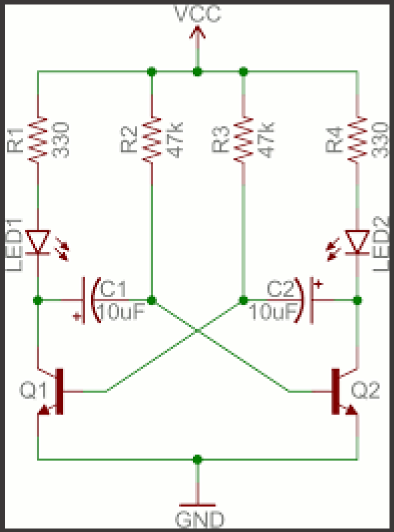
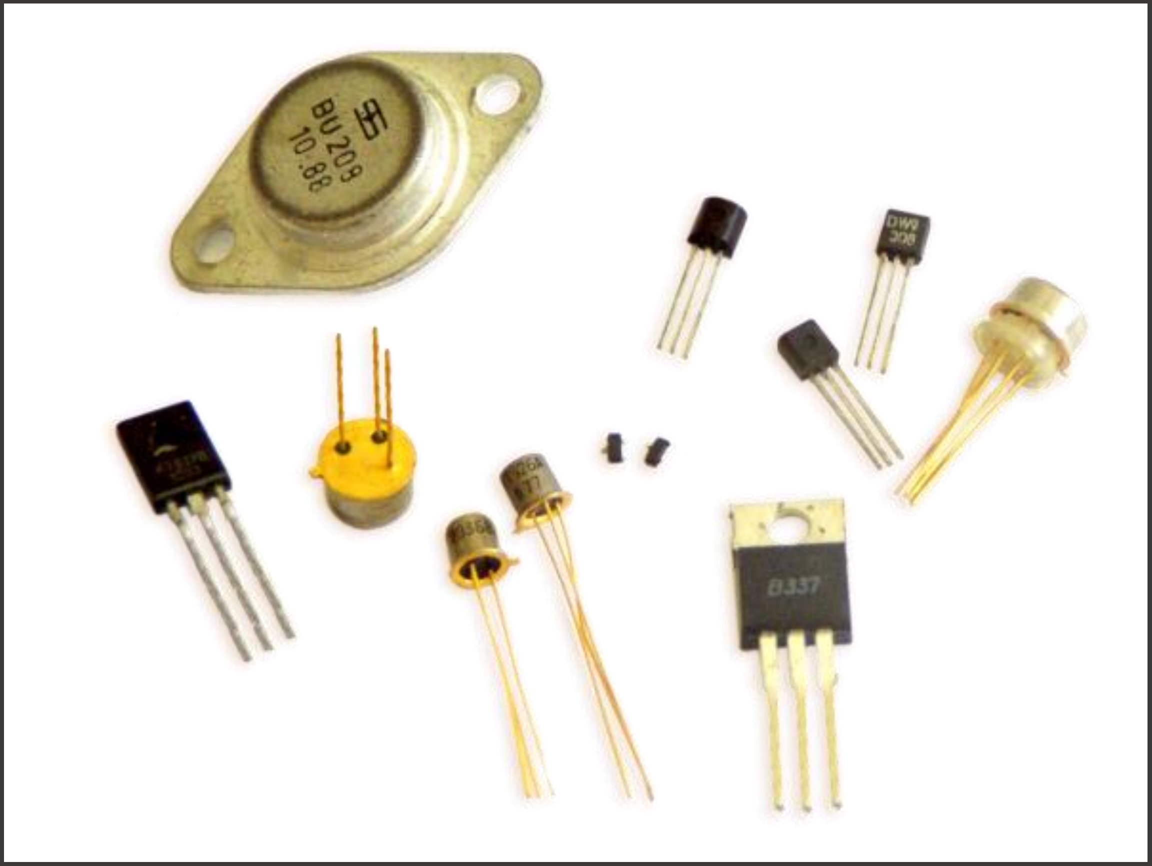
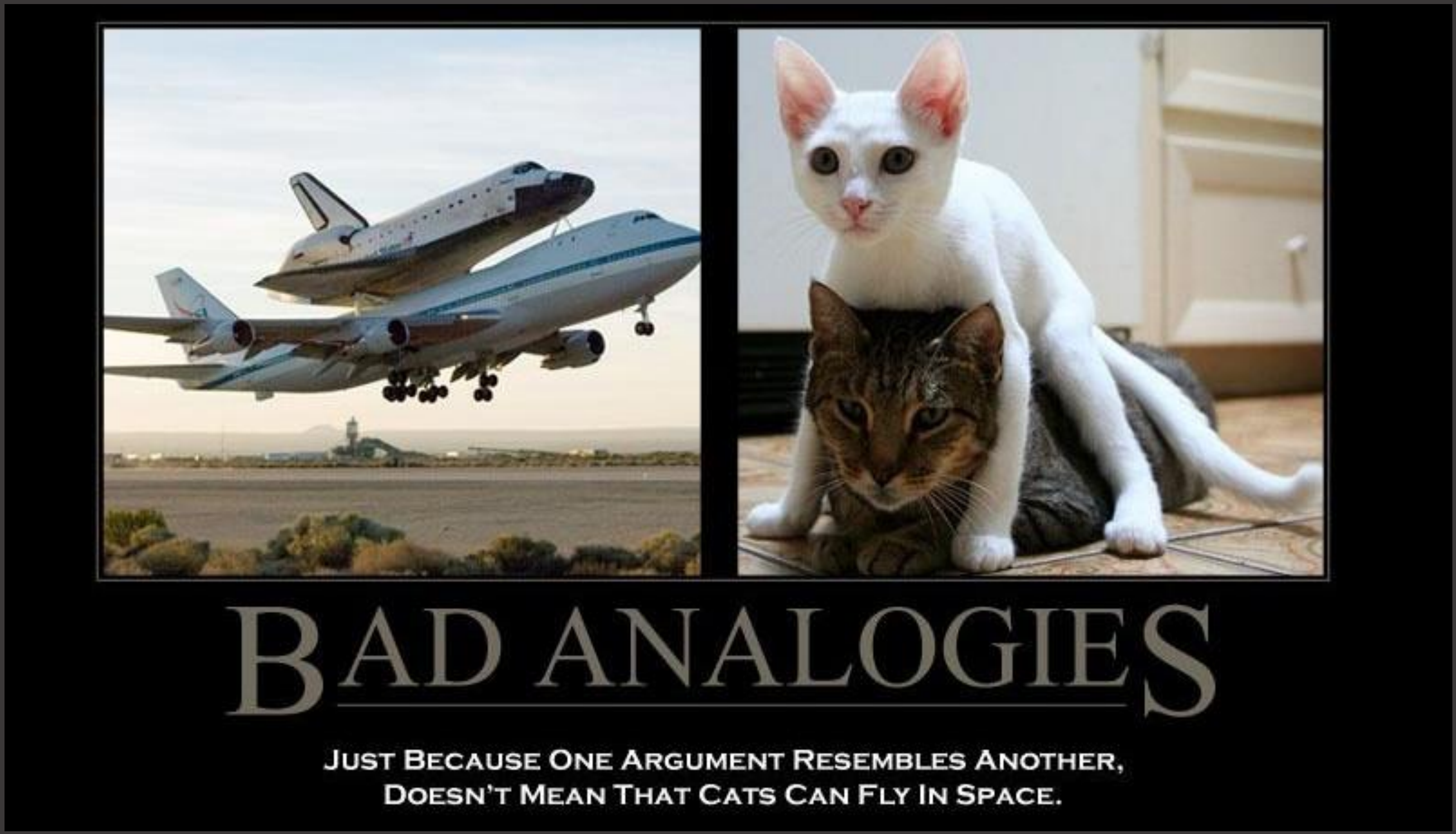
# Using, Choosing and Abusing Transistors

