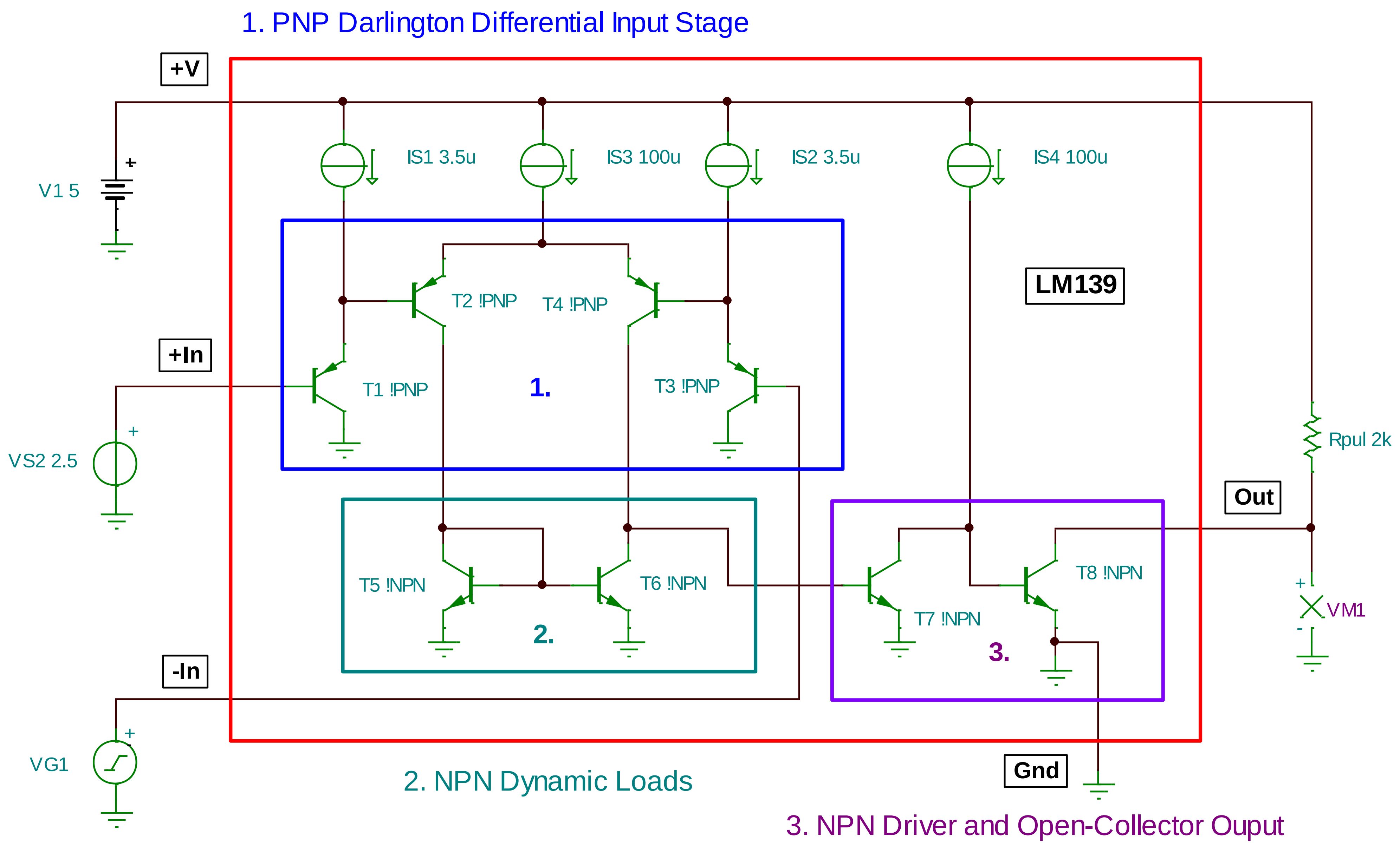


TLV3691
CMOS comparator

- V1 and V2 are two input voltages applied to +IN and -IN inputs
- Either one may be a dc level, or a changing ac signal
- Vout can be one of two levels; V_H − high (1), or V_L − low (0)
- $V_H \approx$ V+ and $V_L \approx$ 0 V, or GND
- Non-inverting condition
  - If V1 > V2, Vout will be high
  - If V1 < V2, Vout will be low
- Inverting condition
  - If V2 > V1, Vout will be low
  - If V2 < V1, Vout will be high

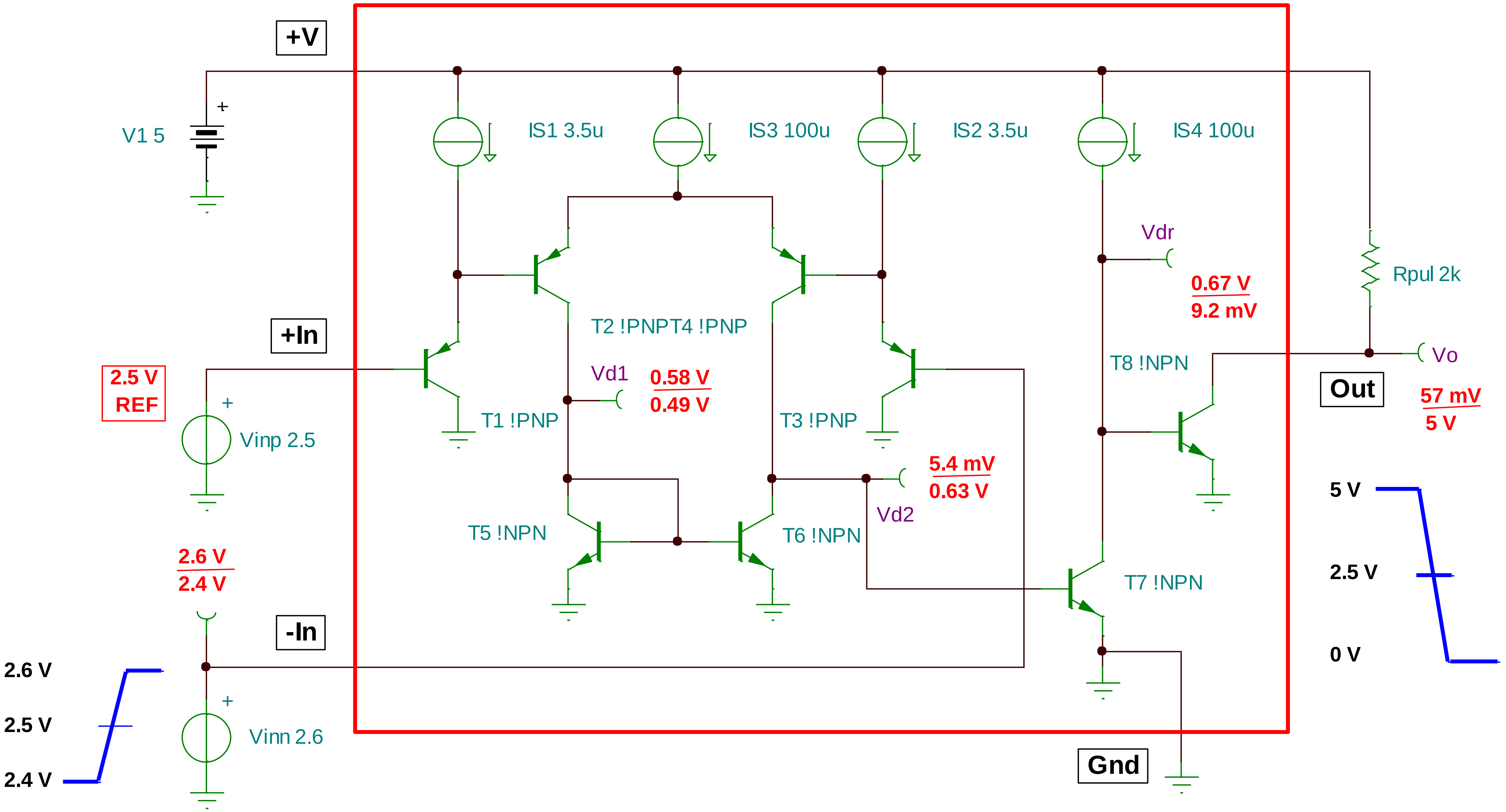
Inside the comparator

Basic comparator design – a bipolar transistor comparator



Inside the comparator

Comparing an input voltage ±100 mV below and above a reference level

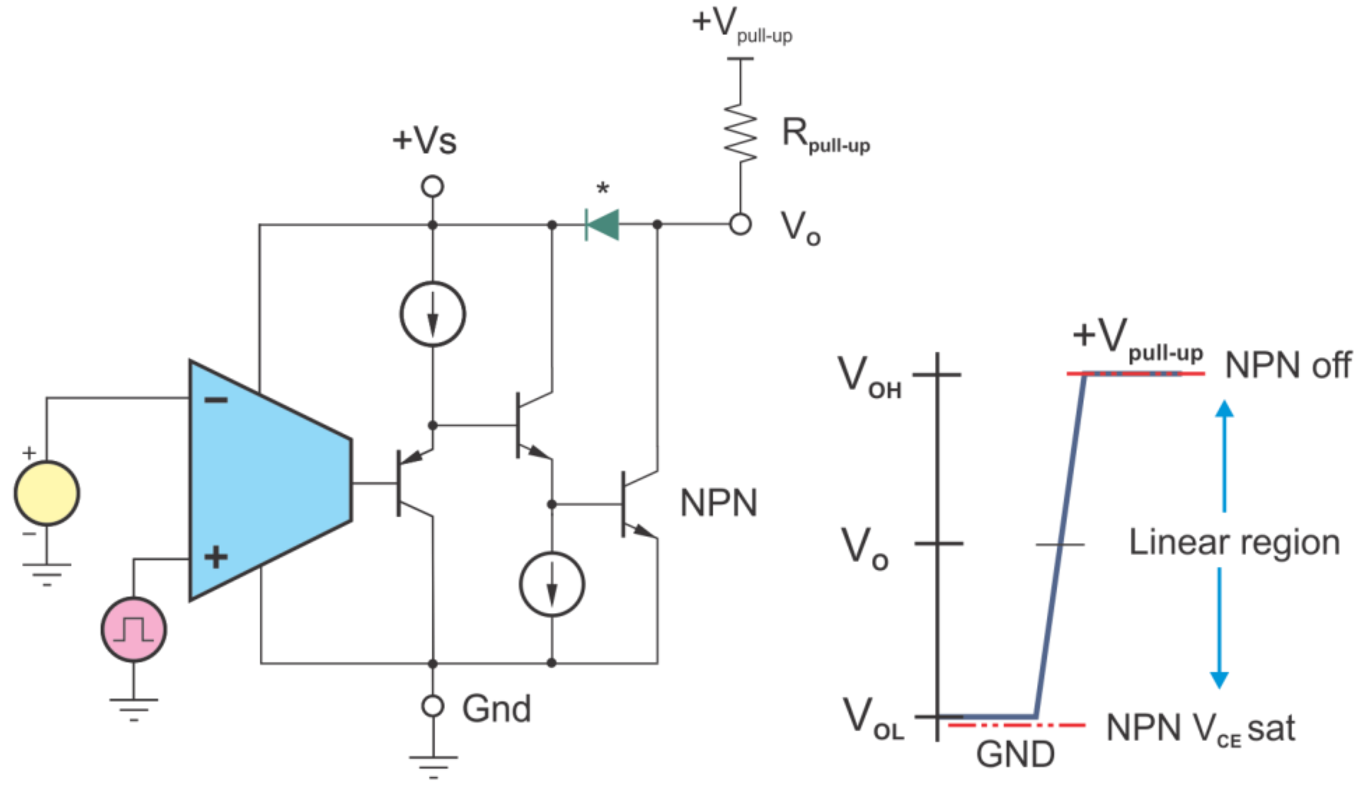


Two types of comparator outputs

Neither one dwells in its linear region for long

Open-drain, or open-collector output

Most TI comparators are open-drain, or open-collector

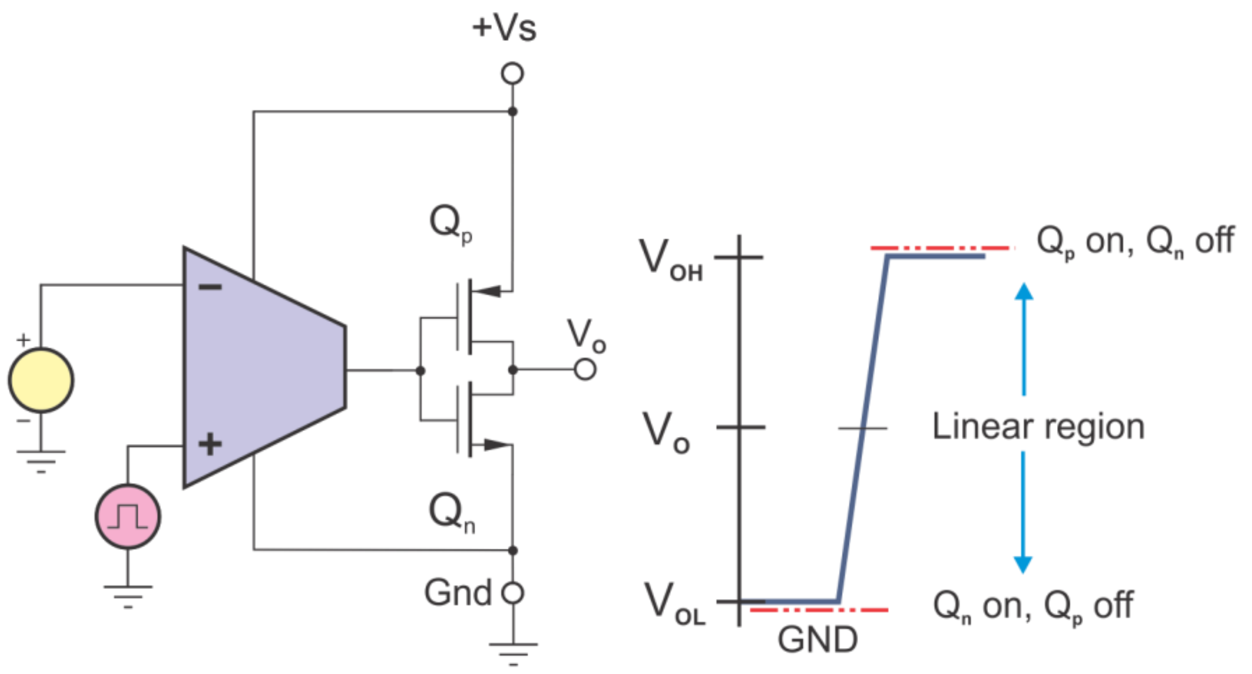


* not present in TLV1701
+Vs and $V_{pull-up}$ may be at any level between +2.2 to +36 V

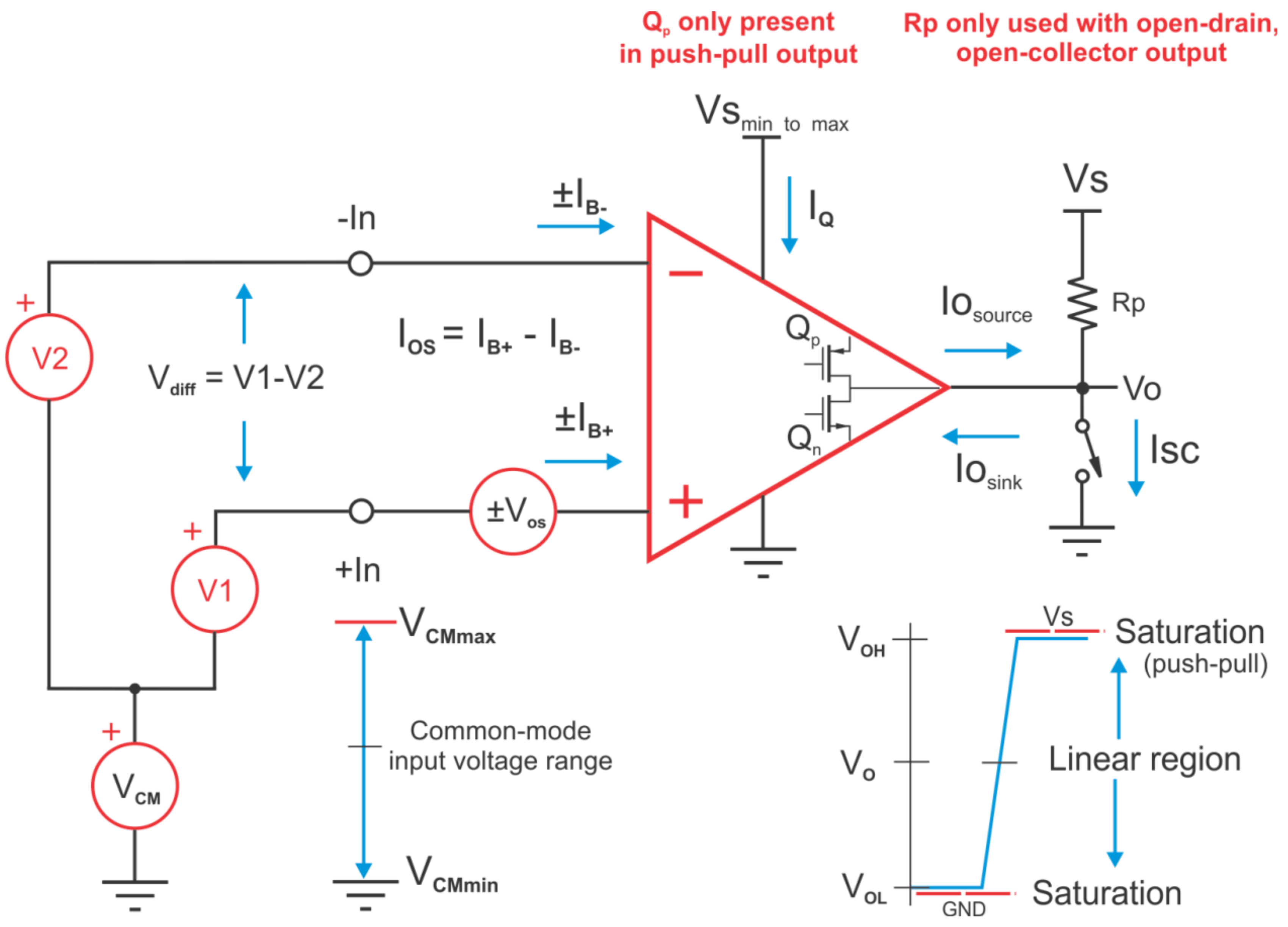
Useful for wired-OR output applications

Push-pull drain-drain, or collector-collector, output

No pull-up resistor – capable of sourcing and sinking current



Comparator dc parameters are similar to an op amp



Commonly specified dc parameters

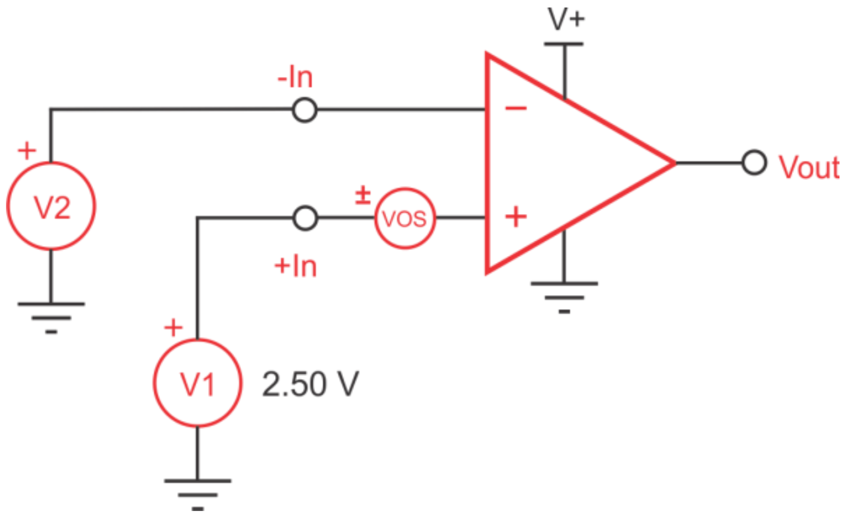
- V_{os} Voltage offset
- I_B Input bias current
- I_{OS} Input offset current
- V_{CM} Common-mode voltage range
- C_{DM} C_{CM} Input capacitances
- V_{OH} Voltage output high from rail
- V_{OL} Voltage output low from rail
- I_{SC} Output short-circuit current
- I_Q Operating current
- V_S Operating voltage range

