

The BJT switch: load lines and switching times

Where a switch lives on the output characteristics, how hard to drive it, and why it cannot let go instantly.

01 COLD OPEN 0–3 min

The switch that won't let go

You tell a transistor to switch **OFF**. For the next hundred nanoseconds it keeps conducting as if nothing happened. Then it collapses.



POP CULTURE

Wile E. Coyote runs off the cliff and hangs in mid-air, legs still spinning, until he looks down. A saturated transistor does the same thing. Today we measure that hang time, give it a name (**storage time**) and learn to shorten it.

THINK DEEPER

Guess before we start: for a transistor switch driven hard into saturation, which is slower, turning ON or turning OFF?

Turning off. Pushing the switch hard ON makes the ON edge fast, but it also packs the base with extra charge. That charge has to drain before the collector current can fall.

A STRONG ANSWER MENTIONS

- Turning OFF is usually slower.
- Saturation stores extra charge in the base.
- That charge must be removed before the collector current can fall.

Closer to home: an IPS keeping your fan running through load-shedding switches its power devices thousands of times a second. Every slow edge is wasted as heat.

02 CONCEPT 3–8 min

One line, two addresses:

the DC load line

KVL around the collector loop of a common-emitter switch gives the only (I_C, V_{CE}) pairs the **circuit** allows:

$$V_{CC} = I_C R_C + V_{CE} \implies I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

A straight line on the output characteristics. The **transistor** (through I_B) picks where on it you sit: the **Q-point**.

END	V_{CE}	I_C	SWITCH
Cutoff	V_{CC}	≈ 0	OFF (open)
Saturation	$\approx 0.2 \text{ V}$	$(V_{CC} - 0.2)/R_C$	ON (closed)



PRO TIP

Amplifiers live in the middle of the line; switches live only at its two ends. They should race through the middle as fast as possible, because that is where the transistor is both carrying current and dropping voltage, so it heats.

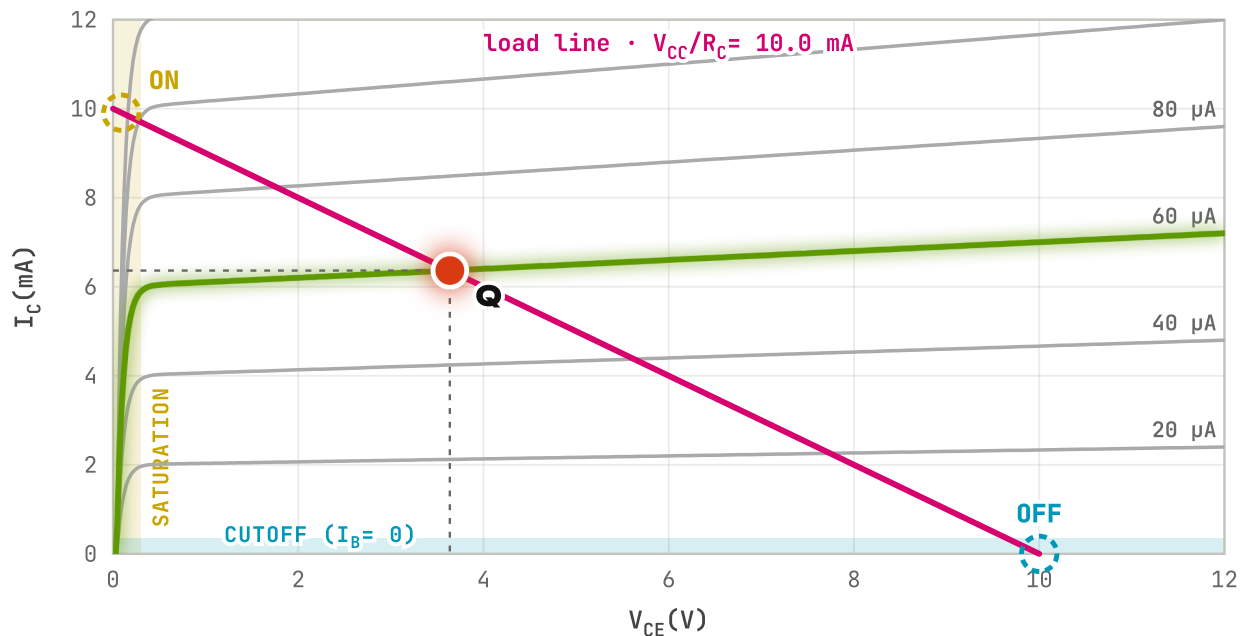


GOTCHA

The ideal intercept is V_{CC}/R_C at $V_{CE} = 0$. The real ON point stops just short of it, at $V_{CE(\text{sat})} \approx 0.2 \text{ V}$. Use $I_{C(\text{sat})} = (V_{CC} - 0.2)/R_C$ in calculations.