Ray Crampton, Feb 2019

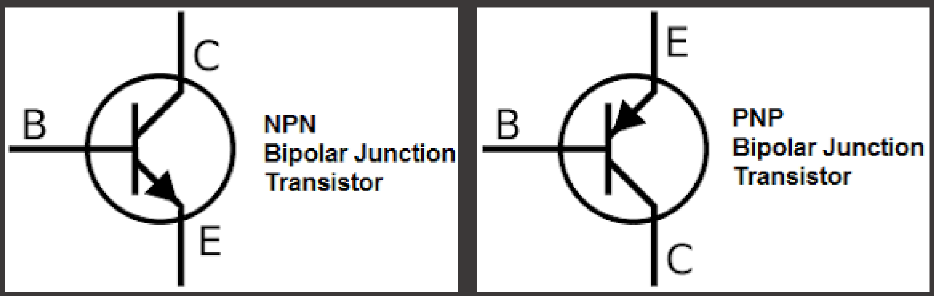


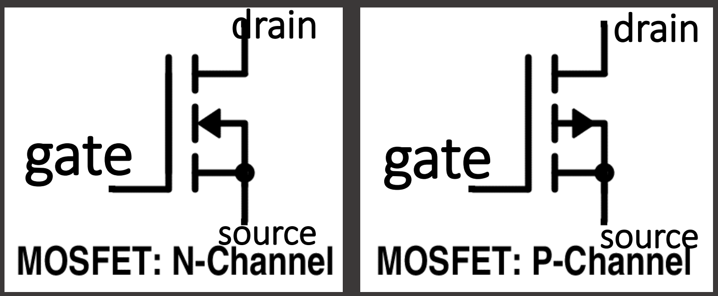




**Rules of thumb, assumptions and mixed-quality analogies to come!**



# Common Types of Transistors



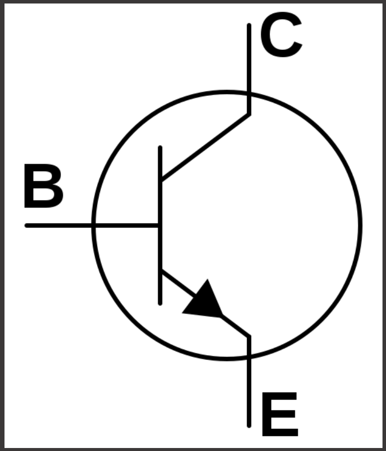




BJT – Base/Emitter/Collector

FETs – Gate/Drain/Source

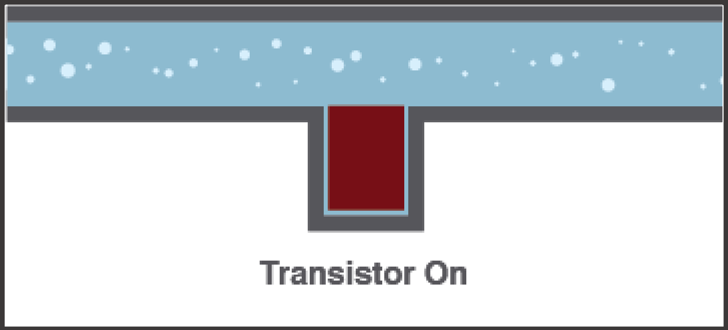
“IN”