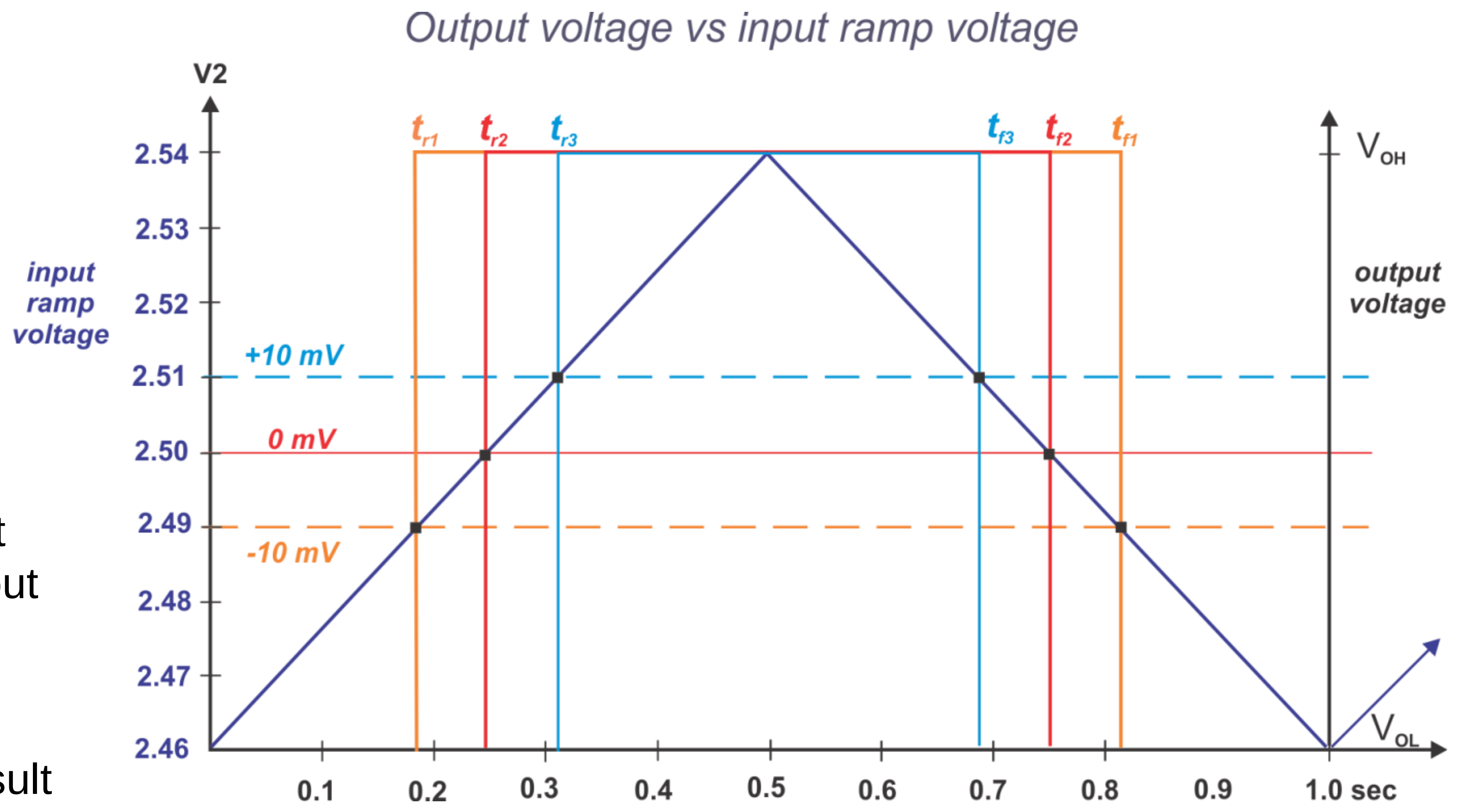
Less common to comparators

- Aol Open loop gain
- dVos/dT Voltage offset drift
- CMRR Common-mode rejection
- PSRR Power supply rejection

Voltage offset affects comparator decision voltage

Example of a comparator with a ±10 mV offset range

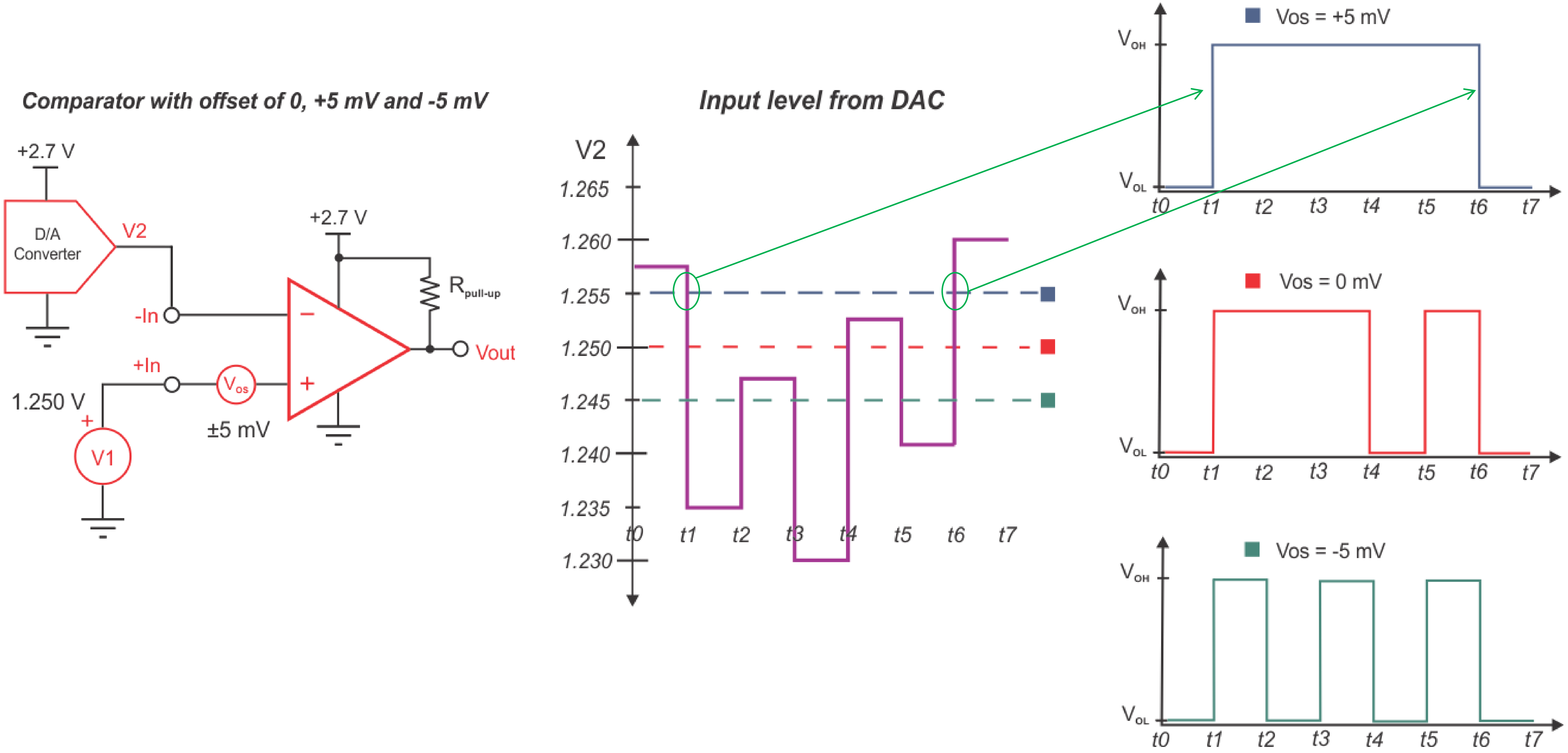




- Comparator maximum offset voltage range runs from about ±2 mV to ±15 mV
  - *not low like an op amp!*
- A fast changing input will result in less output width variation

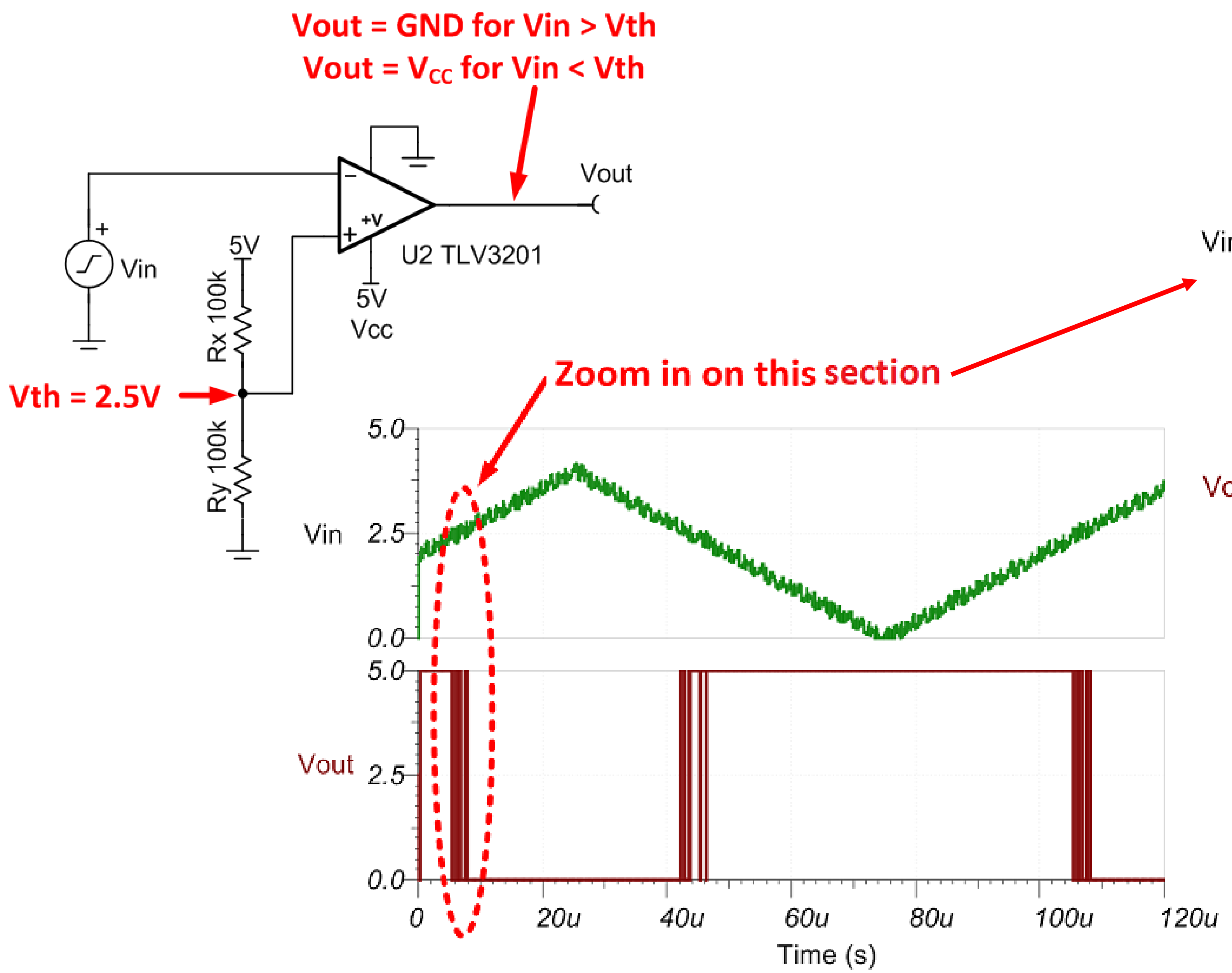
Voltage offset can cause a different output state

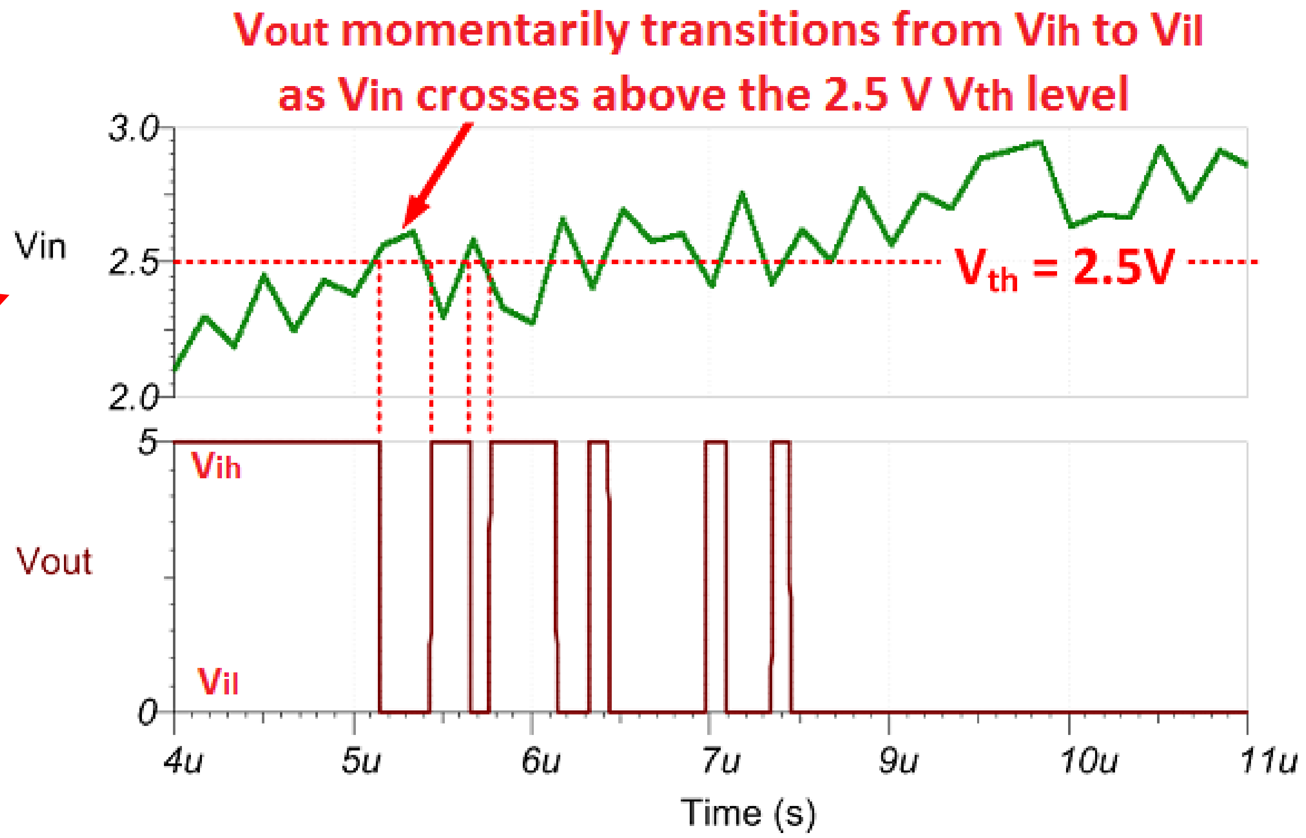
Might be an issue for levels close to the reference voltage



Noise effect on comparator output

Externally or internally generated, and the latter not often specified for comparators

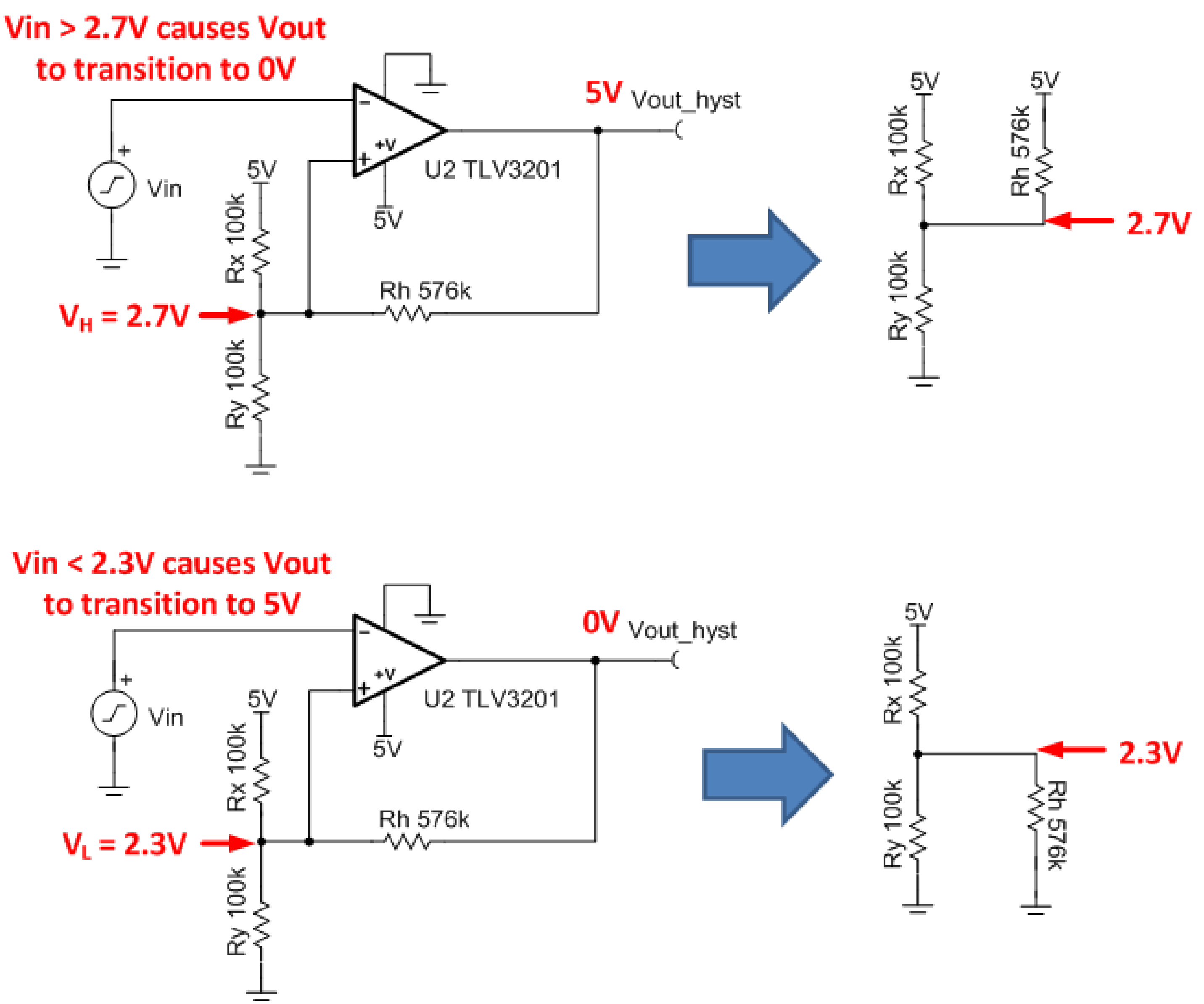


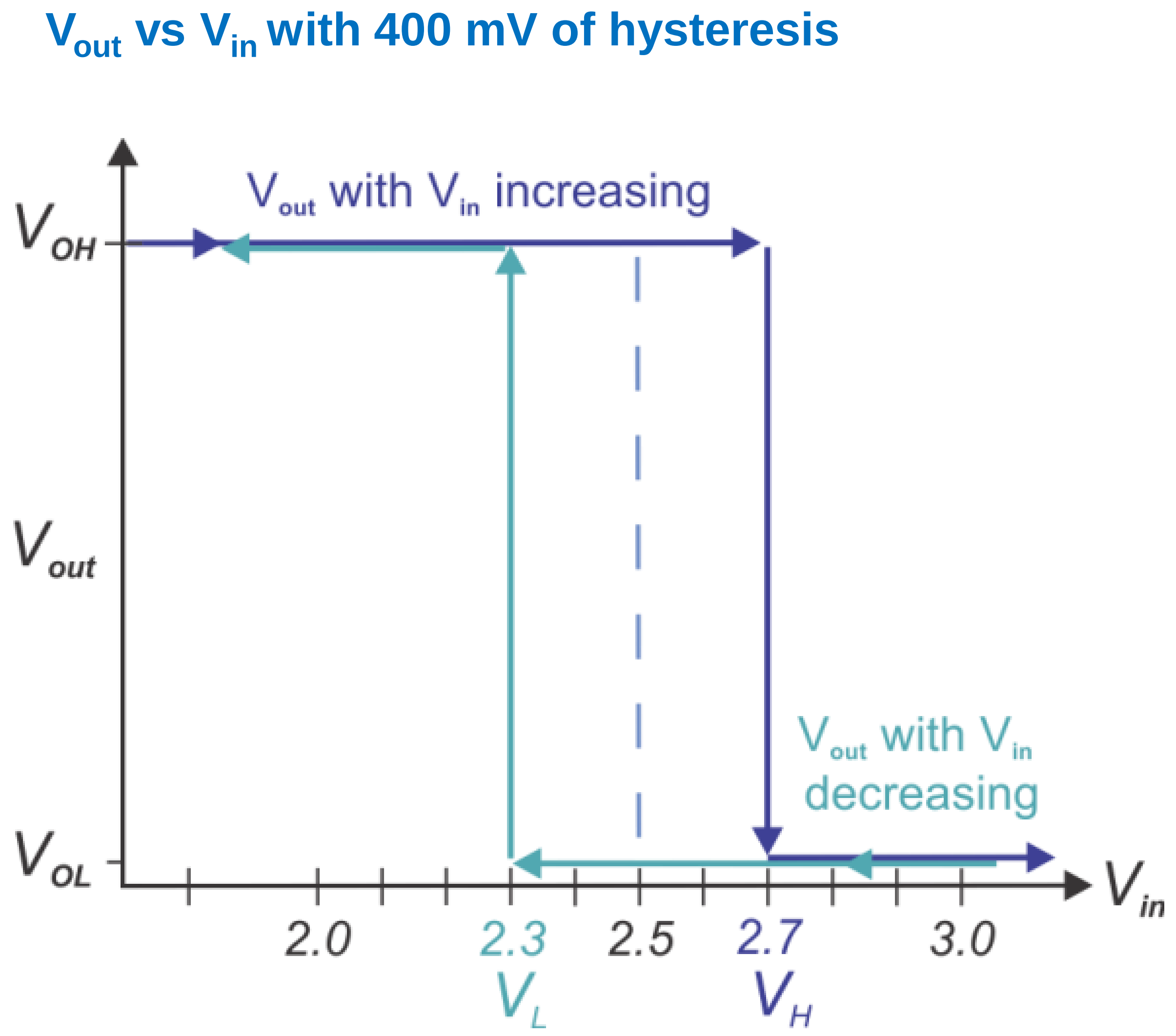


Output rapidly changes state near the threshold point in response to the noise peaks