Slide the Q-point along the line

Load-line explorer Change I_B and the Q-point slides along the load line. A switch should only ever sit at the two ends.



Base current $I_B = 60 \mu\text{A}$

$V_{CC} = 10.0 \text{ V}$

$R_C = 1.0 \text{ k}\Omega$

Active · amplifier territory

V_{CE}
3.64 V

I_C
6.36 mA

$\beta \cdot I_B$
6.00 mA

$I_{B(\min)}$
98 μA

Overdrive
0.61×

$P = V_{CE} \cdot I_C$
23.1 mW

How hard to push:

saturation and overdrive

To reach the ON point, the base must supply at least what the load needs, divided by the **worst** β you might get:

$$I_B \geq I_{B(min)} = \frac{I_{C(sat)}}{\beta_{min}}$$

How far past that minimum you go is the **overdrive factor**:

$$ODF = \frac{I_B}{I_{B(min)}} = \frac{\beta_{min} I_B}{I_{C(sat)}}, \quad \beta_{forced} = \frac{I_{C(sat)}}{I_B} < \beta_{min}$$

Last class: $I_{C(sat)} = 4.8 \text{ mA}$, $\beta_{min} = 50 \Rightarrow I_{B(min)} = 96 \text{ }\mu\text{A}$; with $I_B = 0.43 \text{ mA}$, $ODF = 0.43/0.096 \approx 4.5$.



GOTCHA

In saturation, $I_C \neq \beta I_B$. $\beta \cdot I_B$ is what the transistor *could* carry; R_C decides what it *does* carry. The ratio I_C/I_B in saturation is the forced β , always below β .



PRO TIP

Why β_{min} ? One reel of BC547s can range from about 110 to 800 in β , and β drops at low temperature and at high current. Designs use 2–5× overdrive for margin. Why not 50×? Slide 14.

Your turn • 1: read the load line

1 EXAM CQ

$V_{CC} = 9\text{ V}$, $R_C = 1.5\text{ k}\Omega$, $\beta = \beta_{\min} = 100$, $V_{CE(\text{sat})} = 0.2\text{ V}$.

- Find the load-line end points and the ON point.
- For $I_B = 30\text{ }\mu\text{A}$ find the Q-point. Switch or amplifier?
- Find $I_{B(\min)}$ and the ODF at $I_B = 100\text{ }\mu\text{A}$.
- Compare the transistor's power at (b) and in saturation.

SOLUTION

- Load line $I_C = (9 - V_{CE})/1.5\text{ k}\Omega$: OFF point (9 V, 0), I_C -intercept 6 mA. ON point:

$$I_{C(\text{sat})} = \frac{9 - 0.2}{1.5\text{ k}\Omega} = 5.87\text{ mA} \quad \text{at } V_{CE} = 0.2\text{ V}$$

- With $I_B = 30\text{ }\mu\text{A}$: $\beta I_B = 3\text{ mA} < 5.87\text{ mA}$, so it is **active**:

$$V_{CE} = 9 - (3\text{ mA})(1.5\text{ k}\Omega) = 4.5\text{ V}$$

- Minimum base current and the overdrive at 100 μA :

$$I_{B(\min)} = \frac{5.87\text{ mA}}{100} = 58.7\text{ }\mu\text{A}, \quad \text{ODF} = \frac{100 \times 0.1}{5.87} = 1.70$$

- Transistor power:

$$P_{(4.5\text{ V}, 3\text{ mA})} = 13.5\text{ mW}, \quad P_{ON} = 0.2 \times 5.87 = 1.17\text{ mW}$$

ANSWER

ON (0.2 V, 5.87 mA). At 30 μA , Q = (4.5 V, 3 mA): active, not a switch. $I_{B(\min)} = 58.7\text{ }\mu\text{A}$, ODF 1.70. Mid-line dissipates about 11.5× more.

Worked example: an ESP32 drives a 12 V relay

GIVEN

A rooftop water-pump controller in a Dhaka apartment: an ESP32 pin ($V_{OH} = 3.3\text{ V}$) switches a 12 V relay coil ($R_{\text{coil}} = 240\text{ }\Omega$) through an NPN with $\beta_{\min} = 50$. $V_{BE(\text{sat})} = 0.8\text{ V}$, $V_{CE(\text{sat})} = 0.2\text{ V}$.

FIND

R_B (standard E12 value) for at least 2× overdrive, the resulting ODF, pin current and ON-state dissipation.