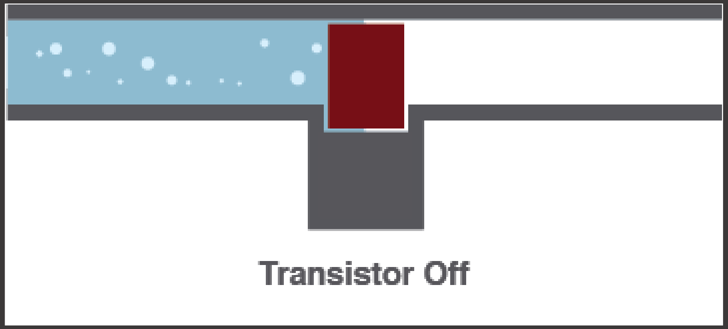
Control Terminal

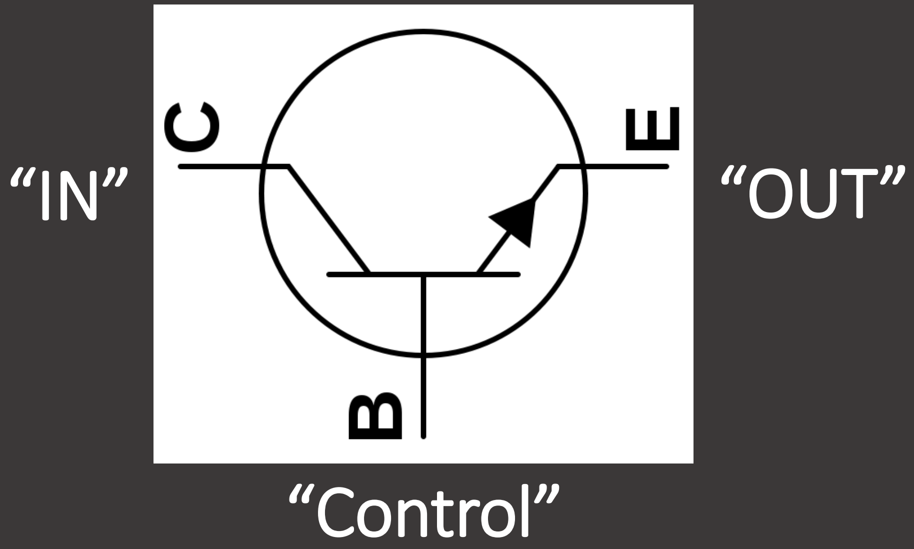


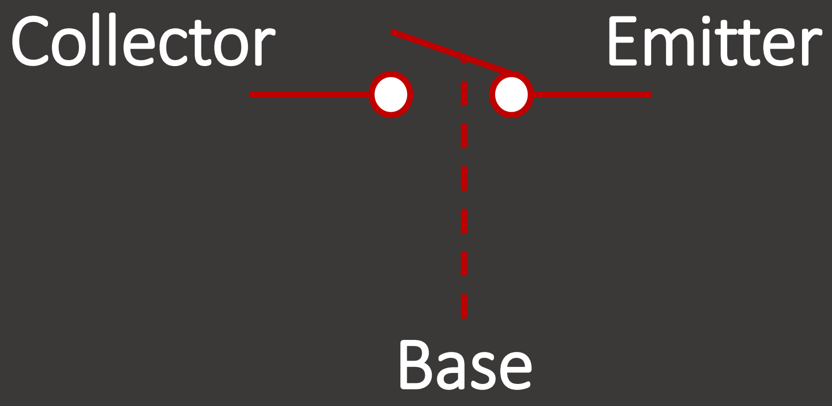

“OUT”