Reducing a comparator's noise sensitivity

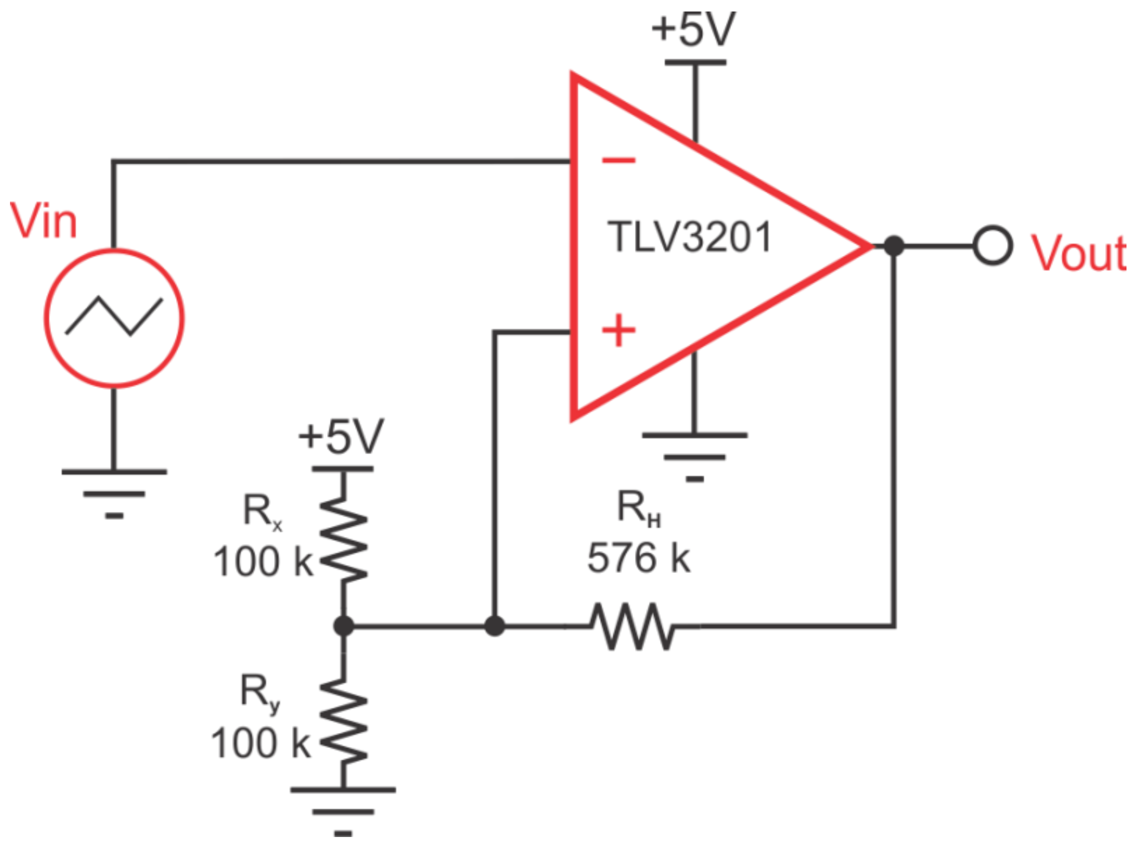
Applying hysteresis creates two distinct threshold levels

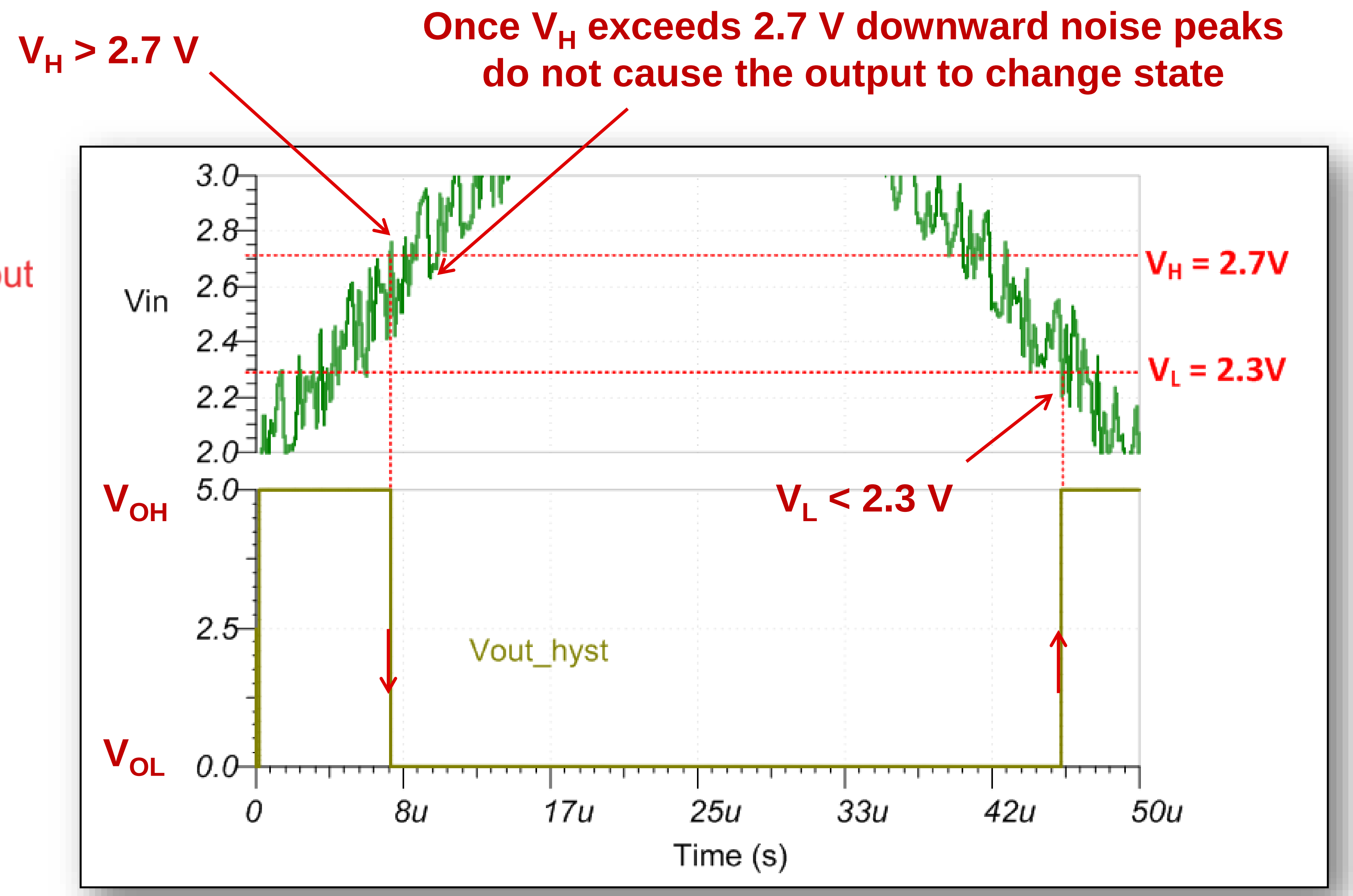




Reducing a comparator's noise sensitivity

Separated thresholds increase noise immunity





Hysteresis is built-in for some comparators

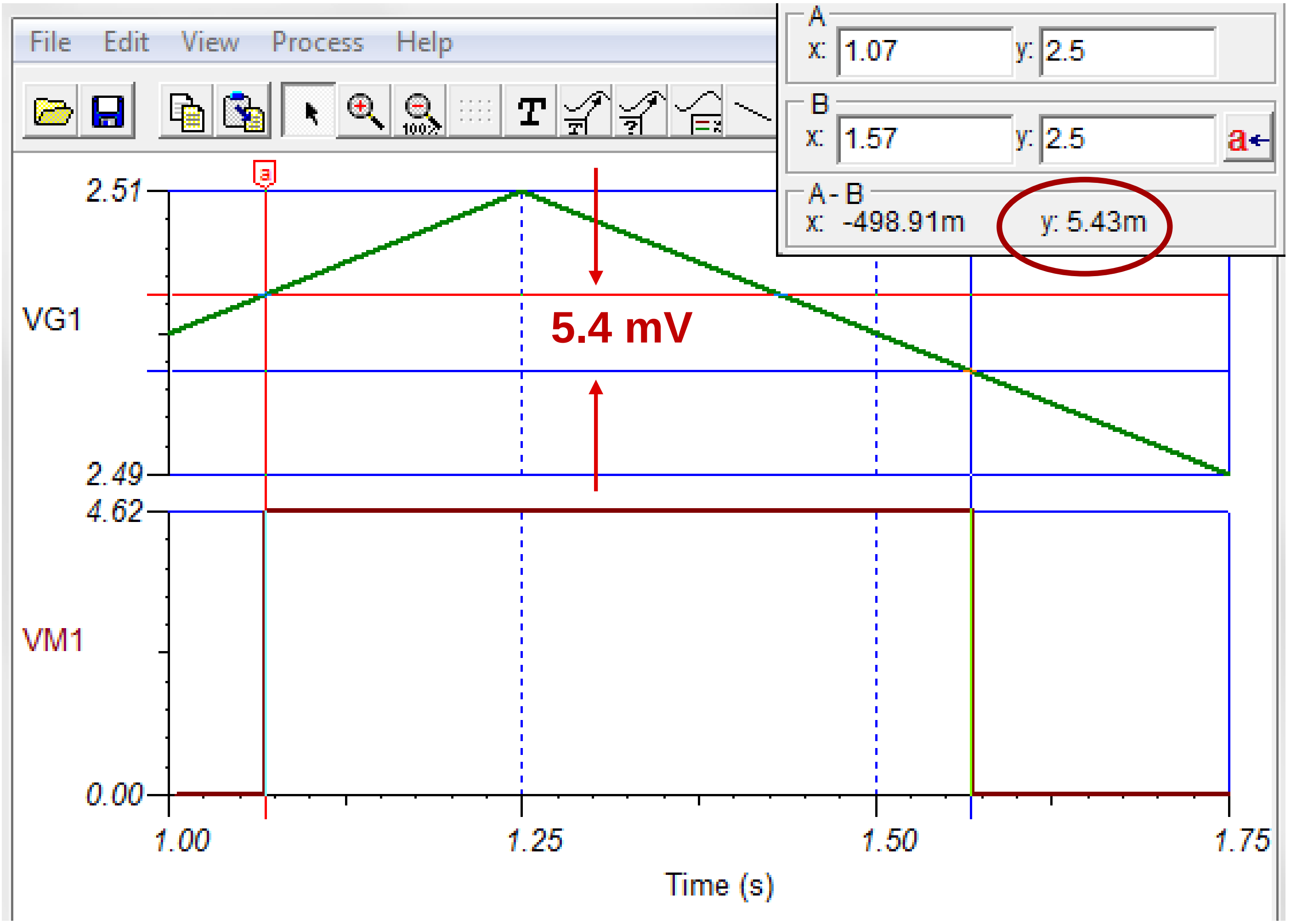
Most internal hysteresis is limited to a few millivolts

TECH DAYS
Texas Instruments

TI comparators having built-in hysteresis

- TLV3202 – *40 ns micropower, push-pull output, V_{HYST} 1.2 mV typ.*
- TLV3501 – *4.5 ns high-speed, push-pull output, V_{HYST} 6 mV typ.*
- TL712 – *25 ns high-speed, differential open-collector, V_{HYST} 5 mV typ.*
- TL714 – *5 ns high-speed, push-pull output, V_{HYST} 10 mV typical*
- LMP7300 – *µPower, open-collector, positive and negative hysteresis set independently*
- External hysteresis can still be applied

TLV3501 simulation model has hysteresis included

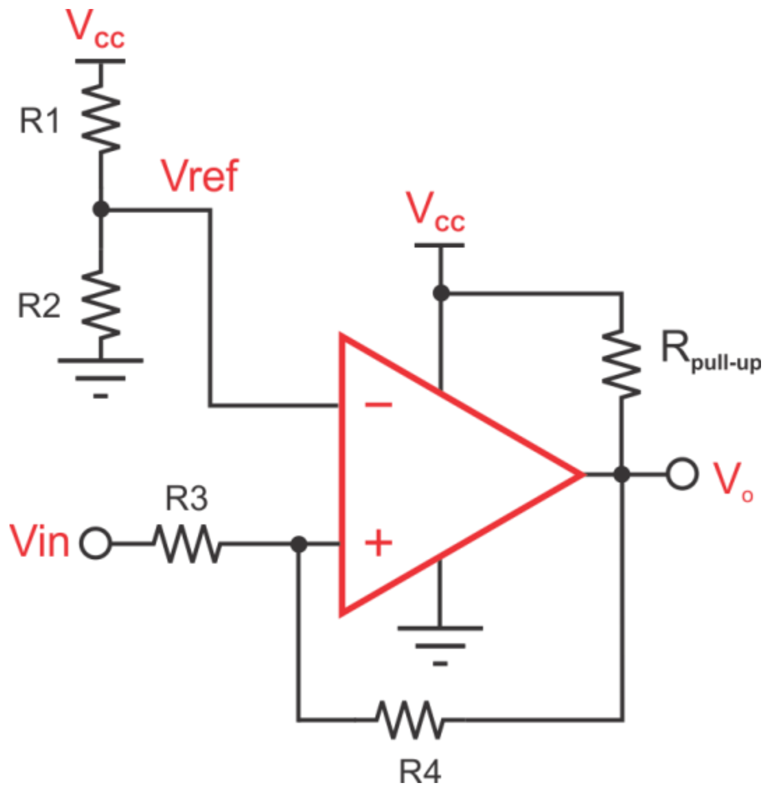


Setting up a comparator circuit to use hysteresis

Non-inverting comparator, open-collector

<u>Goals</u>

V_{HYST} 100 mV, V_{ref} 2.5 V



- Equations simplified by setting $R_{pull\text{-}up} < 0.1*R4$
- Threshold voltage errors are in low percent range

<u>Let</u>

Vcc = 5 V, $V_{O(max)}$ = 5 V, $V_{O(min)}$ = 50 mV

R1 = 100 K, $R_{pull\text{-}up}$ = 10 k

<u>Then</u>

$$R2 = \frac{R1}{\left(\frac{Vcc}{Vref} - 1\right)} = \frac{10^4}{\left(\frac{5.0}{2.5} - 1\right)} = 100\text{ k}$$

$$R3 = \frac{(R1 \cdot R2)}{(R1 + R2)} = \frac{(10^5 \cdot 10^5)}{(10^5 + 10^5)} = 50\text{ k}$$

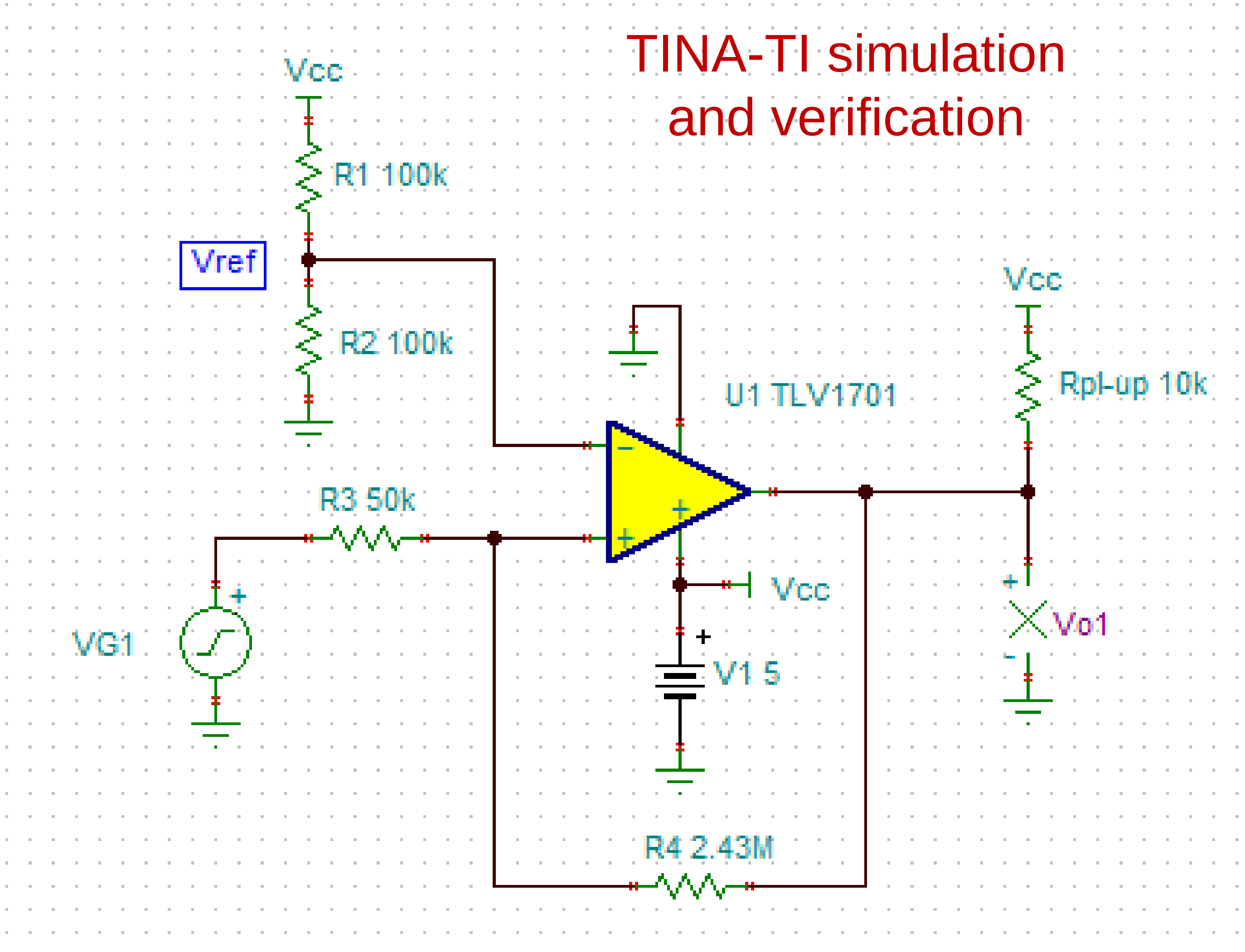
$$R4 = R3\left[\frac{(V_{O(max)} - V_{O(min)})}{V_{HYST}} - 1\right] = 5 \cdot 10^4\left[\frac{(5.0 - 0.05)}{0.10} - 1\right]$$