Method: saturated-switch design (Boylestad, transistor switching networks; Millman & Taub, transistor switch)

SOLUTION

1. Saturated collector current is fixed by the coil, not by β :

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_{coil}} = \frac{12 - 0.2}{240 \, \Omega} = 49.2 \, \text{mA}$$

2. Minimum base current (worst case β_{min}), then 2× overdrive:

$$I_{B(min)} = 49.2/50 = 0.983 \, \text{mA}, \quad I_B = 2 \times 0.983 = 1.97 \, \text{mA}$$

3. Base resistor from the 3.3 V pin through the saturated base-emitter junction:

$$R_B = \frac{V_{OH} - V_{BE(sat)}}{I_B} = \frac{3.3 - 0.8}{1.97 \, \text{mA}} = 1.27 \, \text{k}\Omega$$

4. Standard E12 value, rounded **down** so the drive goes up:

$$R_B = 1.2 \, \text{k}\Omega \Rightarrow I_B = 2.5/1.2 = 2.08 \, \text{mA}, \quad \text{ODF} = 2.08/0.983 = 2.12$$

5. Pin current 2.08 mA: well inside a GPIO budget. ON-state dissipation:

$$P_Q = V_{CE(sat)} I_{C(sat)} = 0.2 \times 49.2 \, \text{mA} = 9.8 \, \text{mW}$$

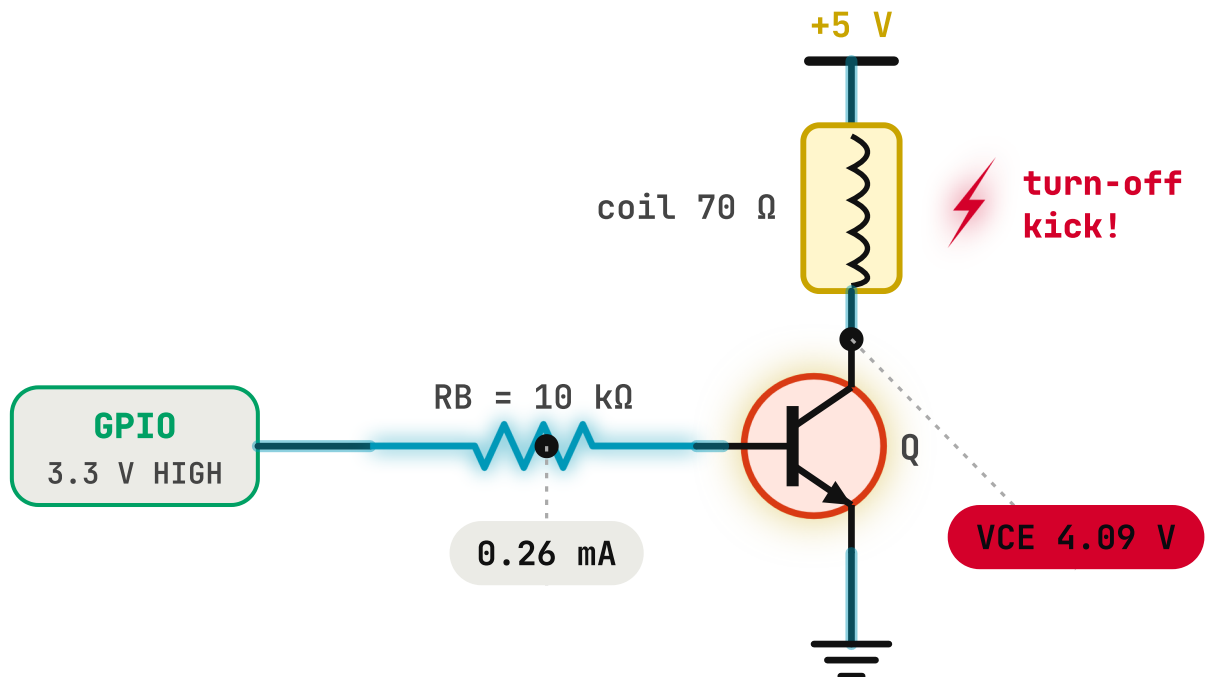
The coil is an inductor: add a flyback diode, cathode to +12 V (slide 17).

ANSWER

$R_B = 1.2 \, \text{k}\Omega \Rightarrow I_B = 2.08 \, \text{mA}$, $\text{ODF} = 2.12$, $P_Q \approx 9.8 \, \text{mW}$. Add a flyback diode across the coil.

Design lab: one pin, three loads

Base-resistor designer Pick a board and a load, then find an R_B that saturates the transistor without cooking the pin.