# Transistor as a Switch
## Plumbing Analogy

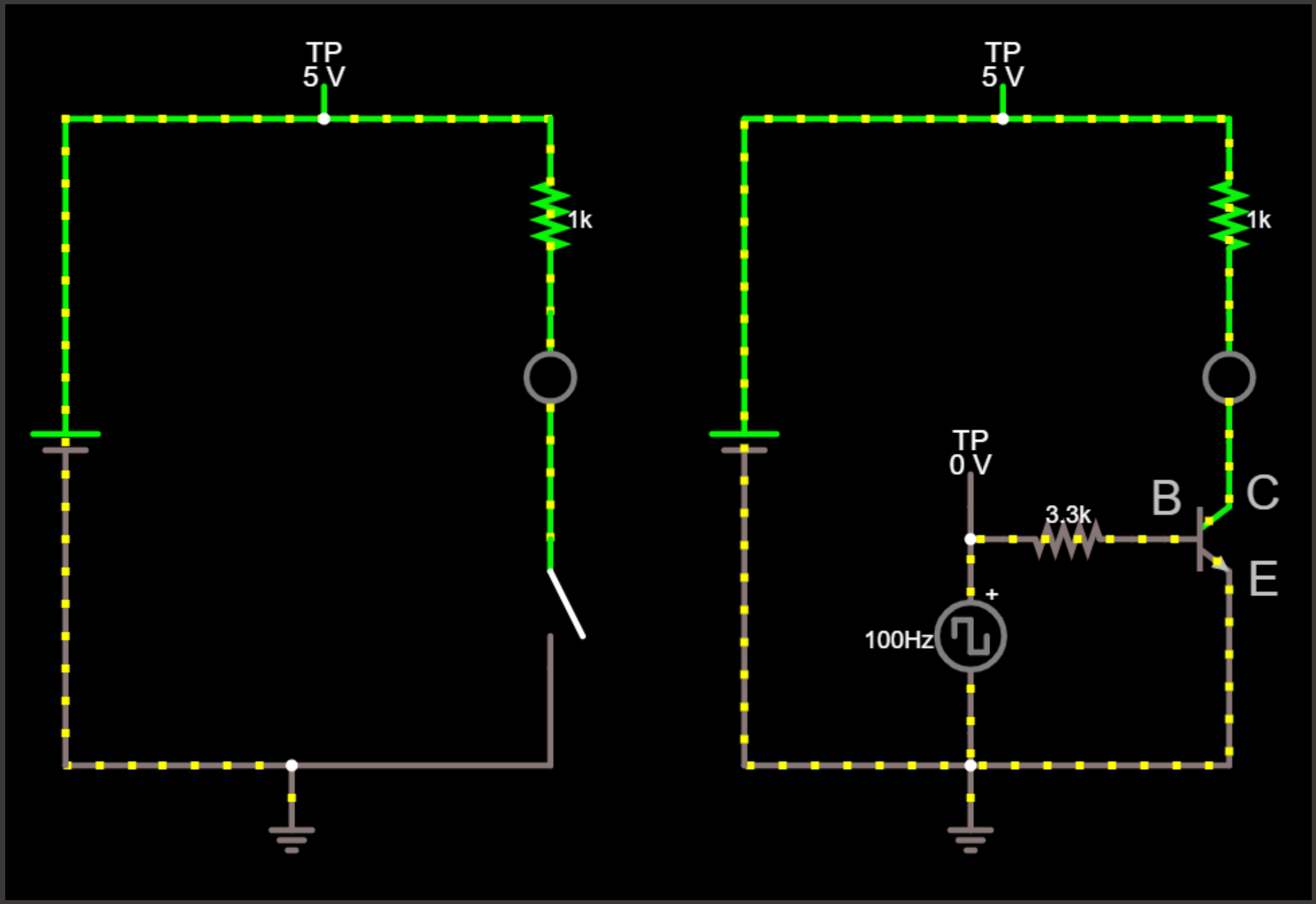


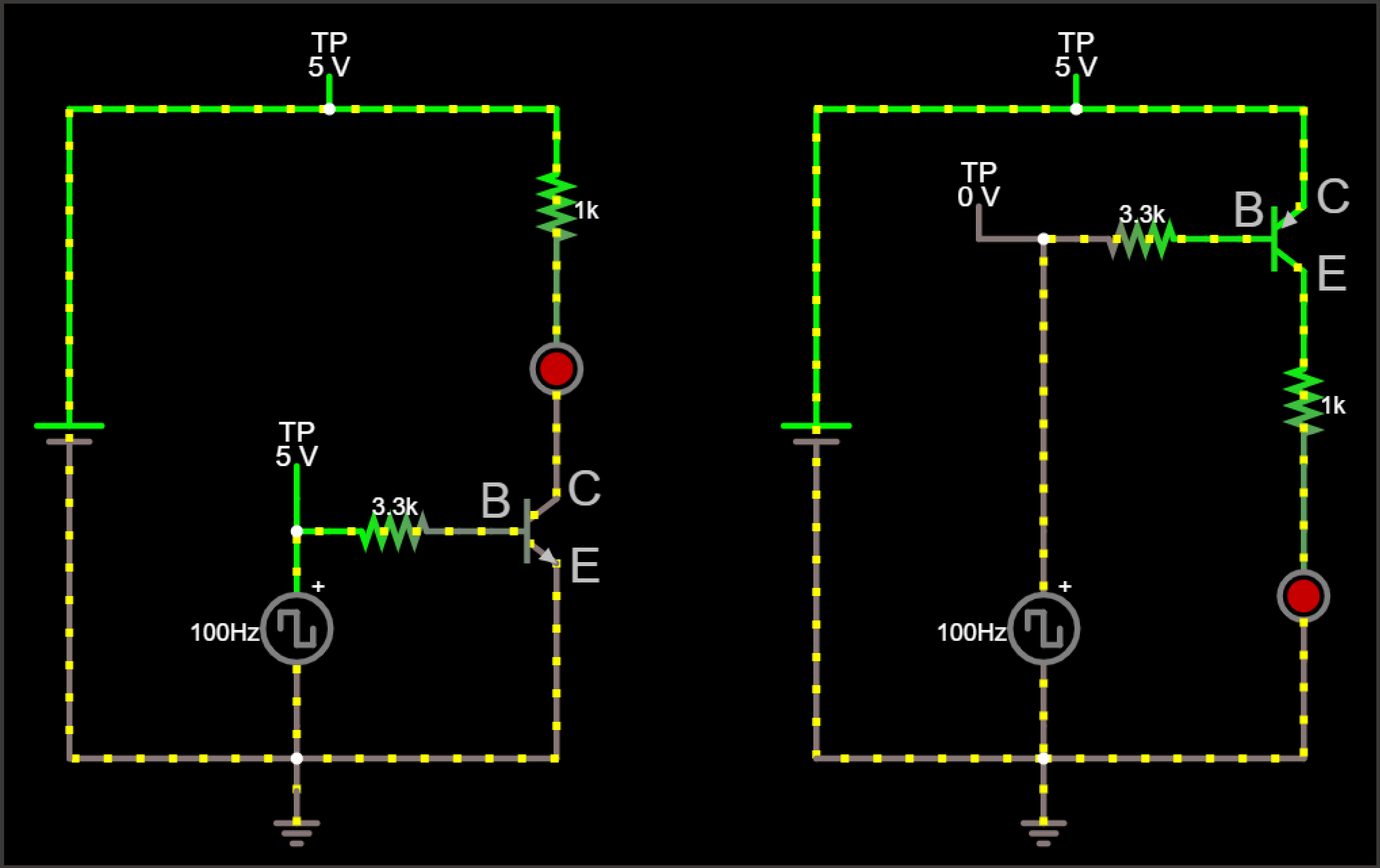



# Falstad.com simulation of NPN Switch




http://falstad.com/circuit/circuitjs.html?cct=$+1+0.000005+3.9121283998153213+59+5+43%0Aw+80+80+192+80+0%0Aw+64+416+64+400+0%0Ag+64+416+64+432+0%0A368+80+80+80+48+0+0%0Aw+-48+400+64+400+0%0Aw+-48+80+80+80+0%0Av+-48+400+-48+80+0+0+40+5+0+0+0.5%0Aw+192+240+192+288+0%0Aw+192+160+192+176+0%0Ar+192+96+192+160+0+1000%0A162+192+176+192+240+2+default-led+1+0+0+0.01%0Aw+192+352+192+400+0%0Aw+192+400+64+400+0%0As+192+288+192+352+0+1+true%0Aw+192+80+192+96+0%0Aw+528+96+528+80+0%0Aw+416+80+528+80+0%0Aw+400+384+400+400+0%0Aw+400+272+400