R4 = 2.43 MEG

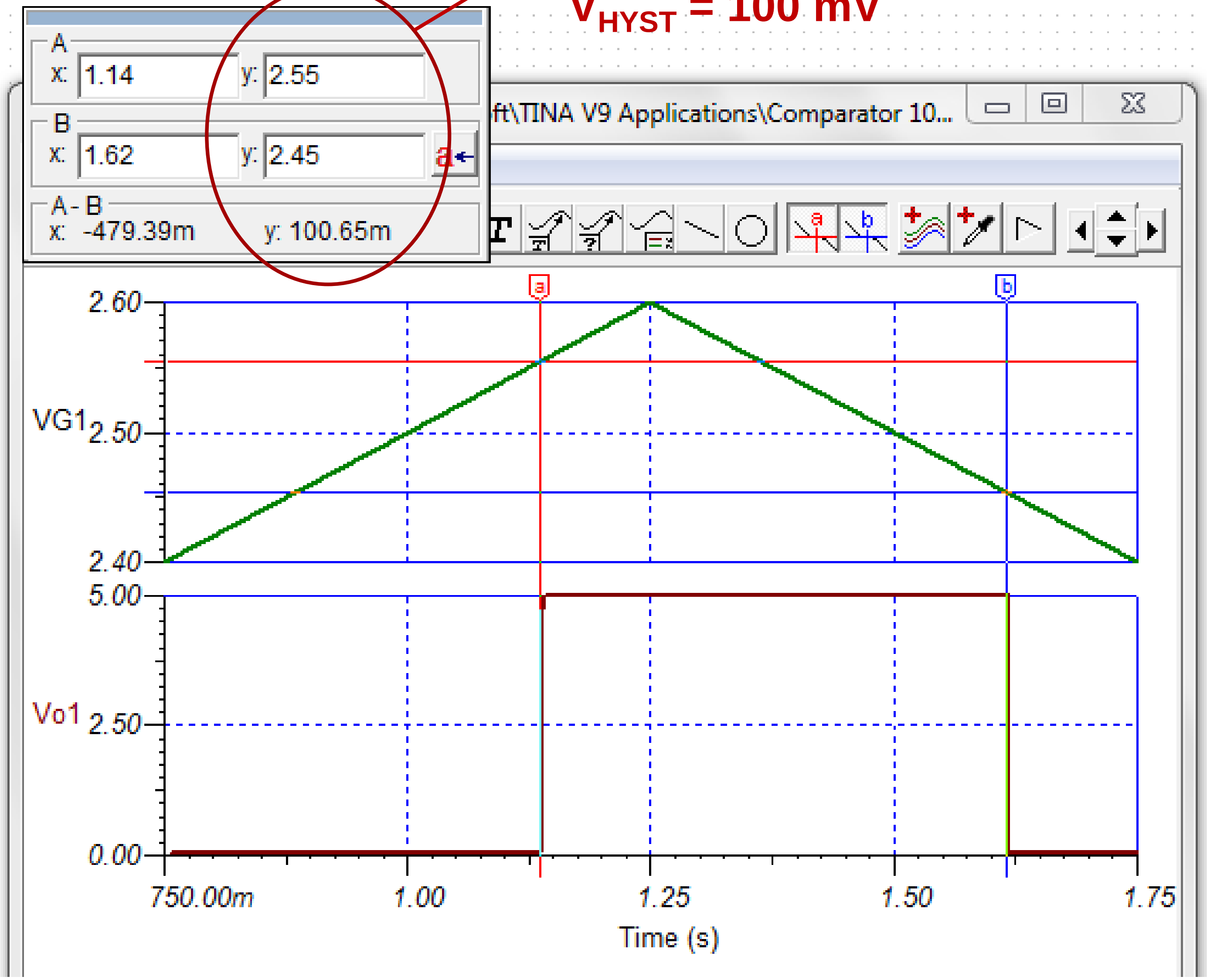
Setting up a comparator circuit to use hysteresis

TLV1701 Non-inverting comparator, open-collector, 100 mV H_{HYST}

TINA-TI simulation and verification



V_H = 2.55 V
V_L = 2.45 V
V_{HYST} = 100 mV



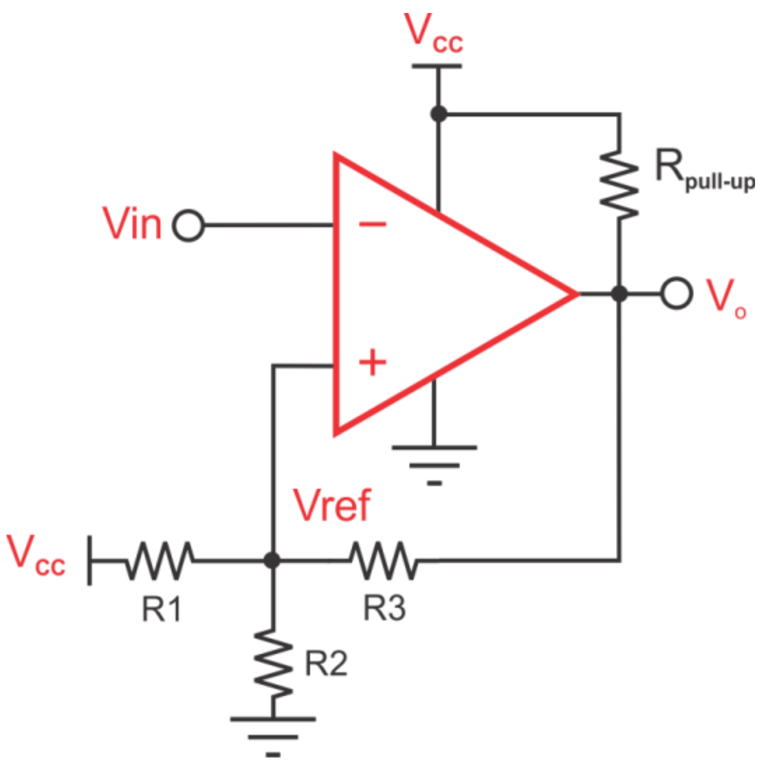
- Hysteresis accuracy improves with $R_{pull\text{-}up}$ < 0.1 R4
- Equations can be used for push-pull output too!

Setting up a comparator circuit to use hysteresis

TLV1701 Inverting comparator, open-collector

Goals

$V_{HYST} = 50\text{ mV}, \quad V_{ref} = 2.5\text{ V}$



Let

$Vcc = 5\text{ V}, \quad V_{O(max)} = 5.0\text{ V}, \quad V_{O(min)} = 0.05\text{ V}$

$R1 = 10\text{ k}, \quad R_{pull\text{-}up} = 10\text{ k}$

Then

$$R2 = \frac{R1}{\left(\frac{Vcc}{Vref} - 1\right)} = \frac{10^4}{\left(\frac{5.0}{2.5} - 1\right)} = 10\text{ k}$$

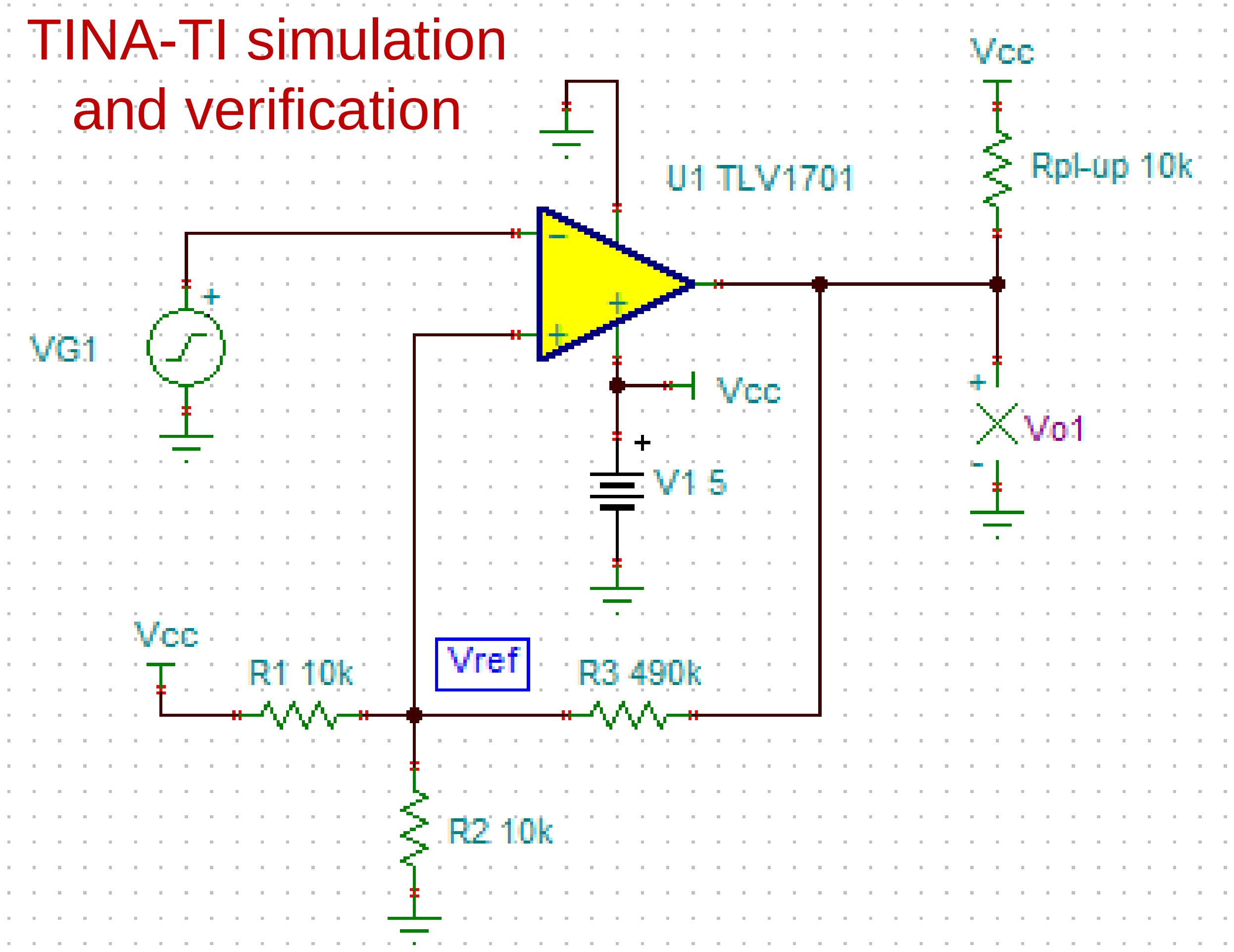
$$R3 = \frac{(R1 \cdot R2)}{(R1 + R2)}\left[\frac{\left(V_{O(max)} - V_{O(min)}\right)}{V_{HYST}} - 1\right]$$

$$R3 = \frac{(10^4 \cdot 10^4)}{(10^4 + 10^4)}\left[\frac{(5.0 - 0.05)}{0.05} - 1\right] = 490\text{ k}$$

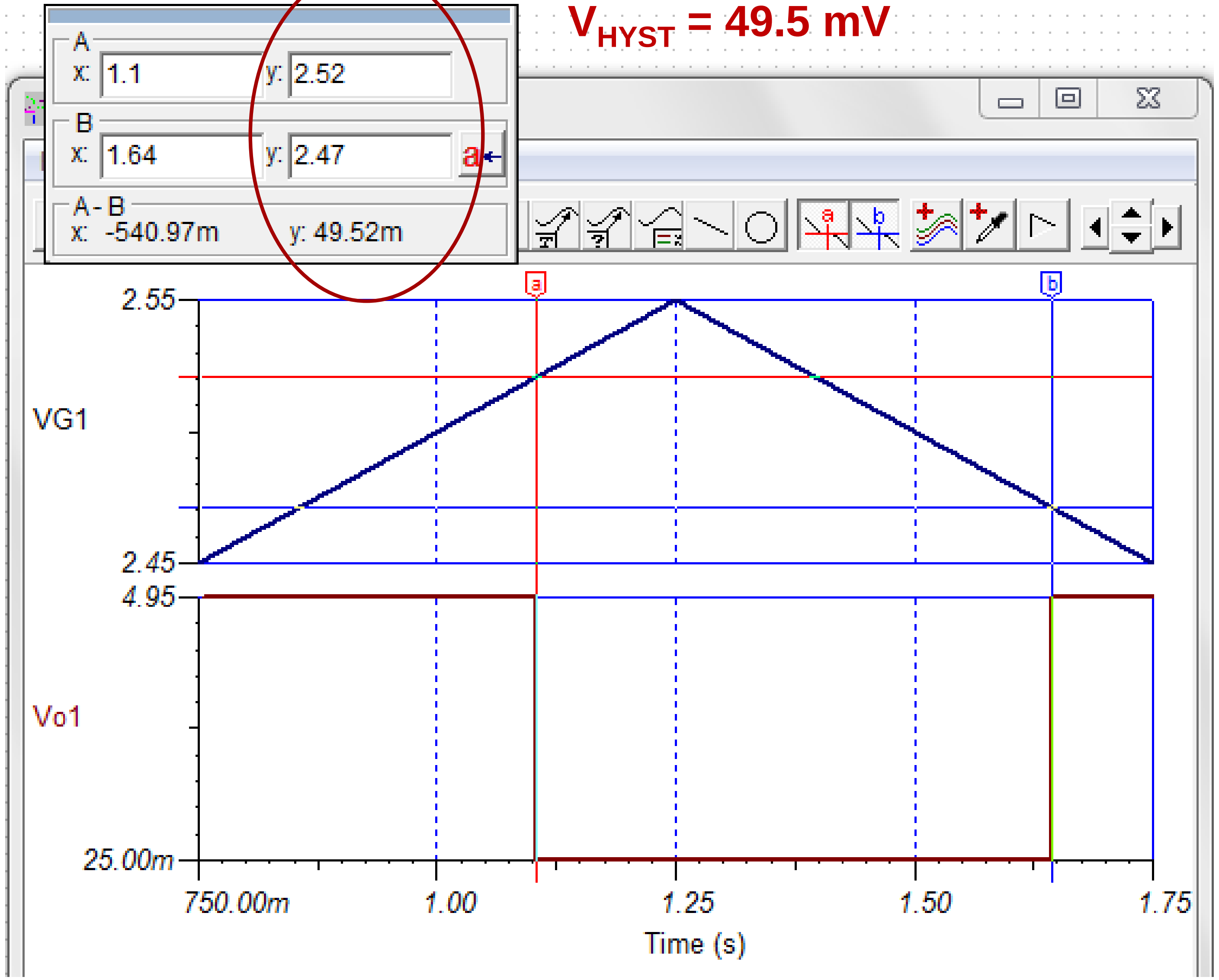
Setting up a comparator circuit to use hysteresis

Inverting comparator, open-collector, 50 mV V_{HYST}

TINA-TI simulation and verification



V_H = 2.52 V
V_L = 2.47 V
V_{HYST} = 49.5 mV



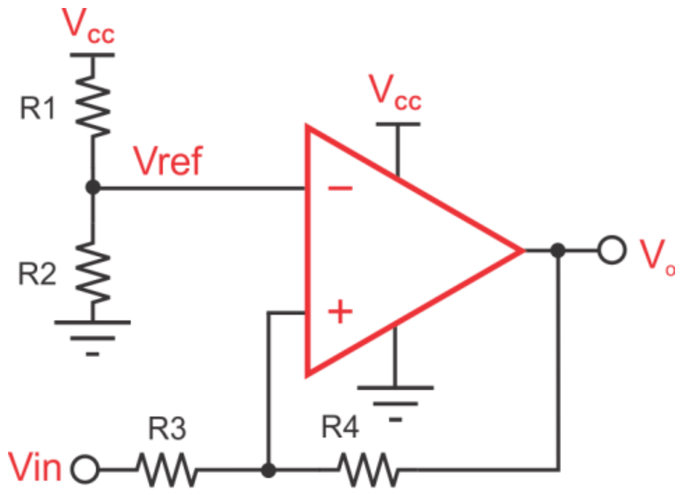
- **Hysteresis accuracy improves with $R_{pull-up}$ < 0.1 R3**
- **Equations can be used for push-pull output too!**

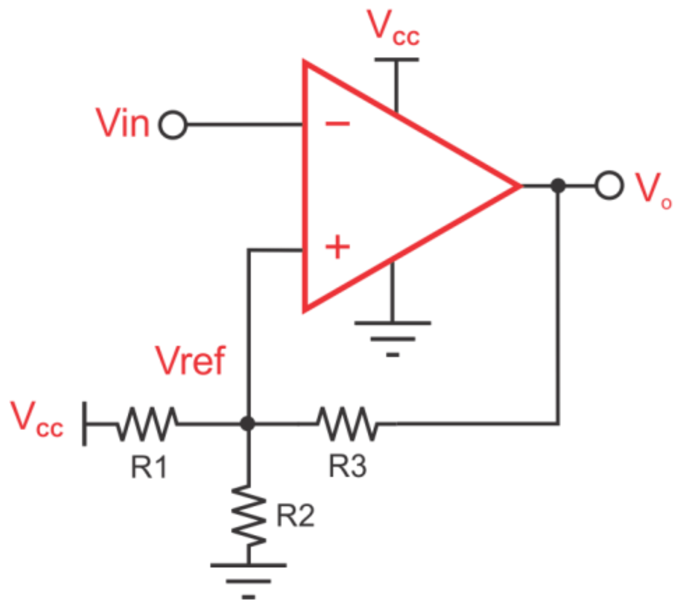
Setting up a comparator circuit to use hysteresis

Some guidelines when applying hysteresis

- The resistor values directly affect the reference voltage and the V_H and V_L levels. Their tolerances are an important factor in hysteresis accuracy
- Keeping $R_{pull\text{-}up} \leq 10\ \%$ of the feedback resistor value for open-drain/ collector outputs assures more accurate V_H and V_L voltage levels
- **The inverting and non-inverting equations can be used for push-pull output comparators**
  - Use the datasheet *Output Voltage vs Output Current* curves to establish $V_{O(max)}$ and $V_{O(min)}$ from the V_{OH} and V_{OL} levels