$R_B = 10 \text{ k}\Omega$ (E12)

$\beta_{\min} = 50$

☐ Flyback diode across the coil

$I_{C(\text{sat})}$ needed

68.6 mA

I_B from pin

0.26 mA

Overdrive

0.19×

I_C actual

13.0 mA

P_Q

53 mW

2× design

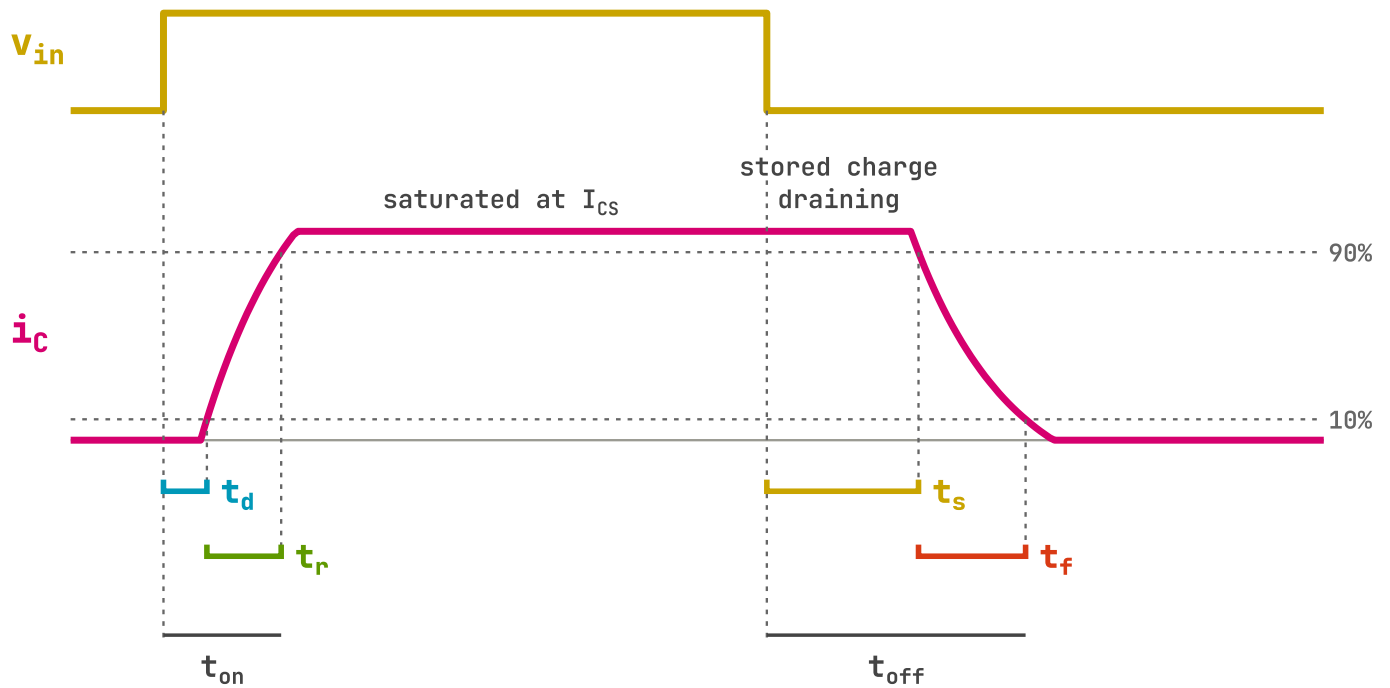
820 Ω

Not saturated. $\beta_{\min} I_B = 13.0 \text{ mA} < 68.6 \text{ mA}$. $V_{CE} = 4.09 \text{ V}$: the load is starved and the transistor heats.

Four times that steal your speed

- **t_d delay:** input edge $\rightarrow i_C$ reaches 10 %. Charging the junction capacitances up to cut-in.
- **t_r rise:** 10 % $\rightarrow$ 90 % of I_{CS} . Building up base charge through the active region.
- **t_s storage:** input falls $\rightarrow i_C$ drops to 90 %. Removing the excess charge stored in saturation.
- **t_f fall:** 90 % $\rightarrow$ 10 %. Back through the active region.

$$t_{on} = t_d + t_r \quad t_{off} = t_s + t_f$$



WHY SATURATION STORES CHARGE

In saturation **both** junctions are forward-biased, so the collector junction injects too and the base fills with minority carriers beyond what I_{CS} needs. That excess Q_S must drain before the collector junction can reverse-bias; until then i_C stays stuck at I_{CS} .

The switching oscilloscope

Switching oscilloscope Watch the beam: i_C lags the input on both edges. Push the overdrive up and see which bracket grows.