+288+0%0A368+400+272+400+240+0+0%0Aw+400+416+400+400+0%0Ag+400+416+400+432+0%0A368+416+80+416+48+0+0%0Aw+288+400+400+400+0%0Aw+288+80+416+80+0%0Av+288+400+288+80+0+0+40+5+0+0+0.5%0Aw+528+240+528+272+0%0Aw+528+160+528+176+0%0Ar+528+96+528+160+0+1000%0A162+528+176+528+240+2+default-led+1+0+0+0.01%0Aw+528+304+528+400+0%0Aw+528+400+400+400+0%0Av+400+384+400+288+0+2+100+2.5+2.5+0+0.5%0At+496+288+528+288+0+1+-4.9998025122489524+3.4649934824506973e-10+100%0Ar+416+288+480+288+0+3300%0Aw+480+288+496+288+0%0Aw+416+288+400+288+0%0Ax+489+276+505+279+4+24+B%0Ax+536+273+553+276+4+24+C%0Ax+537+316+553+319+4+24+E%0A

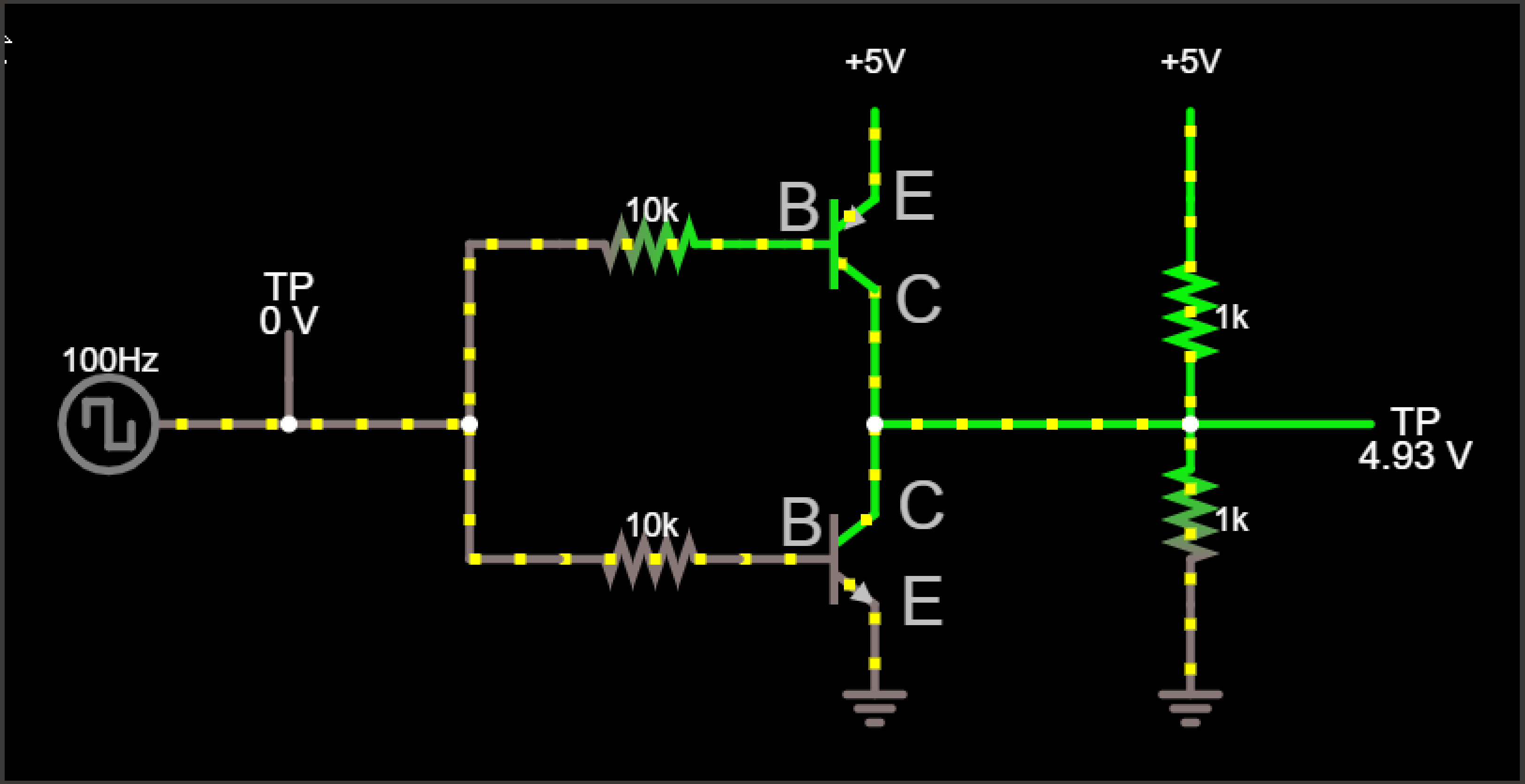
# BJT: PNP vs NPN
## “High Side” vs “Low Side”