Push-pull comparators with hysteresis applied

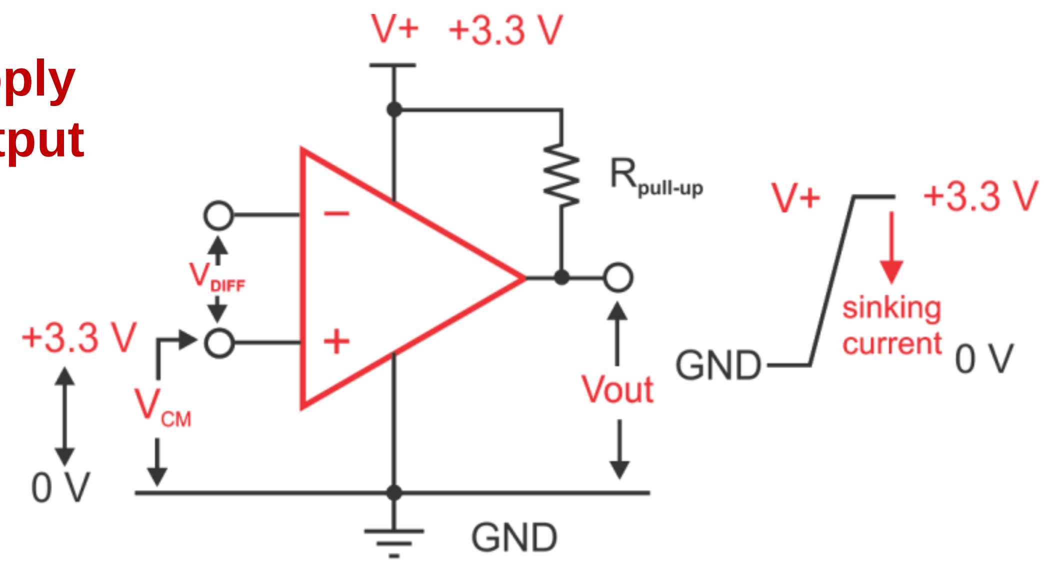




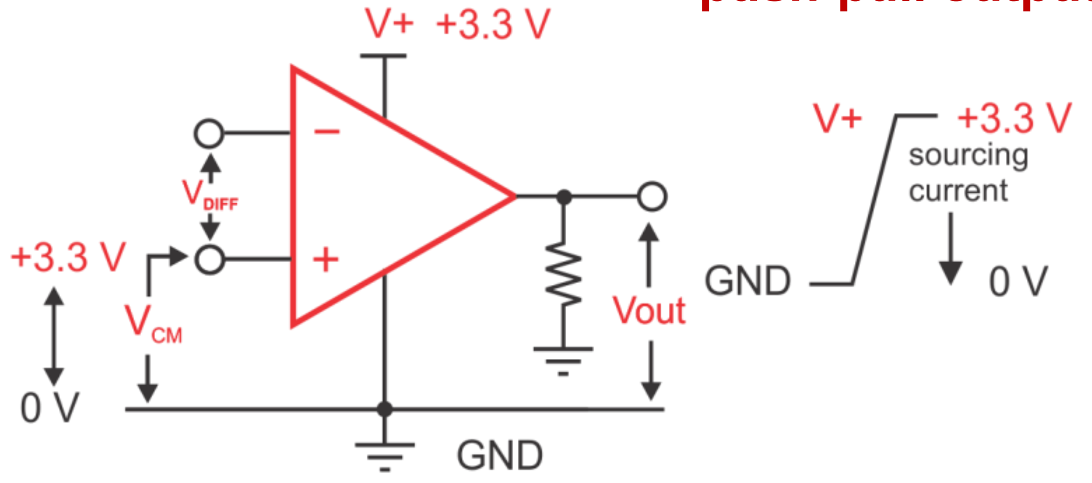
Single or dual supply operation

A +3.3 V rail-to-rail in/out comparator example using either supply plan

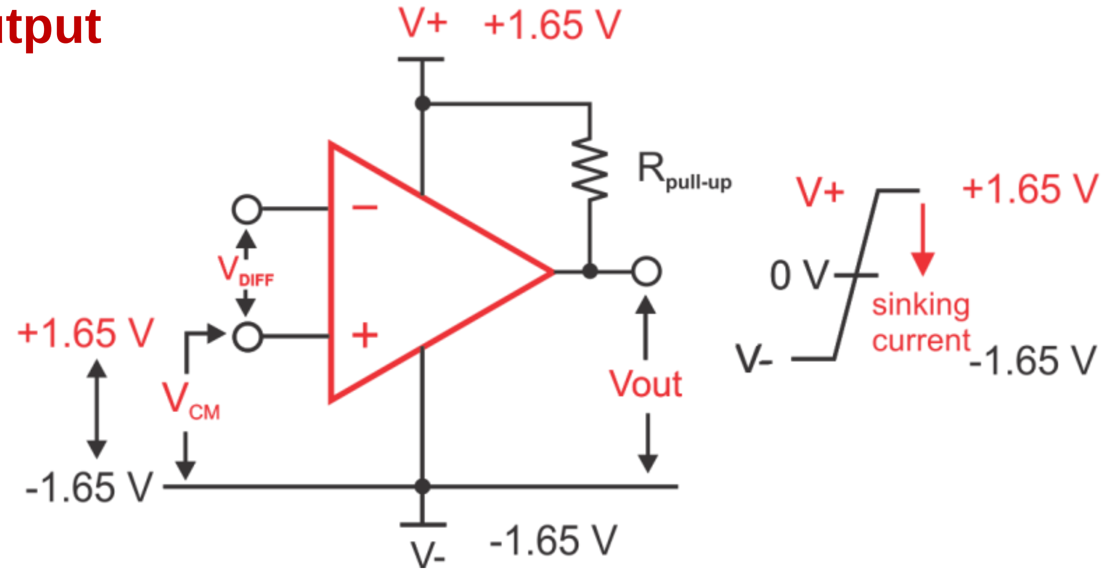
Single-supply pull-up output



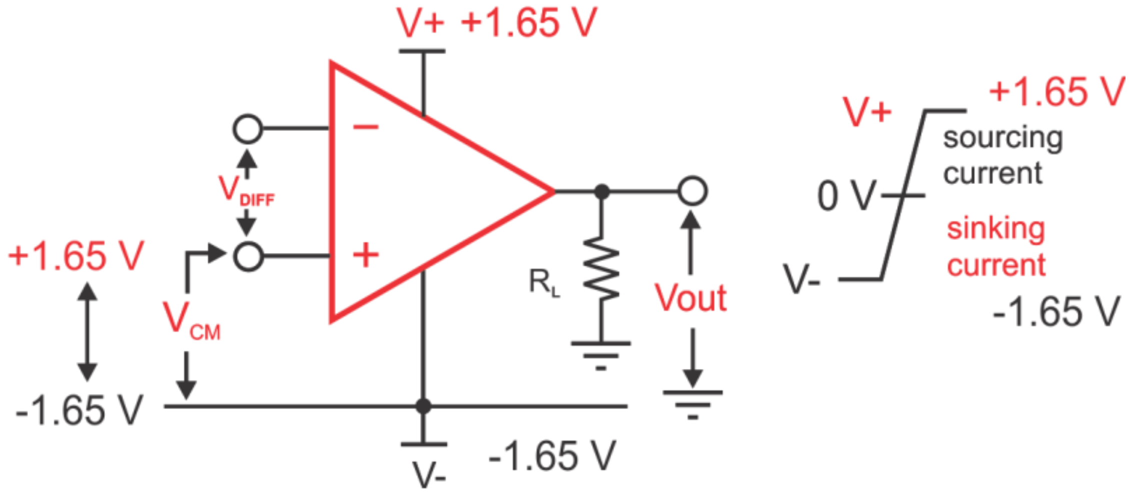
Single-supply push-pull output



Dual-supply pull-up output



Dual-supply push-pull output

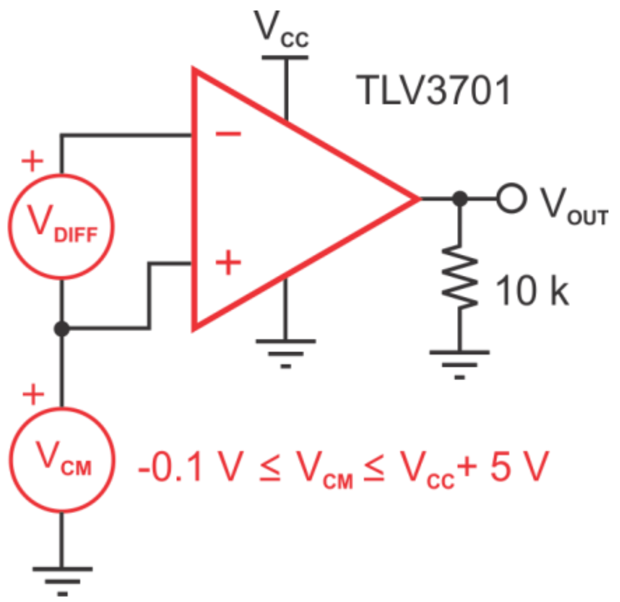


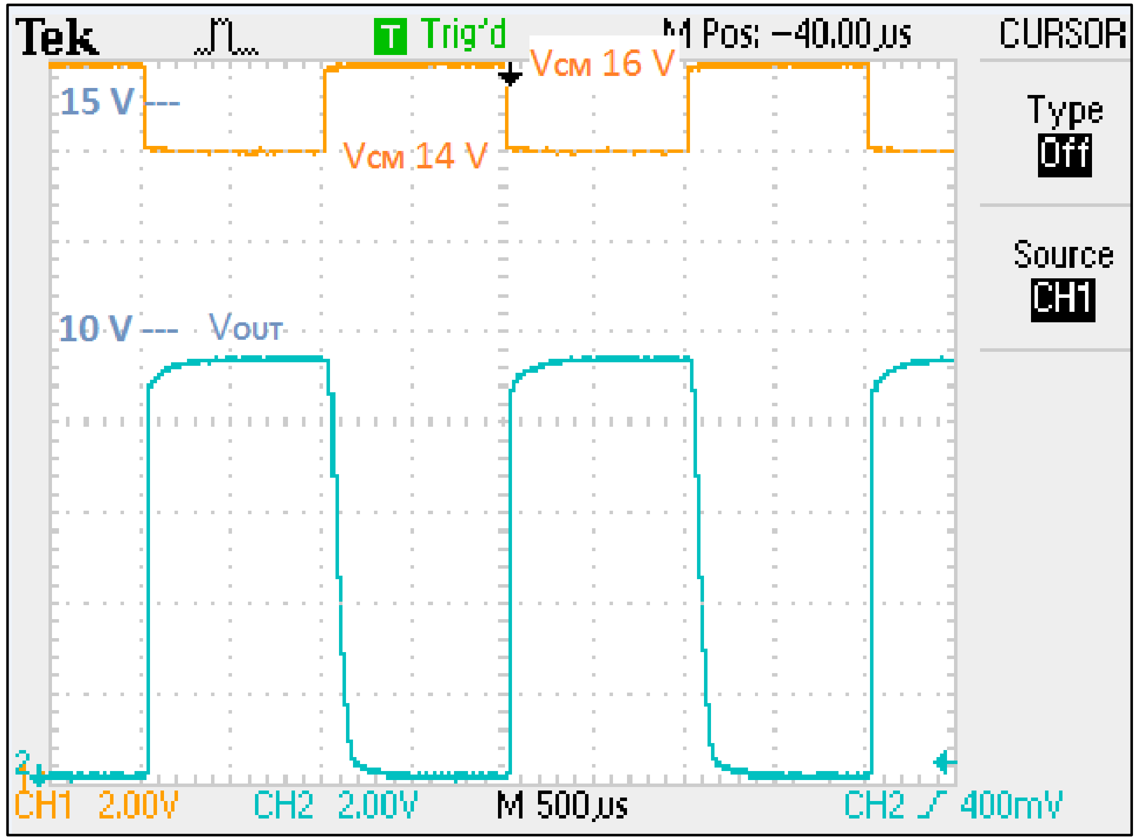
TLV3701/3401 upper CMV limit exceeds V_{CC} by +5 V

Does it still work as a comparator in that range?

recommended operating conditions

Common-mode input voltage range, V_{ICR}	–0.1	V_{CC}+5	V



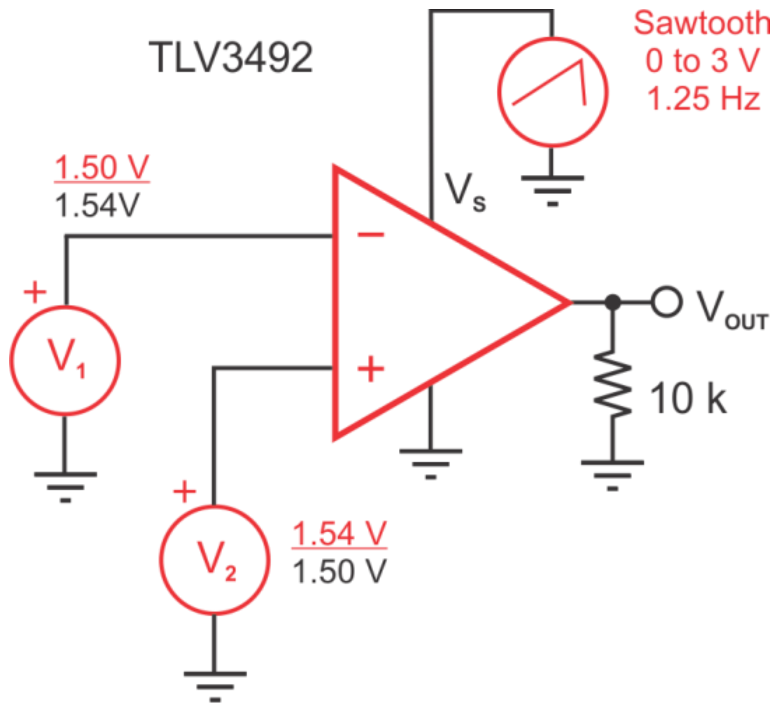


Observed that higher V_{DIFF} drive is required as V_{CC} and V_{CM} increase

V_{CC}	V_{CM}	$V_{DIFFmin}$ pk-to-pk
12 V	17 V	1.8 V
10 V	15 V	1.6 V
5 V	10 V	1.2 V
3 V	8 V	1.0 v

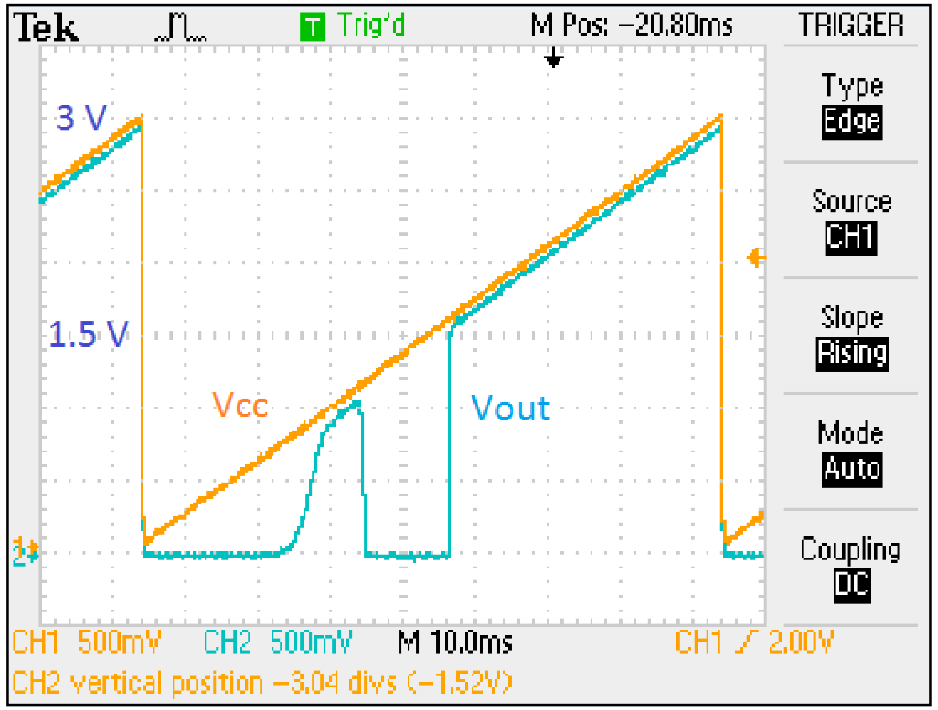
Start-up output state uncertainty

inputs biased at different dc levels as Vcc ramps up from zero to V+

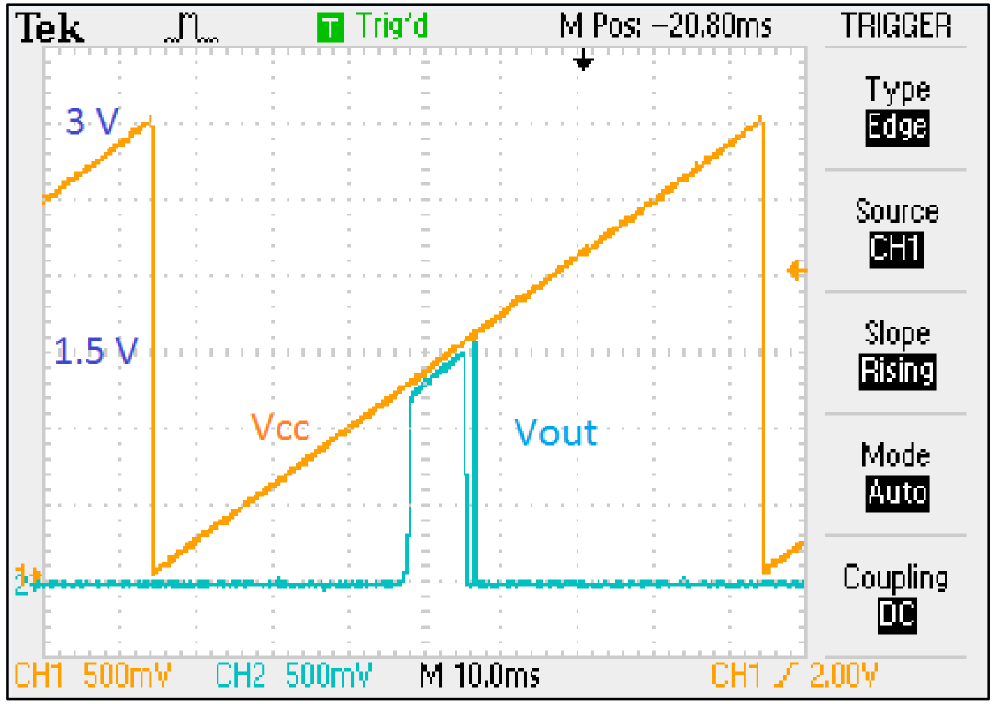


The TLV3492 minimum supply is specified as 1.8 V

V_1 = 1.50 V, V_2 = 1.54 V



V_1 = 1.54 V, V_2 = 1.50 V

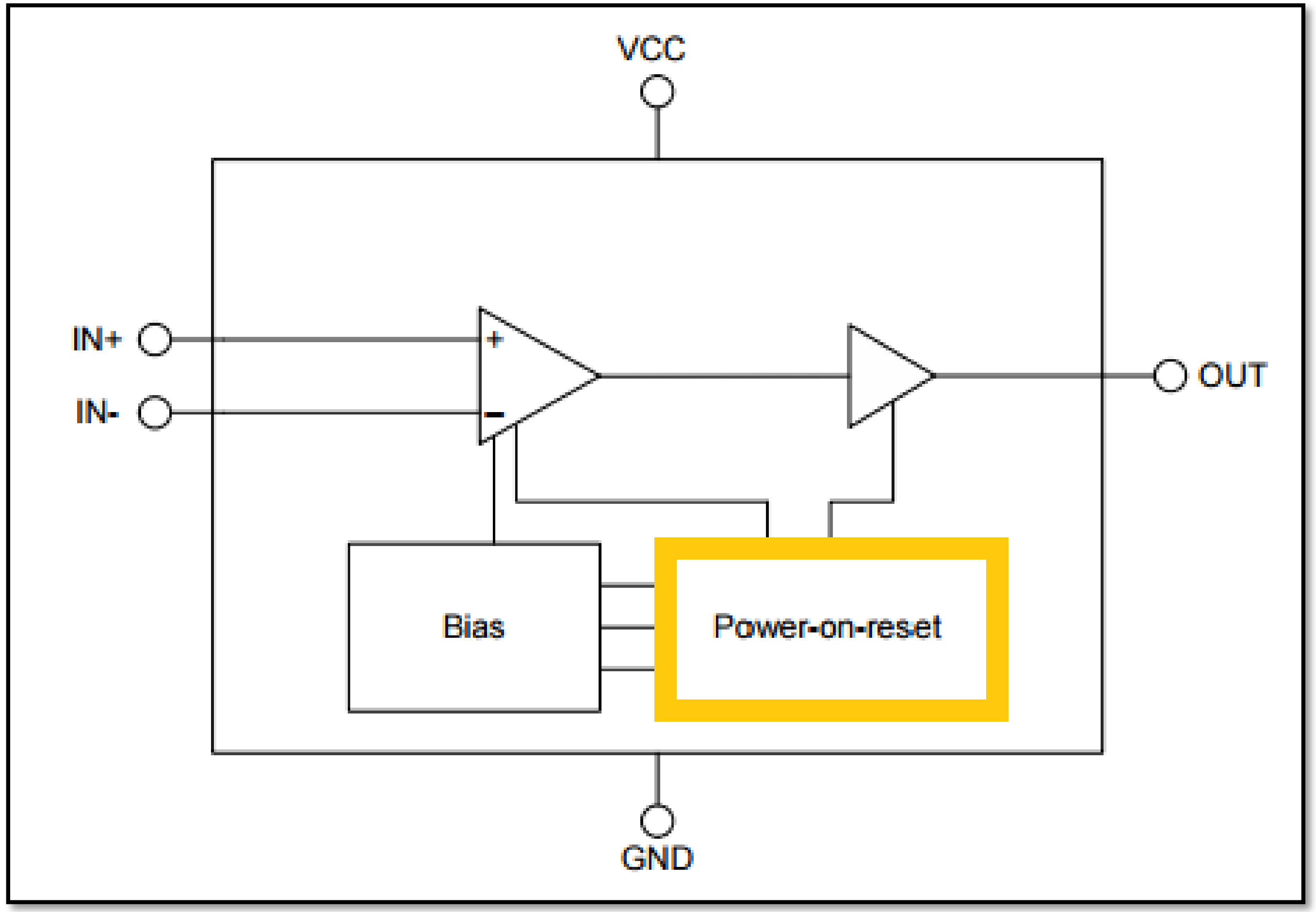


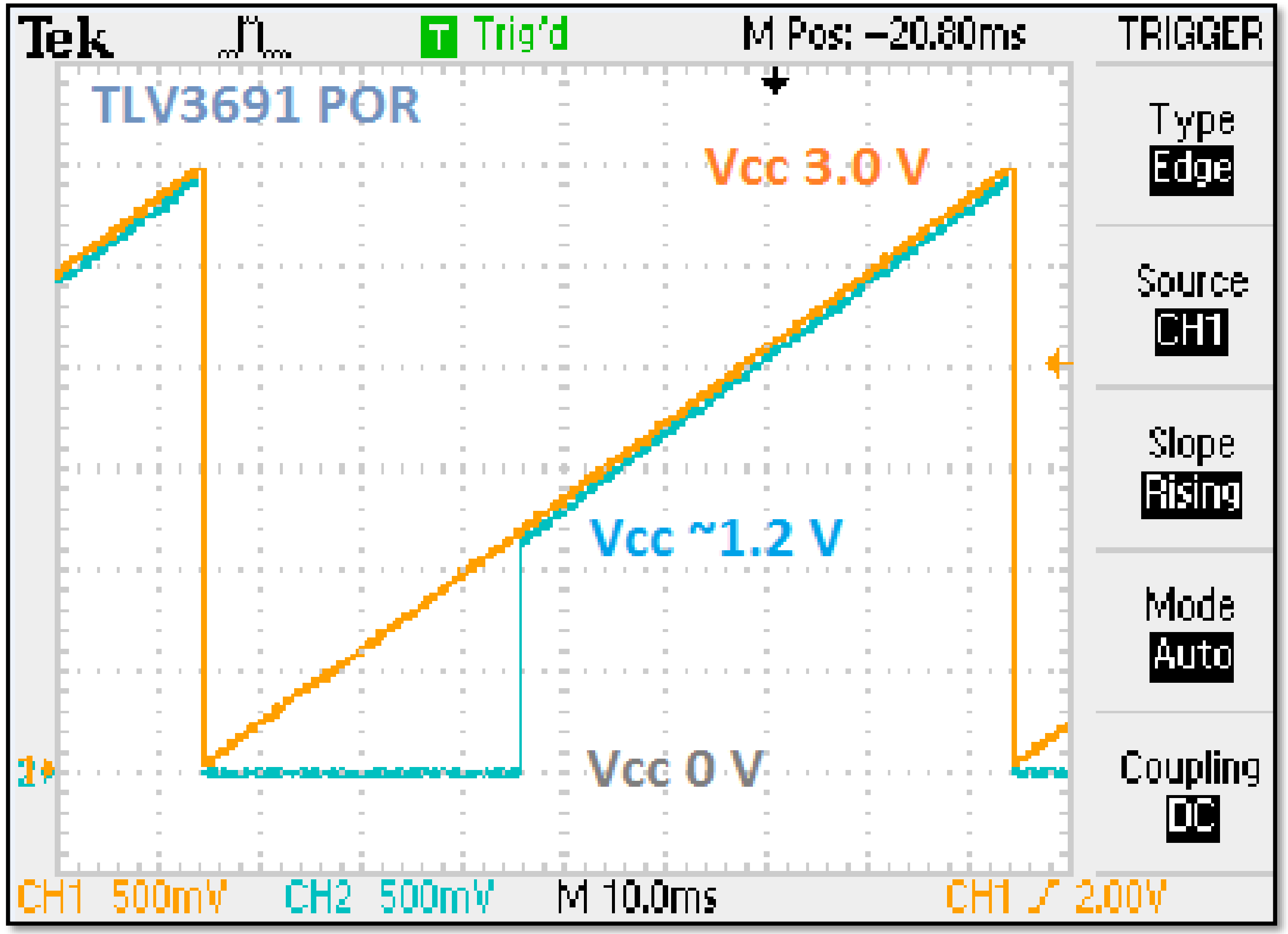
- The TLV3492 output flips state as it is powering up
- This is a common behavior for comparators - *Most TI & competitor comparators show this kind of behavior!*