Turn-on drive $I_{B1} = 0.40$ mA · overdrive **2.0×**

Reverse drive $I_{B2} = 0.20$ mA

Speed-up capacitor

t_d
14 ns

t_r
14 ns

t_s
21 ns

t_f
14 ns

t_{on}
27 ns

t_{off}
35 ns

f_{max}
16.0 MHz

$\beta = 50$, $I_{CS} = 10$ mA, $\tau = 25$ ns, $\tau_s = 50$ ns · leaves saturation after 20 ns (t_s formula: 20 ns); readout t_s is to the 90 % point

Charge control: formulas you can use

While active, i_C relaxes toward βi_B with time constant τ . From 0 toward βI_{B1} :

$$i_C(t) = \beta I_{B1} (1 - e^{-t/\tau}) \Rightarrow t_r = \tau \ln \frac{\beta I_{B1} - 0.1 I_{CS}}{\beta I_{B1} - 0.9 I_{CS}}$$

Excess charge drains with time constant τ_s , pulled by the reverse current I_{B2} :

$$t_s = \tau_s \ln \frac{I_{B1} + I_{B2}}{I_{CS}/\beta + I_{B2}}$$

Same idea for the fall, now heading toward $-\beta I_{B2}$:

$$t_f = \tau \ln \frac{0.9 I_{CS} + \beta I_{B2}}{0.1 I_{CS} + \beta I_{B2}}$$

THE TRADE-OFF

More I_{B1} (overdrive): $\beta I_{B1} \gg I_{CS}$, so t_r shrinks. But I_{B1} sits in the numerator of t_s : storage grows.

More I_{B2} (reverse drive): shrinks t_s and t_f . Costs a negative supply or a clever circuit.



GOTCHA

If $\beta I_{B1} \leq 0.9 I_{CS}$ the log's argument goes negative: i_C never reaches 90 %. Check $\beta I_{B1} > I_{CS}$ (saturation) before using any of these.

11 WORKED EXAMPLE 48–53 min

Worked example: rise, storage and fall

GIVEN

$\beta = 50$, $\tau = 20$ ns, $\tau_s = 40$ ns, $I_{CS} = 10$ mA. Turn-on drive $I_{B1} = 0.5$ mA; turn-off reverse drive $I_{B2} = 0.25$ mA.

FIND

t_r , t_s and t_f . Then: what happens if you double I_{B1} ?

Method: charge-control model (Taub & Schilling; Millman & Taub, switching times)

SOLUTION

1. Saturation check:

$$\beta I_{B1} = 25 \text{ mA} > I_{CS} = 10 \text{ mA} \Rightarrow \text{ODF} = 2.5$$

2. Rise time:

$$t_r = 20 \ln \frac{25 - 1}{25 - 9} = 20 \ln 1.5 = 8.11 \text{ ns}$$

3. Storage time, with $I_{CS}/\beta = 10/50 = 0.2$ mA:

$$t_s = 40 \ln \frac{0.5 + 0.25}{0.2 + 0.25} = 40 \ln 1.667 = 20.4 \text{ ns}$$

4. Fall time (i_C heads toward $-\beta I_{B2} = -12.5$ mA):

$$t_f = 20 \ln (21.5/13.5) = 9.31 \text{ ns}$$

5. Double the overdrive ($I_{B1} = 1$ mA):

$$t_r = 20 \ln \frac{49}{41} = 3.57 \text{ ns } (\downarrow), \quad t_s = 40 \ln \frac{1.25}{0.45} = 40.9 \text{ ns } (\uparrow)$$

Rise 4.5 ns faster, storage 20 ns slower. (With $I_{B2} = 0$ instead: $t_s = 40 \ln 2.5 = 36.7$ ns.)

ANSWER

$t_r = 8.11 \text{ ns}$, $t_s = 20.4 \text{ ns}$, $t_f = 9.31 \text{ ns}$. Doubling the overdrive cuts t_r to 3.57 ns but doubles t_s to 40.9 ns.

12 YOUR TURN 53–58 min

Your turn • 2: how much reverse drive?

2

EXAM CQ

$\beta = 40$, $\tau = 15 \text{ ns}$, $\tau_s = 60 \text{ ns}$, $I_{CS} = 20 \text{ mA}$, $I_{B1} = 1.0 \text{ mA}$, $I_{B2} = 0.5 \text{ mA}$.

- Confirm saturation and find the ODF.
- Find t_r and t_s .
- What I_{B2} would cut t_s to 10 ns?