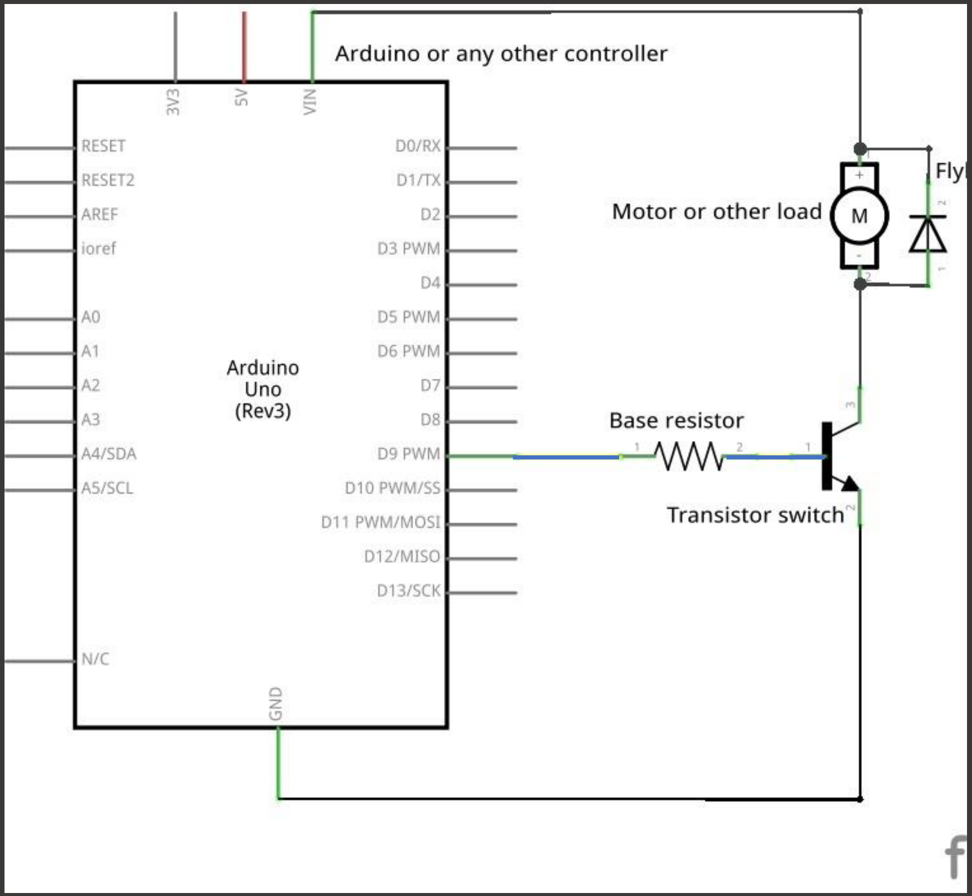
http://falstad.com/circuit/circuitjs.html?cct=$+1+0.000005+3.9121283998153213+59+5+43%0Aw+176+128+176+112+0%0Aw+64+112+176+112+0%0Aw+48+416+48+432+0%0Aw+48+304+48+320+0%0A368+48+304+48+272+0+0%0Aw+48+448+48+432+0%0Ag+48+448+48+464+0%0A368+64+112+64+80+0+0%0Aw+-64+432+48+432+0%0Aw+-64+112+64+112+0%0Av+-64+432+-64+112+0+0+40+5+0+0+0.5%0Aw+176+272+176+304+0%0Aw+176+192+176+208+0%0Ar+176+128+176+192+0+1000%0A162+176+208+176+272+2+default-led+1+0+0+0.01%0Aw+176+336+176+432+0%0Aw+176+432+48+432+0%0Av+48+416+48+320+0+2+100+2.5+2.5+0+0.5%0At+144+320+176+320+0+1+-4.999811893634119+3.464993792036408e-10+100%0Ar+64+320+128+320+0+3300%0Aw+128+320+144+320+0%0Aw+64+320+48+320+0%0Aw+496+176+512+176+0%0Ar+432+176+496+176+0+3300%0Av+416+416+416+320+0+2+100+2.5+2.5+3.141592653589793+0.5%0Aw+544+432+416+432+0%0Aw+544+384+544+432+0%0A162+544+320+544+384+2+default-led+1+0+0+0.01%0Ar+544+224+544+288+0+1000%0Aw+544+192+544+208+0%0Av+304+432+304+112+0+0+40+5+0+0+0.5%0Aw+304+112+432+112+0%0Aw+304+432+416+432+0%0A368+432+112+432+80+0+0%0Ag+416+448+416+464+0%0Aw+416+448+416+432+0%0A368+384+176+384+144+0+0%0Aw+416+176+416+320+0%0Aw+416+416+416+432+0%0Aw+432+112+544+112+0%0Aw+544+128+544+112+0%0At+512+176+544+176+0+-1+4.999788025922517+-3.4649882962867196e-10+10000%0Aw+544+160+544+128+0%0Aw+544+208+544+224+0%0Aw+544+288+544+320+0%0Aw+416+176+432+176+0%0Aw+416+176+384+176+0%0A