Internal power-on-reset (POR)

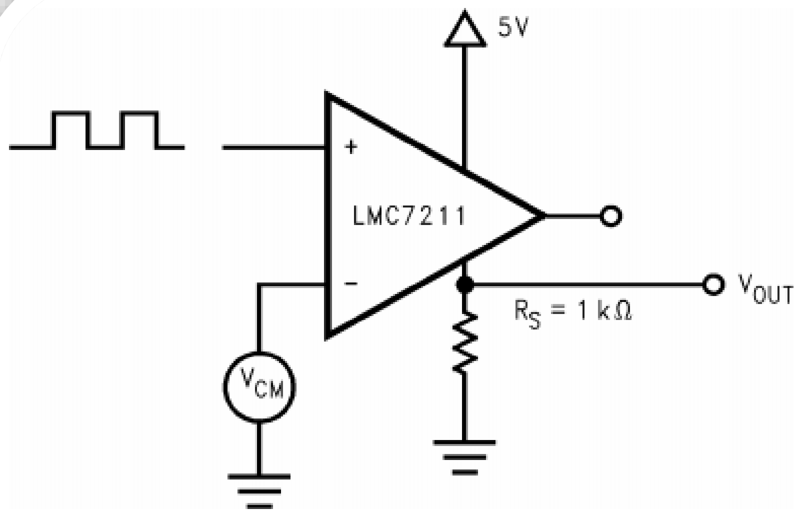
TLV3691 – output remains low during power up and until $V_{cc(min)}$ is reached

TLV3691 Functional Block Diagram

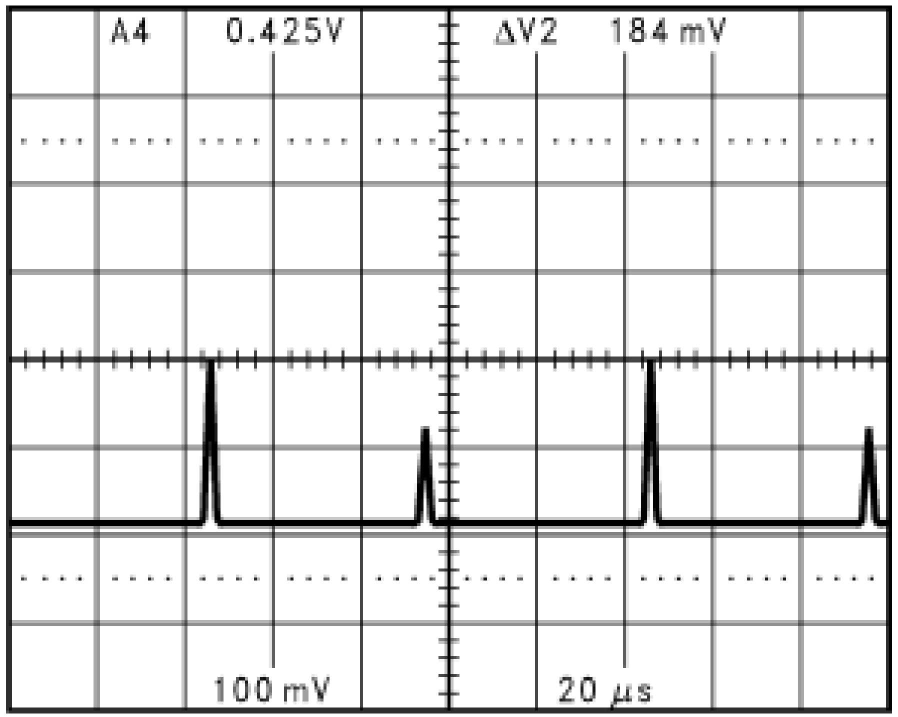




Some ac considerations
Shoot-through current



Shoot-through current measurement circuit



Effect of shoot-through current on V-

- Current surge through output stage from V+ to V-
- Push-pull output stages prone to effect
- Results in glitches on the supply voltages
- Glitches can affect adjacent comparators, or logic
- Transient PSRR can be low, 20 to 40 dB
- Proper bypass capacitors can address issue

LMC7211 datasheet provides bypass capacitor calculations to minimize glitches

Some ac considerations

Maximum toggle frequency – sometimes listed, but not defined in datasheet

- It appears the intent is to relate a maximum switching frequency to the comparator timing parameters, where *f = 1 / t*
- From datasheet numbers and lab:

$$f_{toggle} \cong (t_r + t_f + t_{plh} + t_{phl})^{-1}$$

- Using *TLV3501* datasheet typical timings

$$f_{toggle} \cong (1.5\ ns + 1.5\ ns + 4.5\ ns + 4.5\ ns)^{-1} = \mathbf{83.3\ MHz}$$

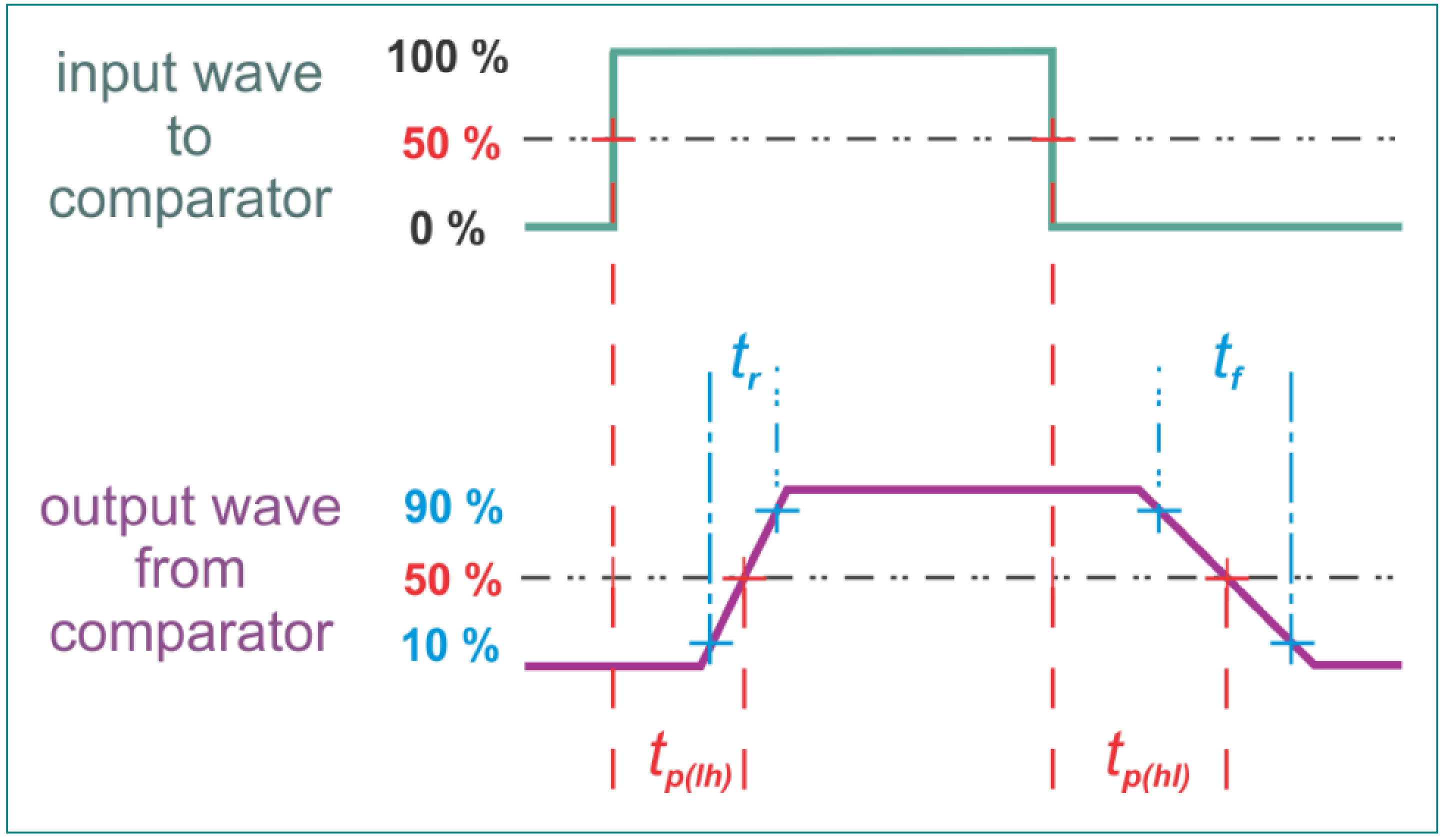
  the datasheet lists $f_{max(toggle)}$ as 80 MHz typical

- Using *TLV3201* datasheet typical timings

$$f_{toggle} \cong (2.9\ ns + 3.7\ ns + 43\ ns + 42\ ns)^{-1} = \mathbf{10.9\ MHz}$$

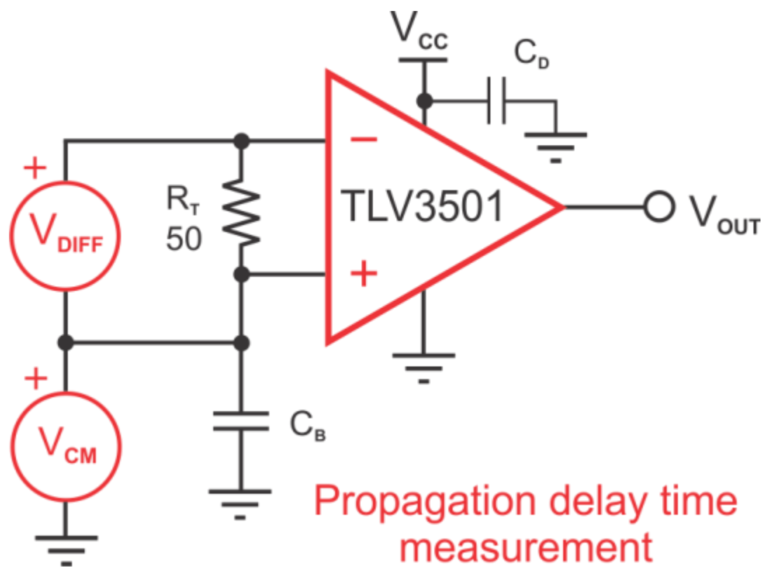
  Not listed in datasheet, but verified in lab to be about 10 MHz

Comparator input to output timing relationships



Some ac considerations

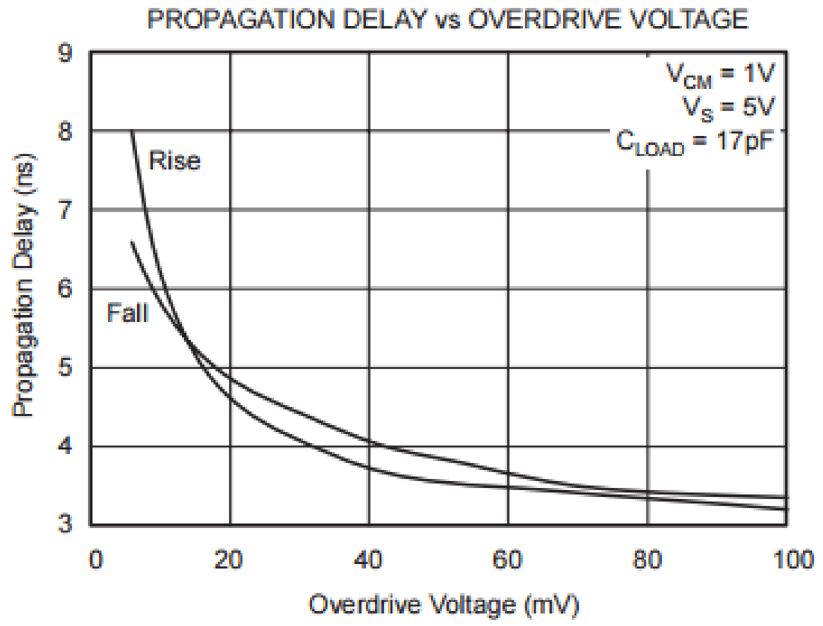
input overdrive's effect on propagation delay

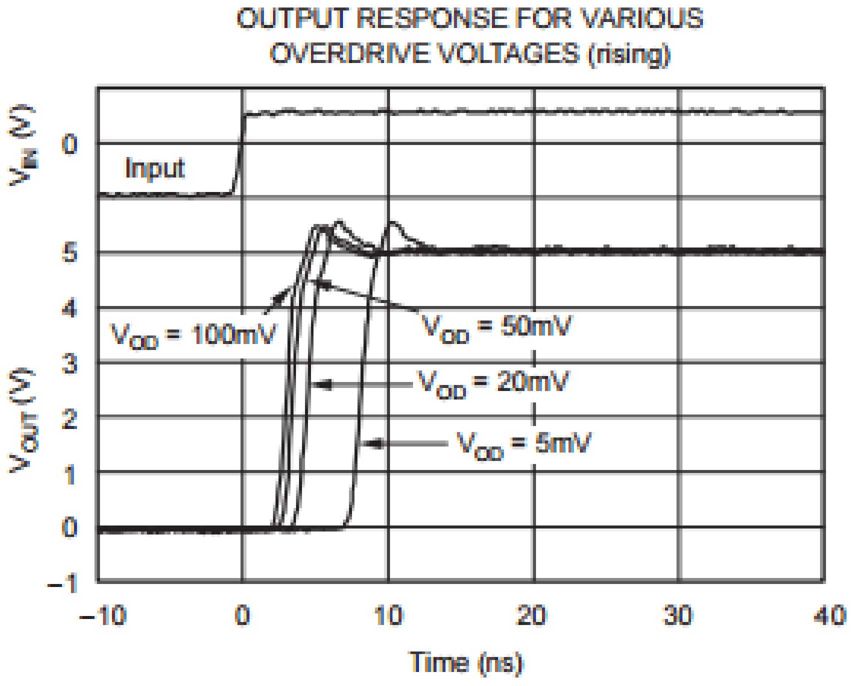


Propagation delay time measurement

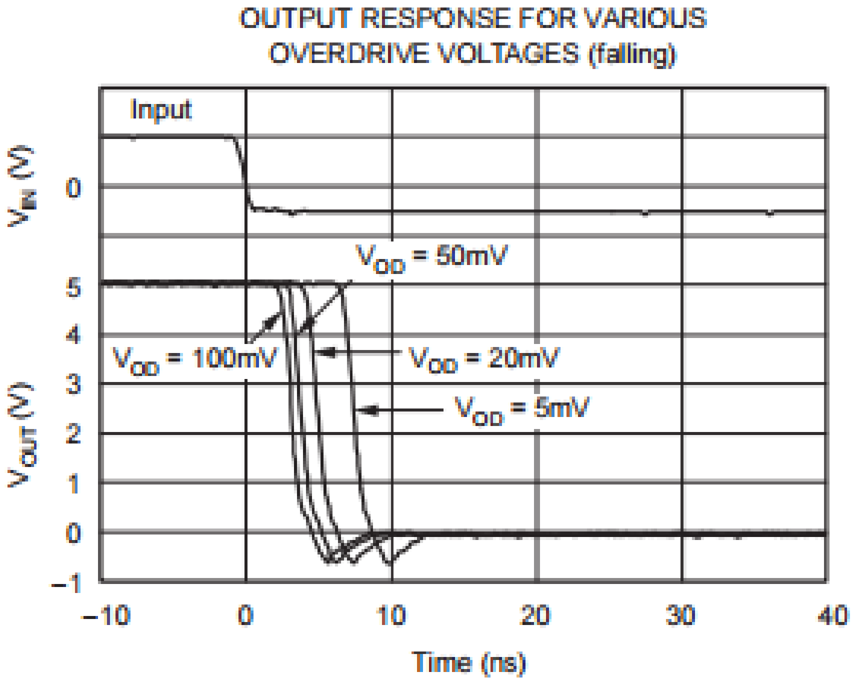
Propagation delay t_{pd}

Temp C	Overdrive	Typical	Maximum
25° -40° to 85°	5 mV	7.5 ns	10 ns 12 ns
25° -40° to 85	20 mV	4.5 ns	6.4 ns 7 ns





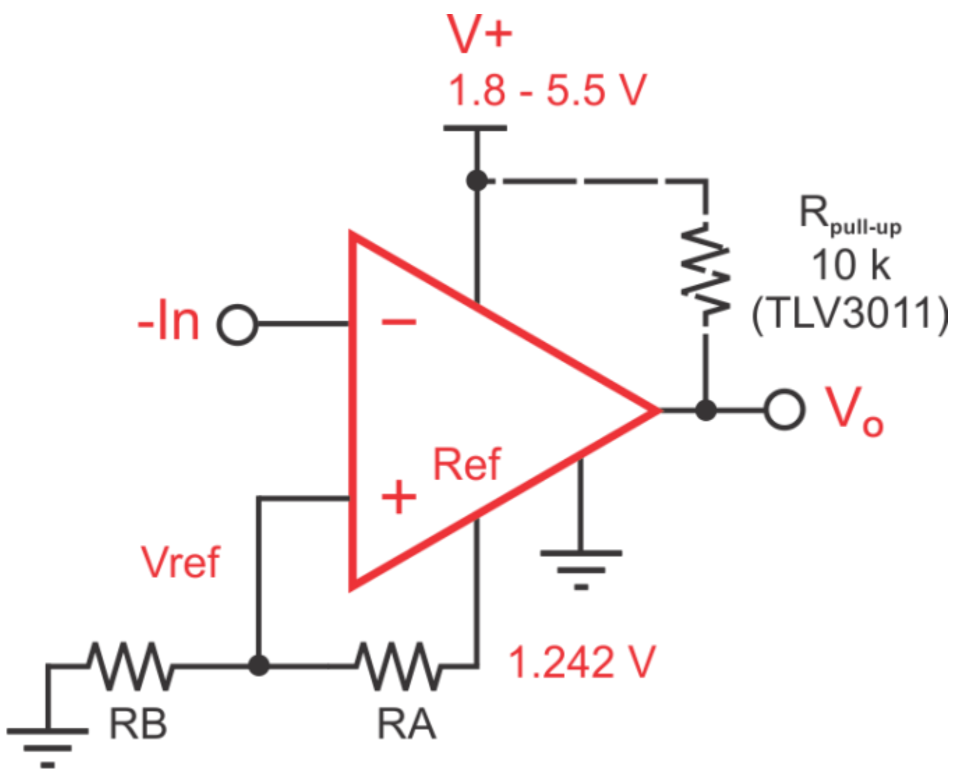
prop delay tp(LH)



prop delay tp(HL)