SOLUTION

- Saturation check:

$$\beta I_{B1} = 40 \times 1.0 = 40 \text{ mA} > 20 \text{ mA}, \quad \text{ODF} = 2$$

- Rise time:

$$t_r = 15 \ln \frac{40 - 2}{40 - 18} = 15 \ln \frac{38}{22} = 15 \times 0.5465 = 8.20 \text{ ns}$$

- $I_{CS}/\beta = 20/40 = 0.5 \text{ mA}$. Storage time:

$$t_s = 60 \ln \frac{1.0 + 0.5}{0.5 + 0.5} = 60 \ln 1.5 = 24.3 \text{ ns}$$

- For $t_s = 10 \text{ ns}$: $(1 + I_{B2})/(0.5 + I_{B2}) = e^{10/60} = 1.1814$, so $1 + I_{B2} = 0.5907 + 1.1814 I_{B2}$:

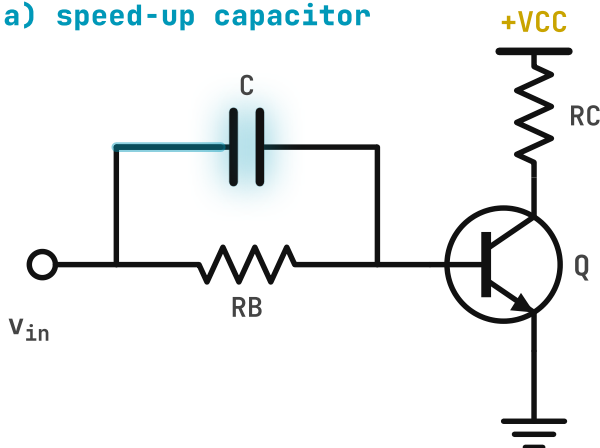
$$I_{B2} = \frac{1 - 0.5907}{1.1814 - 1} = \frac{0.4093}{0.1814} = 2.26 \text{ mA}$$

ANSWER

$t_r = 8.20 \text{ ns}$, $t_s = 24.3 \text{ ns}$. $t_s = 10 \text{ ns}$ needs $I_{B2} \approx 2.26 \text{ mA}$: over twice the forward drive. Expensive; next slide has cheaper fixes.

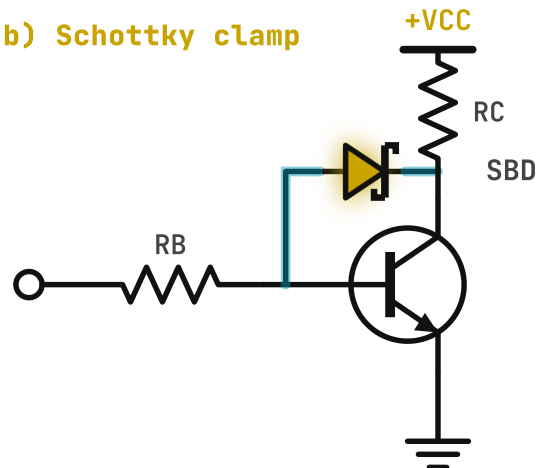
Two cheap fixes for storage time

(a) speed-up capacitor



edges: spike through C · DC: R_B only

(b) Schottky clamp



excess $I_B \rightarrow$ collector, not the base

(a) At each edge C is momentarily a short: a big current spike pours charge in on the rising edge and yanks it out on the falling edge. In steady state C is an open circuit, so R_B alone sets a modest I_{B1} and little charge is stored. Both edges get faster. Rule of thumb: $R_B C \approx \tau$.

(b) A Schottky diode ($V_F \approx 0.3\text{--}0.4\text{ V}$) from base to collector turns on before the collector junction ($\approx 0.5\text{ V}$) can. Extra base current is diverted into the collector, so the transistor sits at the edge of saturation instead of deep in it.

$$V_{CE} \approx V_{BE} - V_{SBD} \approx 0.3\text{--}0.4\text{ V}$$

No deep saturation, so almost no excess charge: $t_s \approx 0$.



PRO TIP

This is the “S” in **74S** and **74LS** TTL, where every transistor that could saturate carries a built-in Schottky clamp. Week 3.

Critical thinking • two arguments

THINK DEEPER

“More base current is always safer. Let's drive the base with 50× overdrive.” Argue against it.

$V_{CE(sat)}$ barely drops after about 3–5×, so the ON state does not improve. The stored charge keeps rising, so turn-off slows (in Worked 2, 50× would give $t_s \approx 40 \ln(10.25/0.45) \approx 125$ ns). And the driving pin pays for every extra milliamp.

A STRONG ANSWER MENTIONS

- t_s grows with $\ln(I_{B1})$: turn-off gets much slower.
- Wasted pin current and base power; the driver may be overloaded.
- Gain beyond about 5× buys no extra margin: I_C is already fixed by R_C .

THINK DEEPER

A Schottky diode is still a diode. Why doesn't the clamp diode itself suffer storage time?

A Schottky junction conducts by majority carriers (electrons in n-type silicon) crossing into the metal. It injects essentially no minority carriers, so nothing is stored. The clamp adds speed without adding its own storage problem.