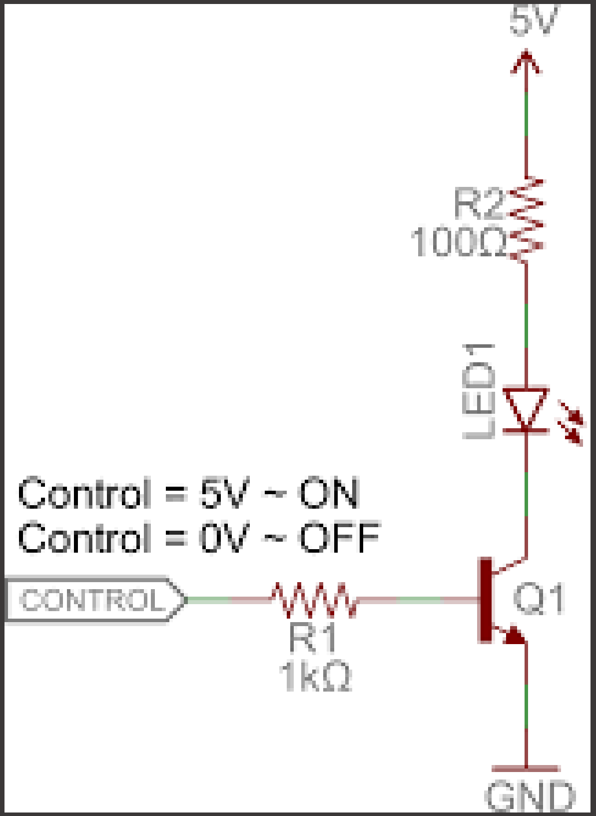
# Complementary Bipolar



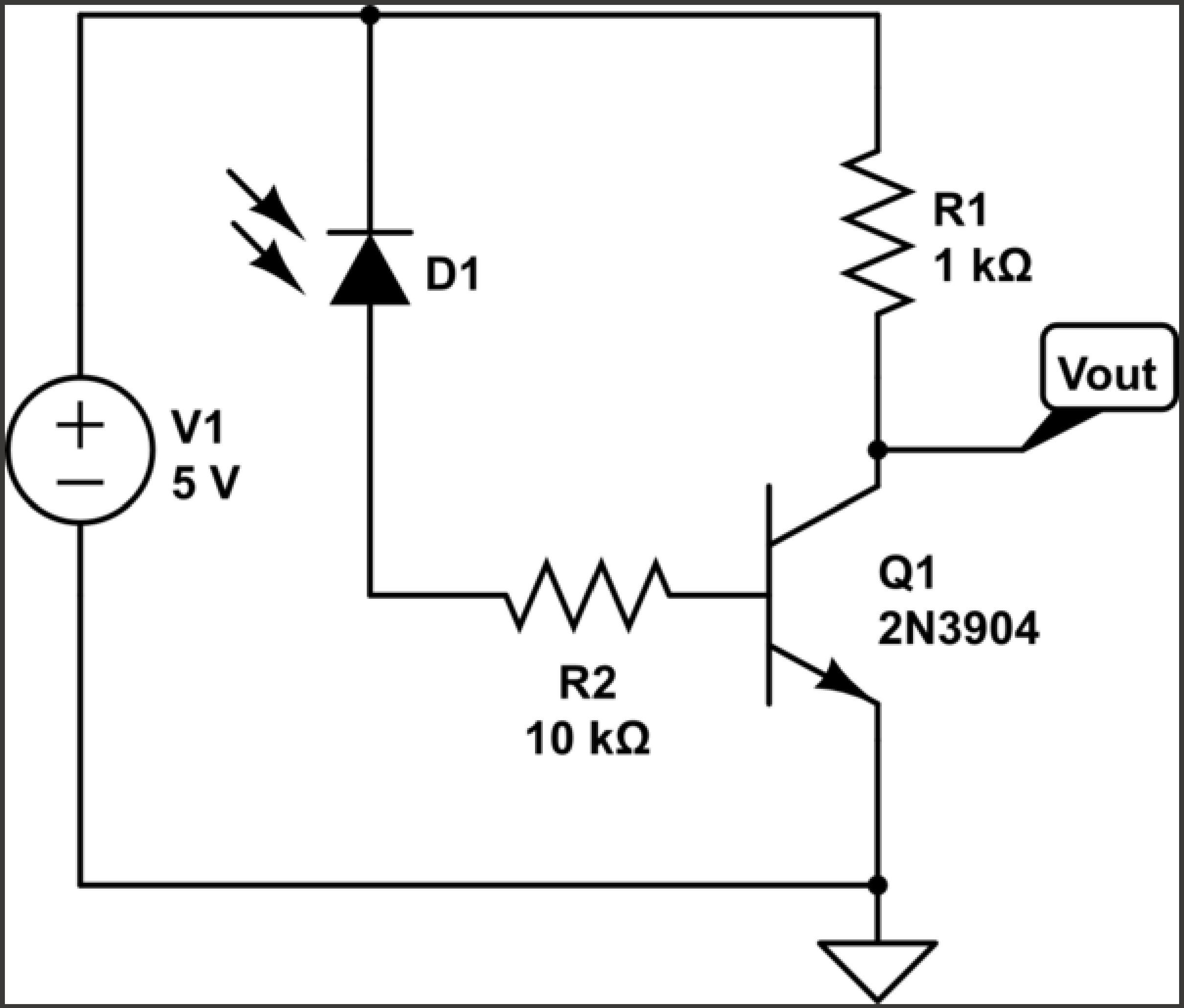

http://falstad.com/circuit/circuitjs.html?cct=$+1+0.000005+3.9121283998153213+59+5+43%0At+224+320+272+320+0+1+0.5705218733467872+0.6402159636357576+100%0Ar+160+320+224+320+0+10000%0Aw+224+208+240+208+0%0Ar+160+208+224+208+0+10000%0Ar+384+272+384+336+0+1000%0Aw+272+224+272+240+0%0A368+64+256+64+224+0+0%0At+240+208+272+208+0+-1+4.930305908661726+-1.0493037549963447e-9+10000%0Aw+272+240+272+272+0%0AR+272+192+272+144+0+0+40+5+0+0+0.5%0Aw+272+272+272+304+0%0