Comparators providing additional functions

TLV3011/12 provide a 1.242 V internal reference



$$RA = RB\left(\frac{1.242\ V}{Vref} - 1\right)$$

For Vref = 1.000 V, let RB = 100 k

$$RA = 100\ k\left(\frac{1.242}{1.000} - 1\right) = 24.2\ k$$

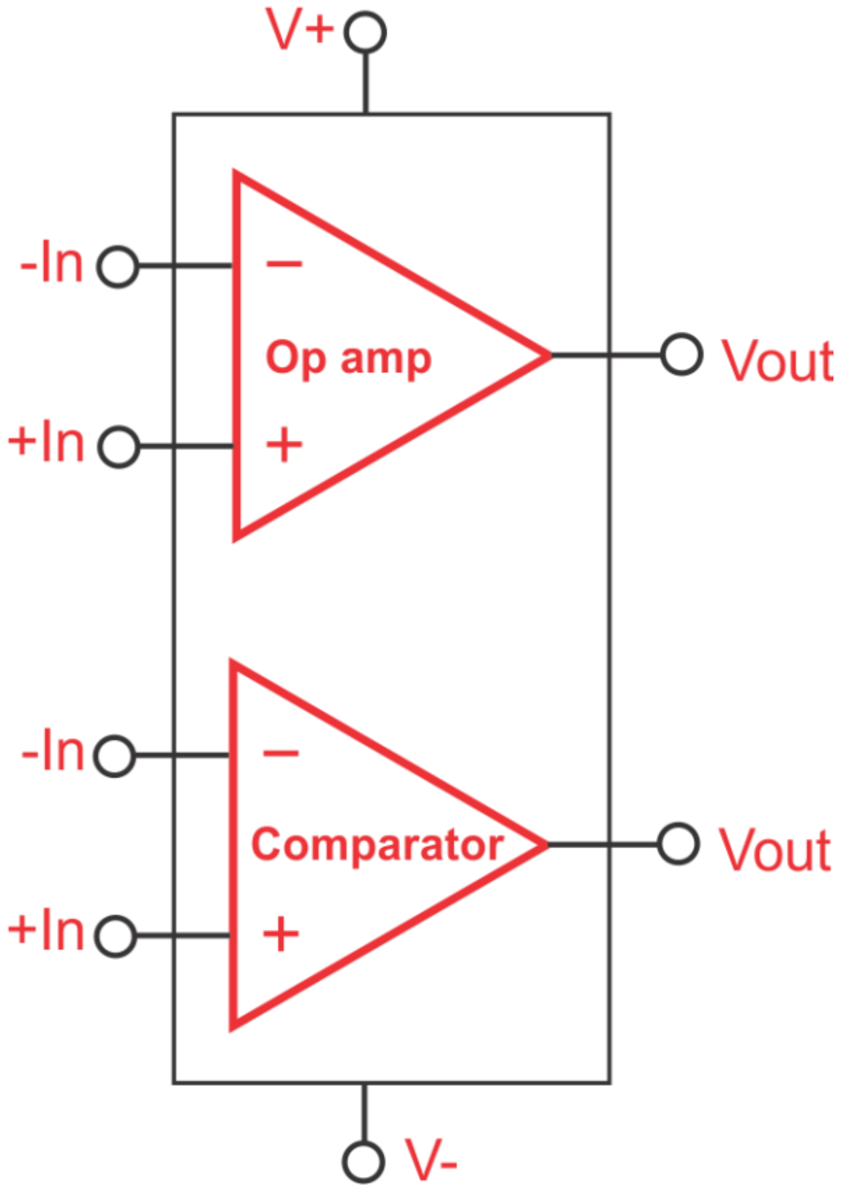
VOLTAGE REFERENCE		$V_{IN} = 5V$				
Initial Accuracy	V_{OUT}		1.230	1.242	1.254	V
					±1	%
Temperature Drift	dV_{OUT}/dT	$-40°C \le T_A \le 125°C$		40	100	ppm/°C
Load Regulation						
Sourcing	dV_{OUT}/dI_{LOAD}	$0mA < I_{SOURCE} \le 0.5mA$		0.36	1	mV/mA
Sinking		$0mA < I_{SINK} \le 0.5mA$		6.6		mV/mA
Output Current	I_{LOAD}			0.5		mA
Line Regulation	dV_{OUT}/dV_{IN}	$1.8V \le V_{IN} \le 5.5V$		10	100	µV/V

Comparators providing additional functions

sub-micropower op amp and comparator in the same package

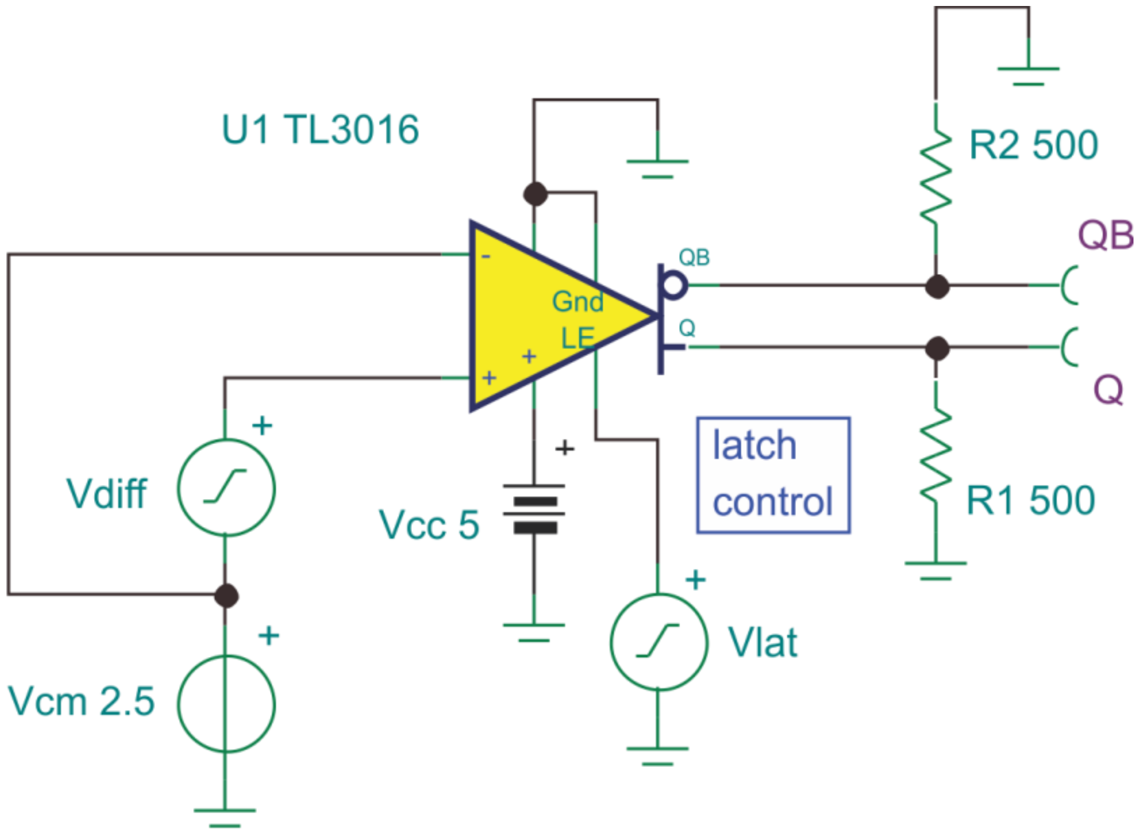
- TLV2302 RIRO op amp, plus open-drain comparator
- TLV2702 RIRO op amp, plus push-pull output comparator
- Input Common-Mode Range exceeds the rails -0.1 V to V_{CC} + 5 V
- Reverse battery protection up to 18 V
- Typical supply current 1.4 uA
- Supply voltage range 2.5 V to 16 V

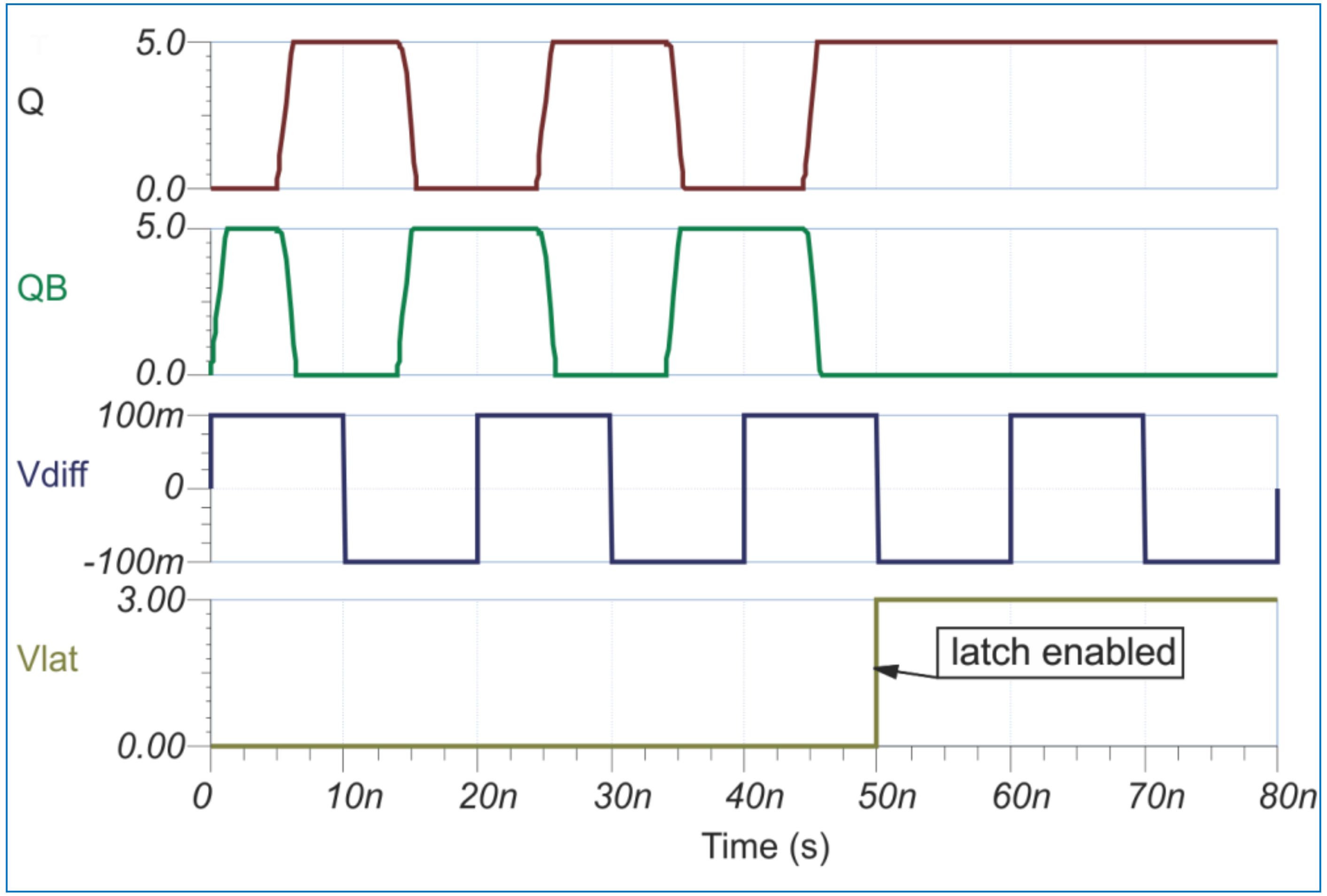
TLV2302/ TLV2702



Comparators providing additional functions

TL3016 complementary outputs and output latch





- Output holds current state when latch is enabled
- Inputs can change and outputs maintain their latched-state levels

Applying op amps as comparators

Reasons to use them

- Convenience and cost reduction
- Utilize unused sections of dual and quad op amps for comparator needs
- Saves PC board space
- Improved dc precision. For example, low voltage offset, low noise
- Slew rate limited edge rates (dV/dt) reduce chances of EMI

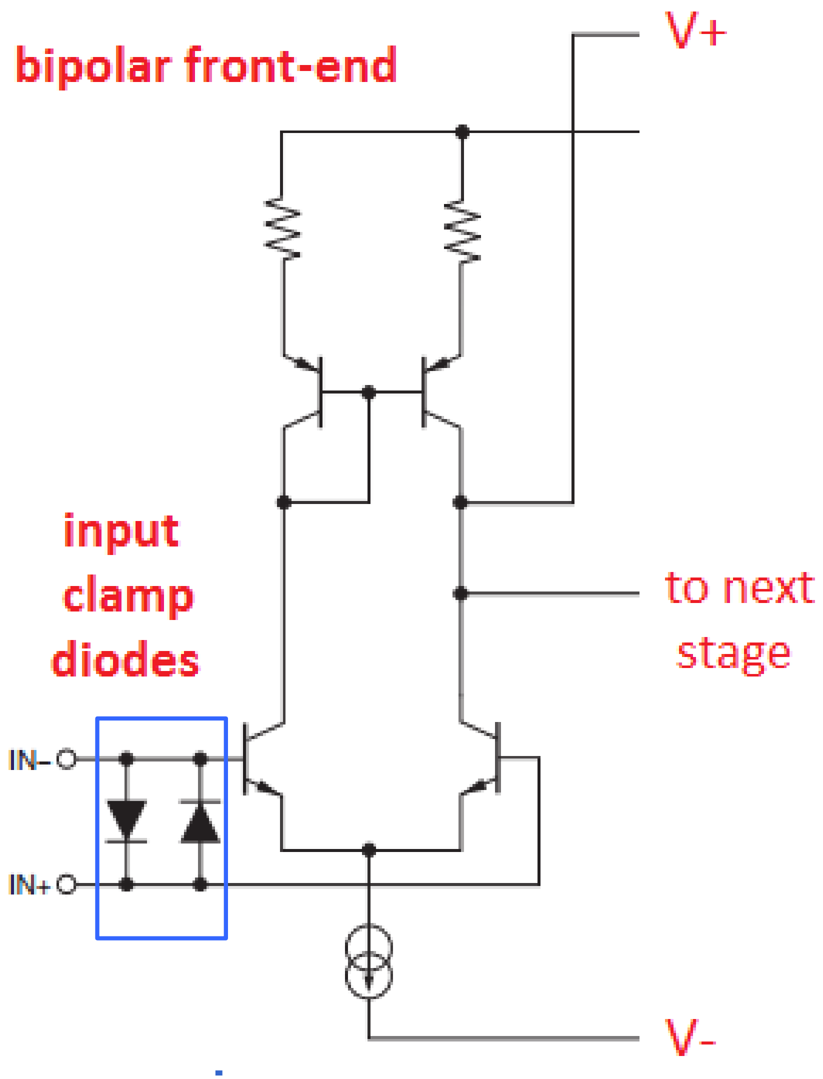
Reasons not to use them

- Typically, higher power consumption for the equivalent comparator function
- Input differential voltage may be limited due to input clamps
- CMV range, especially on positive end, may not like being exceeded
- Output recovery from saturation may not be characterized and is often 100s us, or ms
- t_{rise} and t_{fall} limited by slew rate
- No open-collector, open-drain equivalent

Applying op amps as comparators

Differential input voltage limited by clamps

- Most bipolar front-ends require input clamps to protect against emitter-base reverse breakdown
- Without clamps a differential voltage greater than V_{BE} + $BV_{(REV)\ EB}$ can cause reverse breakdown
- Once broken down the affected transistor's current gain and noise degrade changing the front-end matching and noise performance
- Adding clamping diodes limits the differential voltage to a safe level
- Op amps having clamps OPA209, OPA211, OPA227, OPA1611
- Some JFET input op amps have clamps