A STRONG ANSWER MENTIONS

- Metal–semiconductor junction: current is carried by majority carriers.
- No minority-carrier injection, so no stored charge to remove.
- That is also why it can switch in picoseconds and has a lower V_F .

Your turn • 3: the dim LED

3 **TRAP**

An Arduino (5 V pin) drives a red LED ($V_F = 2.0$ V) with a $150\ \Omega$ series resistor from +5 V through an NPN ($\beta_{\min} = 100$). A student picks $R_B = 100\ \text{k}\Omega$ "because the base only needs microamps".

Is the LED fully on? Find I_C , V_{CE} and the transistor's power. Then fix R_B .

SOLUTION

1. What the LED branch needs if the switch saturates:

$$I_{C(sat)} = \frac{5 - 2.0 - 0.2}{150\ \Omega} = 18.7\ \text{mA}$$

2. Base current with $R_B = 100\ \text{k}\Omega$ (active, so $V_{BE} = 0.7$ V):

$$I_B = \frac{5 - 0.7}{100\ \text{k}\Omega} = 43\ \mu\text{A} \Rightarrow \beta I_B = 4.3\ \text{mA} < 18.7\ \text{mA}$$

3. Not saturated: $I_C = 4.3\ \text{mA}$ (dim, and it changes with every transistor's β).

$$V_{CE} = 5 - 2.0 - (4.3)(0.15) = 2.36\ \text{V}, \quad P_Q = 2.36 \times 4.3 = 10.1\ \text{mW}$$

4. Fix for 2× overdrive ($V_{BE(sat)} = 0.8$ V):

$$I_B = \frac{2 \times 18.7}{100} = 0.373\ \text{mA}, \quad R_B = \frac{5 - 0.8}{0.373} = 11.3\ \text{k}\Omega \rightarrow 10\ \text{k}\Omega$$

ANSWER

The LED runs at 4.3 mA instead of 18.7 mA and the transistor dissipates 10.1 mW (vs 3.7 mW saturated). Use $R_B = 10\ \text{k}\Omega$: $I_B = 0.42\ \text{mA}$, ODF = 2.25.

Where the switch gets hot

ON: tiny voltage, full current. **OFF:** full voltage, no current. Both are cheap:

$$P_{ON} \approx V_{CE(sat)} I_C \cdot D \quad (D = \text{duty}), \quad P_{OFF} \approx 0$$

Every edge passes through the middle of the load line where V and I are both large. For a resistive load with linear edges each transition costs $V_{CC}I_C t/6$:

$$P_{sw} \approx \frac{1}{6} V_{CC} I_C (t_r + t_f) f$$

EXAMPLE: 12 V LED STRIP, 0.5 A, PWM AT 50 % DUTY

$V_{CE(sat)} = 0.2 \text{ V}$, $t_r + t_f = 1 \mu\text{s}$ (a slow power BJT).

$P_{ON} = 0.2 \times 0.5 \times 0.5 = \mathbf{50 \text{ mW}}$

At 20 kHz: $P_{sw} = \frac{1}{6} \times 12 \times 0.5 \times 10^{-6} \times 20\,000 = \mathbf{20 \text{ mW}}$

At 200 kHz: **200 mW**. Switching loss now dominates.



PRO TIP

Faster edges = cooler switch. That is why t_r and t_f matter even in power electronics, not just in logic.

17 REAL WORLD 70–73 min

The valve that killed its transistor



BME CORNER

A dialysis machine or infusion pump opens and closes a 12 V solenoid pinch valve on the tubing (coil 24Ω , $L \approx 50 \text{ mH}$, $I = 0.49 \text{ A}$). A transistor switches it. On the bench it works perfectly. **After about a week in the ward, the transistor is dead.**

At turn-off the coil insists on keeping its current: $v = L \, di/dt$. Interrupting 0.5 A in $1 \mu\text{s}$ asks for $0.05 \times 0.5/10^{-6} = \mathbf{25 \text{ kV}}$. The transistor avalanches at its breakdown voltage instead and absorbs the coil's energy:

$$E = \frac{1}{2}LI^2 = \frac{1}{2}(0.05)(0.5)^2 = 6.25 \text{ mJ per turn-off}$$

THINK DEEPER

Why does it survive the bench test but die after a week? And what is the fix?

A few clicks on the bench is a few avalanche events. In service, each cycle damages the junction a little more until it fails short, and a stuck-open valve on a patient line is a safety event.

A **flyback diode** gives the coil current a harmless loop and clamps V_{CE} at $V_{CC} + 0.7 \text{ V}$.