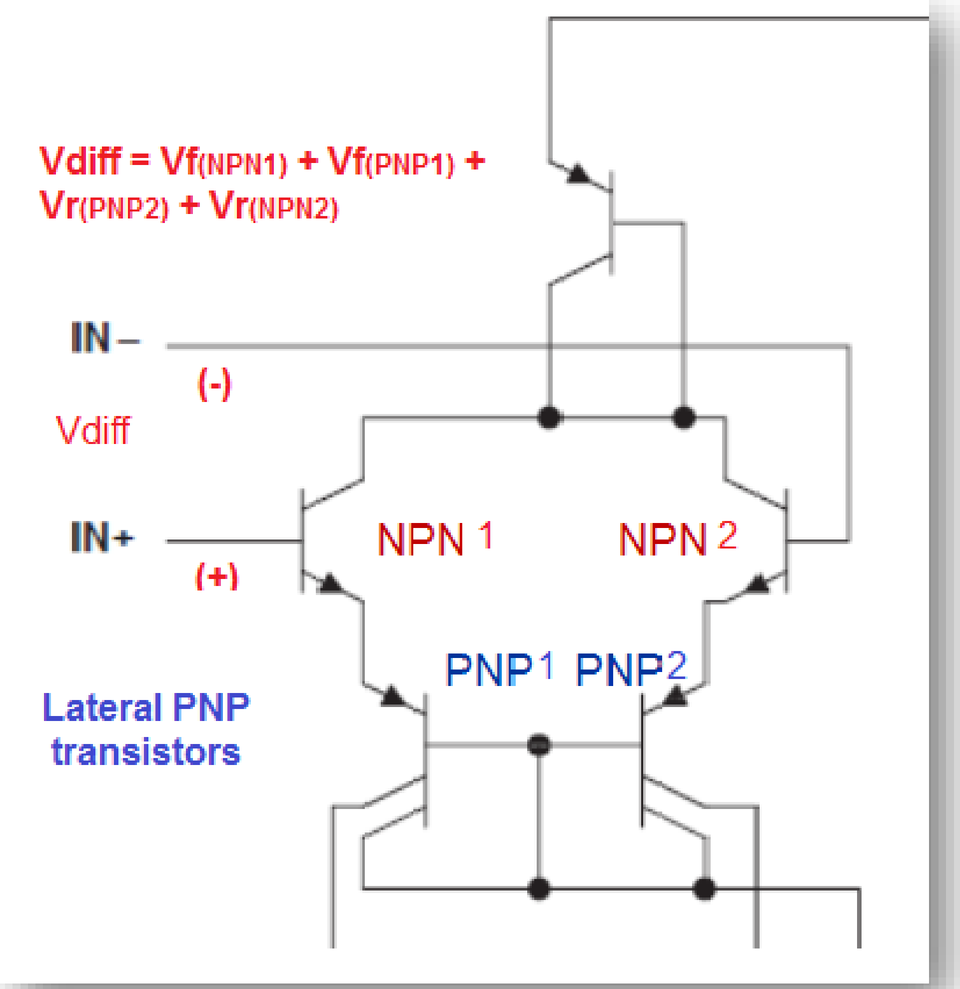


$BV_{(REV)EB}$ range is about 2 V to 7 V for input NPN transistors

Applying op amps as comparators

bipolar inputs using lateral PNP transistors don't require diode clamps

$BV_{(REV)EB}$ is typically about 18 V for a lateral PNP



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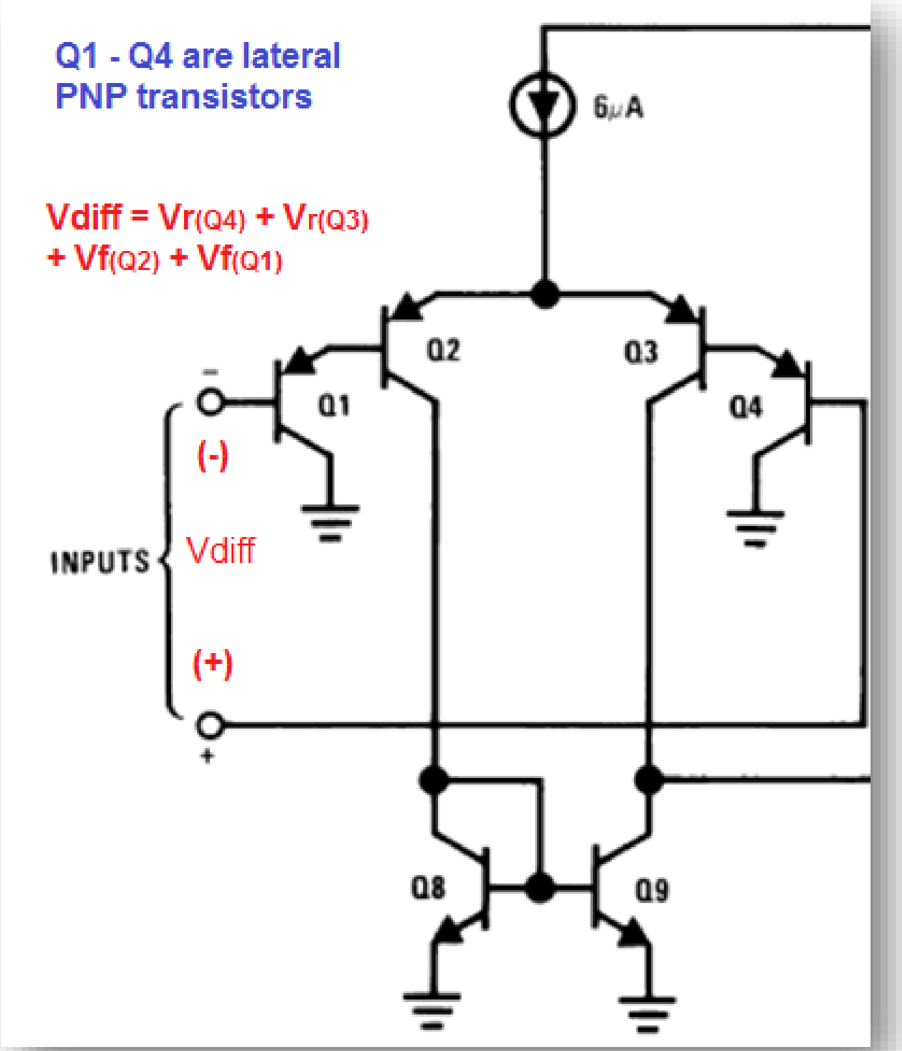
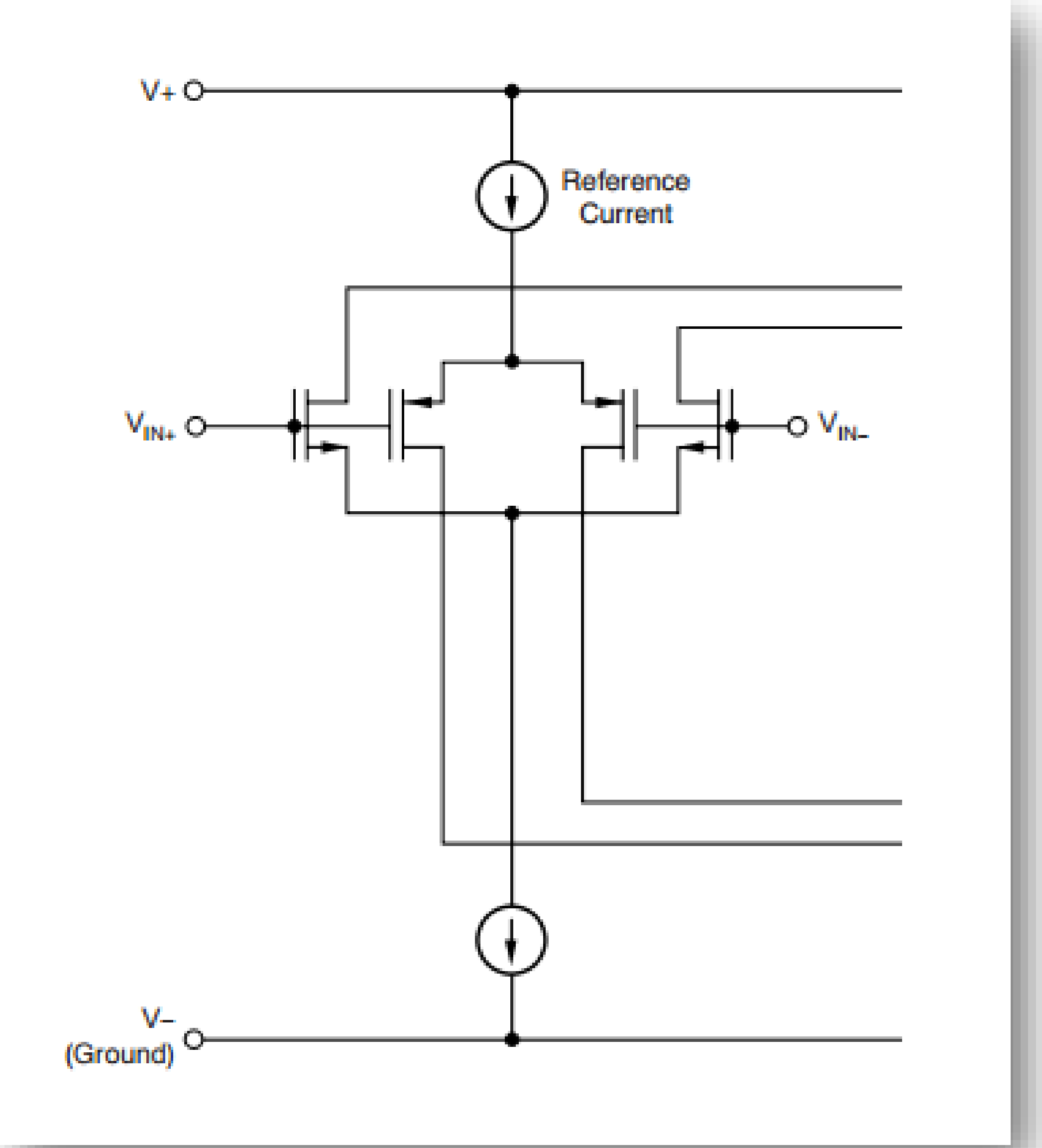


LM358, OPA234, OPA244, OPA2251

Applying op amps as comparators

Inquire on the amplifier E2E forums about input-to-input clamps

- JFET input op amps may have input clamps
- Most high-voltage CMOS op amps such as the OPA171 have input clamps
- Chopper op amps such as OPA330, OPA333 and OPA188 have parasitic input diodes associated with the switches
- Most low-voltage CMOS (1.8 to 16 V) OPA, TLC, and TLV op amps do not have input clamps

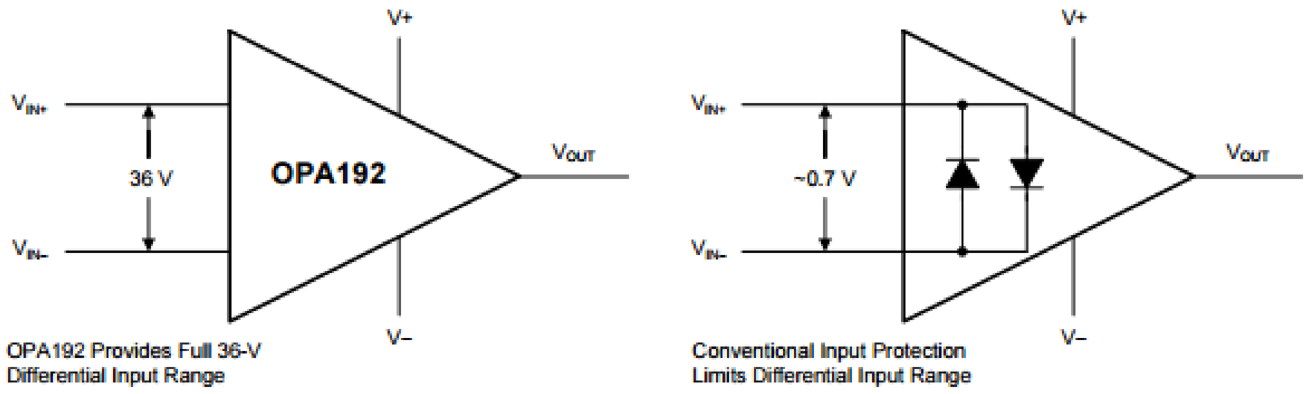


OPA314, OPA316, TLV2374, etc.

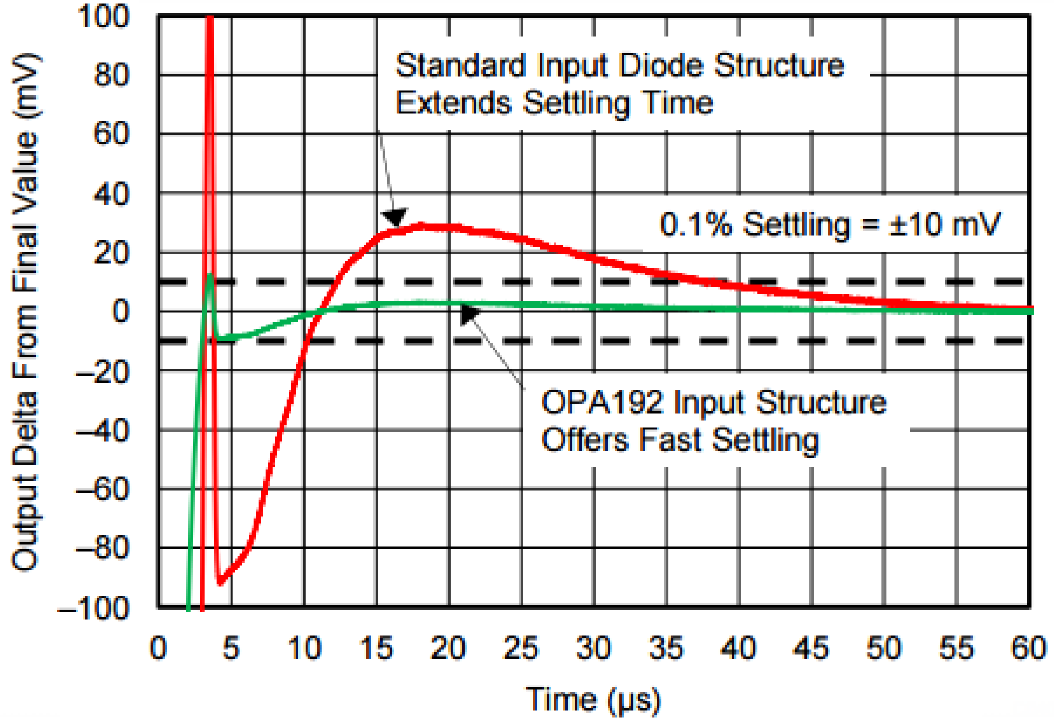
Applying op amps as comparators

OPAx192, OPx197 as precision comparators

- HV CMOS op amp uses patented frontend that doesn’t use a diode input clamp
- Differential input voltage range to supply rail
- Common-mode input range and output swing range are rail-to-rail
- Voltage offset
  - **OPA2192 is 25 uV max @ 25°C**
  - **OPA2197 is 250 uV max @ 25°C**
- Gain-bandwidth 10 MHz, Slew rate 20 V/us
- Overload recovery t_{OR} 200 ns
- Fast settling input structure
- 4.5 to 36 V supply range



OPA192 input protection does not limit differential input capability



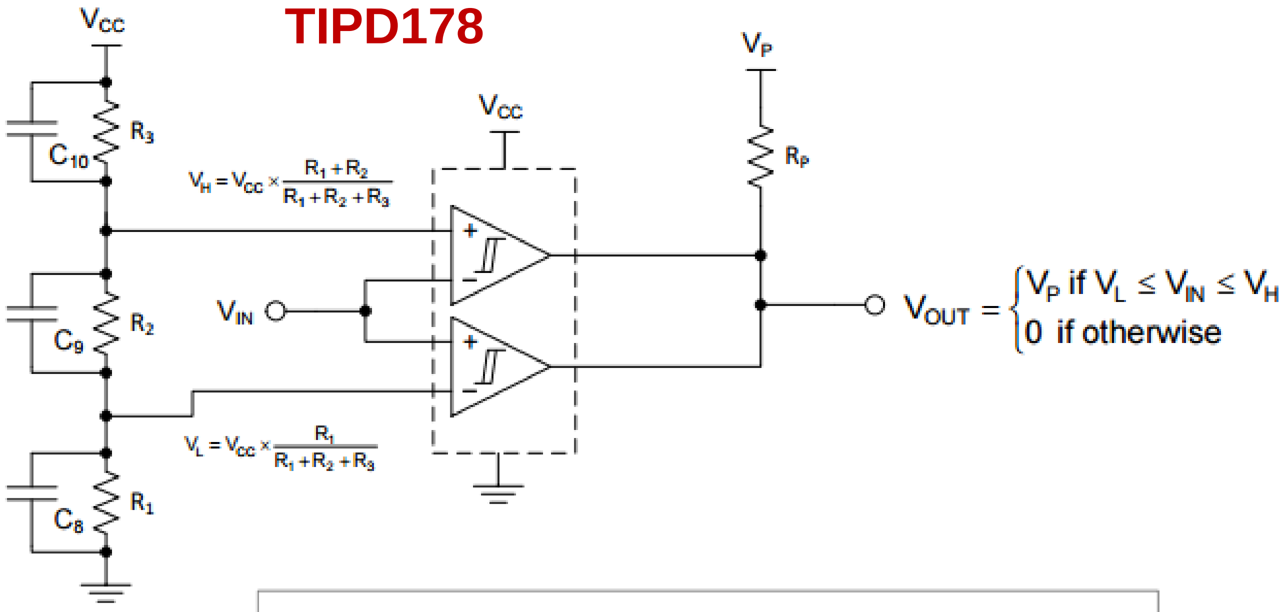
OPA192 input protection maintains fast-settling transient response

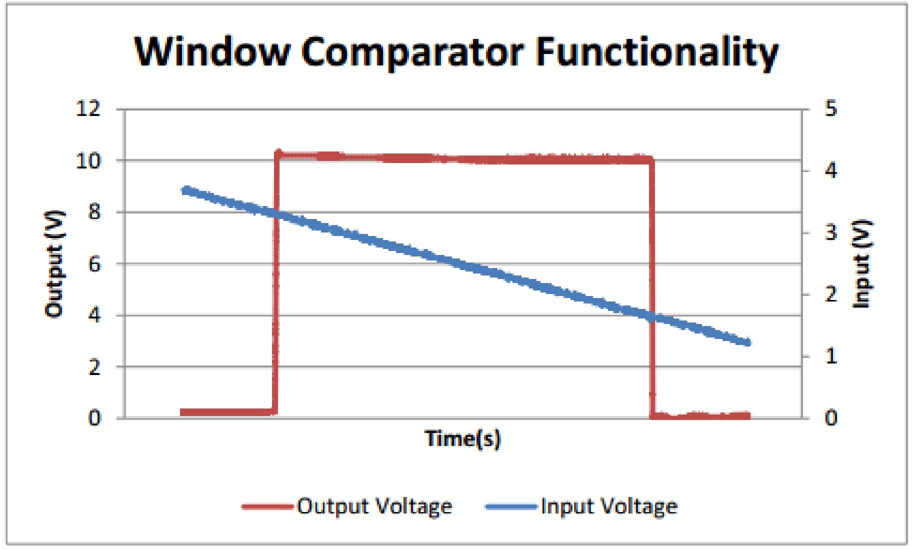
TIPD application resources for comparators

TIPD Reference Designs

- TIPD106 – AC coupled comparator, 2 kHz to 32 MHz
- TIPD130 – Dual Polarity High-Voltage Differential Input Interface for Low-Voltage Comparators
- TIPD141 – Comparator with Hysteresis
- TIPD178 – Window Comparator

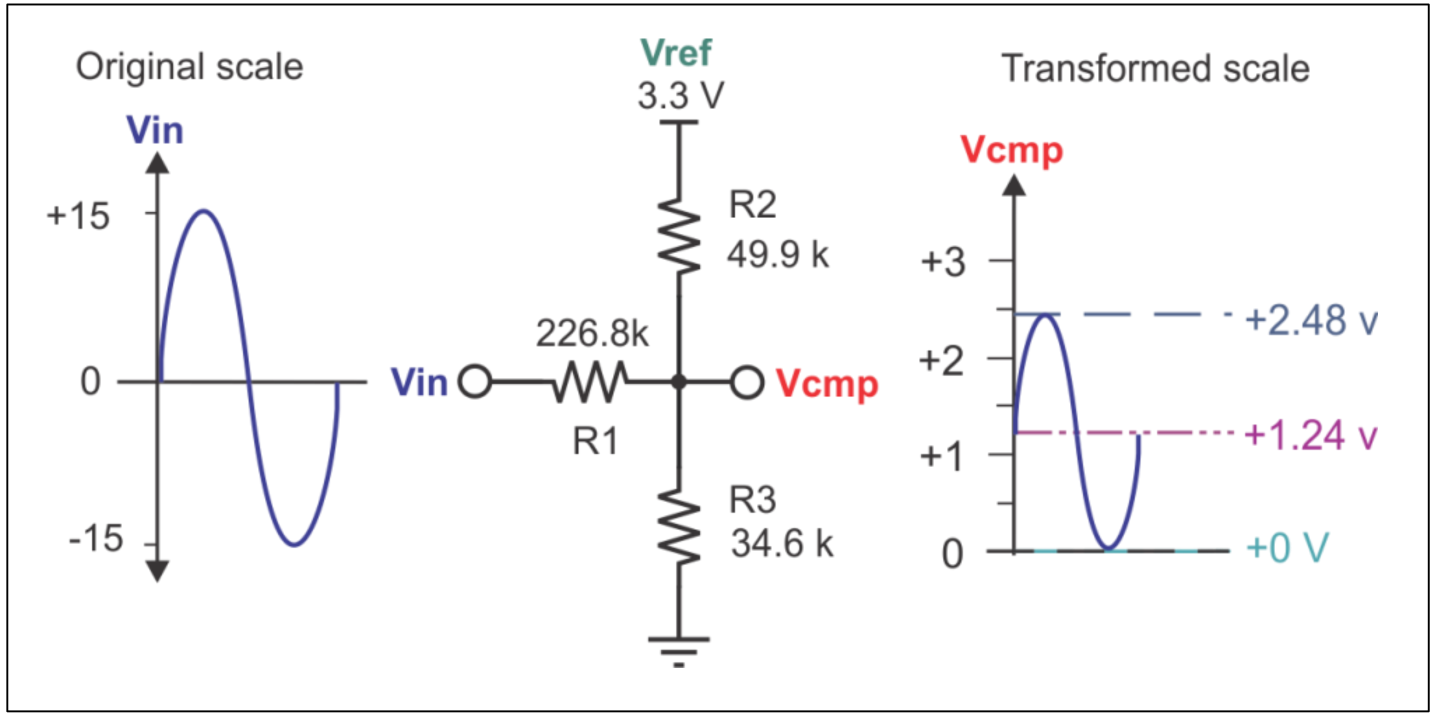
TIPD178

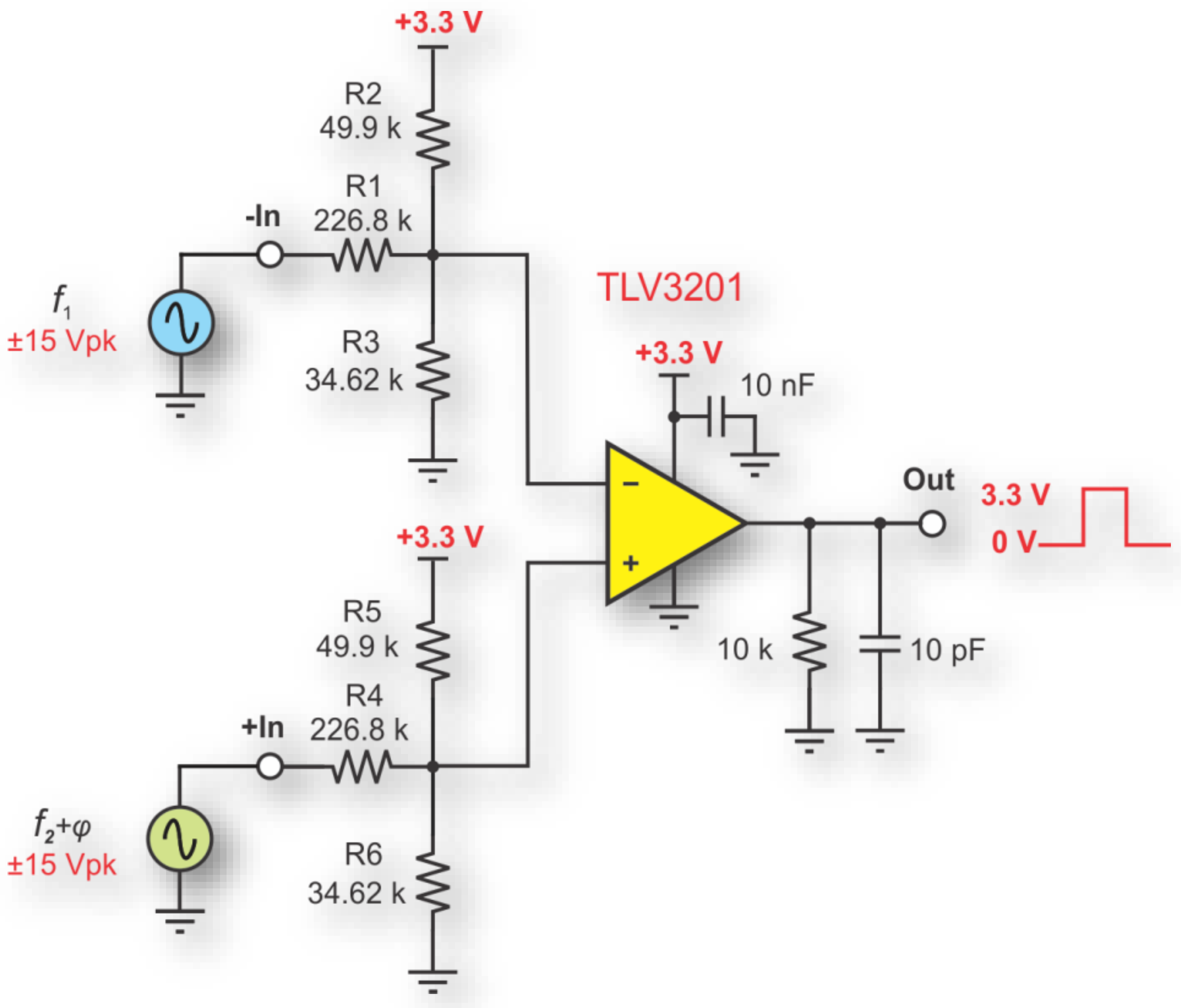




TIPD application resources for comparators

- TIPD130
- Interfaces inputs of a single-supply, LV comparator to accept HV bipolar (+/-) input levels
- Low-cost solution for HV ac white-goods and consumer electronics





Thank you