A STRONG ANSWER MENTIONS

- Each turn-off dumps about 6 mJ into a tiny spot of silicon: avalanche stress accumulates.
- One valve cycle per second for a week is 604 800 hits.
- Fix: flyback diode across the coil (cathode to +12 V), clamping V_{CE} at about 12.7 V.
- Trade-off: the valve now releases slower (current decays with $L/R \approx 2 \text{ ms}$); a Zener in series speeds it up.

18 POP QUIZ 73–78 min

Pop quiz

1. On the DC load line, where does a BJT switch sit when it is ON?

- A. $(V_{CC}, 0)$
- B. $(V_{CE(sat)}, I_{C(sat)})$, the top-left end of the line ✓**
- C. The middle of the line
- D. $(0, \beta I_B)$

ON = saturation: $V_{CE} \approx 0.2 \text{ V}$ and $I_C = (V_{CC} - 0.2)/R_C$. $(V_{CC}, 0)$ is OFF; the middle is the amplifier's Q-point.

2. $\beta_{min} = 40$, $I_{C(sat)} = 20 \text{ mA}$, $I_B = 1 \text{ mA}$. The overdrive factor is:

- A. 0.5
- B. 1
- C. 2 ✓**
- D. 40

ODF = $\beta_{min} I_B / I_{C(sat)} = 40 \times 1/20 = 2$. The base gets twice the minimum current it needs.

3. You double I_{B1} and keep I_{B2} the same. Then:

- A. t_r and t_s both fall
- B. t_r falls, t_s rises ✓**
- C. t_r rises, t_s falls
- D. Nothing changes once it is saturated

More drive charges the base faster (shorter rise) but stores more excess charge that must be removed at turn-off (longer storage).

4. Why does a Schottky-clamped transistor turn off faster?

- A. The Schottky diode raises β
- B. The diode keeps the collector-base junction from forward-biasing, so almost no excess charge is stored ✓**
- C. It raises V_{CC}
- D. It replaces the base resistor

Excess base current is diverted through the Schottky diode into the collector. No deep saturation, so $t_s \approx 0$. The Schottky diode itself is a majority-carrier device and stores almost nothing.

5. A flyback diode across a relay coil is connected:

- A. Anode to $+V_{CC}$, forward-biased while the relay is on
- B. Cathode to $+V_{CC}$, reverse-biased while the relay is on ✓**
- C. In series with the coil
- D. From base to emitter

Normally it is reverse-biased and idle. At turn-off the coil reverses its voltage to keep current flowing; the diode gives that current a loop and clamps V_{CE} at about $V_{CC} + 0.7 \text{ V}$.

Three things to remember

A switch lives at two ends of the load line: OFF (V_{CC} , 0) and ON (0.2 V, $I_{C(sat)}$). Saturate with $I_B \geq I_{C(sat)}/\beta_{min}$, times a 2–5× overdrive.

02

$t_{on} = t_d + t_r$, $t_{off} = t_s + t_f$. Overdrive speeds the rise but stores charge and lengthens t_s ; reverse drive drains it.

03

Fixes: speed-up capacitor, Schottky clamp (74LS, Week 3), or a device with no stored charge: the MOSFET, next class. Always put a diode across a coil.

HW

BEFORE NEXT CLASS

$\beta = 60$, $\tau = 25$ ns, $\tau_s = 50$ ns, $I_{CS} = 12$ mA, $I_{B1} = 0.6$ mA, $I_{B2} = 0.3$ mA, $t_d = 5$ ns. Find t_r , t_s , t_f , t_{on} , t_{off} and the rough maximum switching frequency $1/(t_{on} + t_{off})$.

SOLUTION

1. $\beta I_{B1} = 60 \times 0.6 = 36$ mA > 12 mA (ODF 3).

$$t_r = 25 \ln \frac{36 - 1.2}{36 - 10.8} = 25 \ln 1.381 = 8.07 \text{ ns}$$

2. $I_{CS}/\beta = 0.2$ mA; $\beta I_{B2} = 18$ mA.

$$t_s = 50 \ln \frac{0.9}{0.5} = 29.4 \text{ ns}, \quad t_f = 25 \ln \frac{10.8 + 18}{1.2 + 18} = 25 \ln 1.5 = 10.1 \text{ ns}$$

3. Totals:

$$t_{on} = 5 + 8.07 = 13.1 \text{ ns}, \quad t_{off} = 29.4 + 10.1 = 39.5 \text{ ns}$$

4. Maximum switching frequency:

$$f_{max} \approx \frac{1}{t_{on} + t_{off}} = \frac{1}{52.6 \text{ ns}} = 19 \text{ MHz}$$

ANSWER

$t_r = 8.07$, $t_s = 29.4$, $t_f = 10.1$ ns; $t_{on} = 13.1$, $t_{off} = 39.5$ ns; $f_{max} \approx 19$ MHz (a ceiling, not a design target).

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