Aw+272+272+384+272+0%0Ar+384+192+384+272+0+1000%0AR+384+192+384+144+0+0+40+5+0+0+0.5%0Ag+384+336+384+368+0%0Aw+160+208+128+208+0%0Aw+128+208+128+272+0%0Aw+128+272+128+320+0%0Aw+160+320+128+320+0%0AR+64+272+0+272+0+2+100+2.5+2.5+0+0.5%0Aw+64+272+128+272+0%0Aw+64+256+64+272+0%0Ag+272+336+272+368+0%0A368+384+272+464+272+0+0%0Ax+279+236+296+239+4+24+C%0Ax+237+203+253+206+4+24+B%0Ax+280+309+297+312+4+24+C%0Ax+238+315+254+318+4+24+B%0Ax+281+343+297+346+4+24+E%0Ax+278+199+294+202+4+24+E%0A

# BJT Motor or LED Driver Example

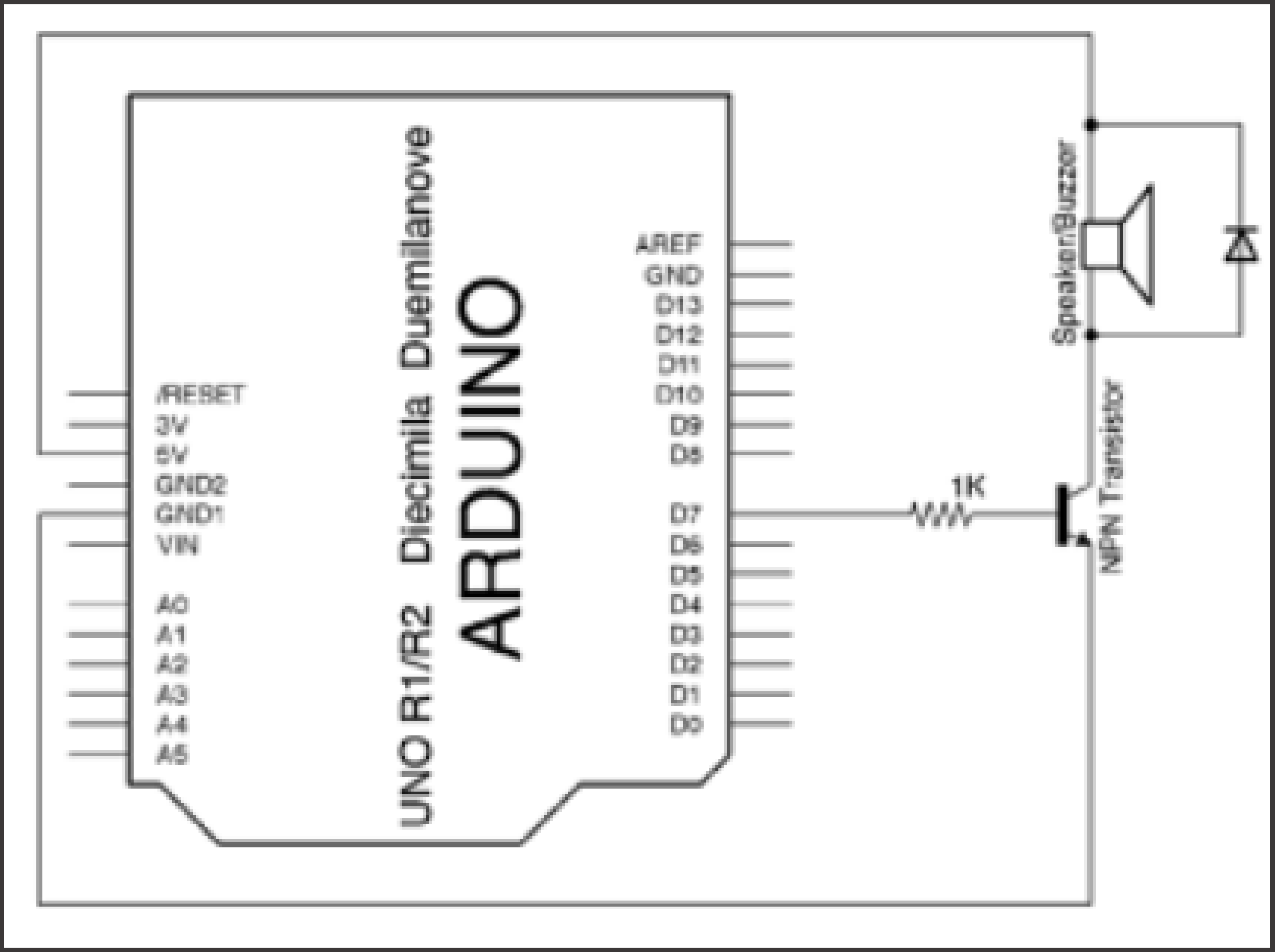


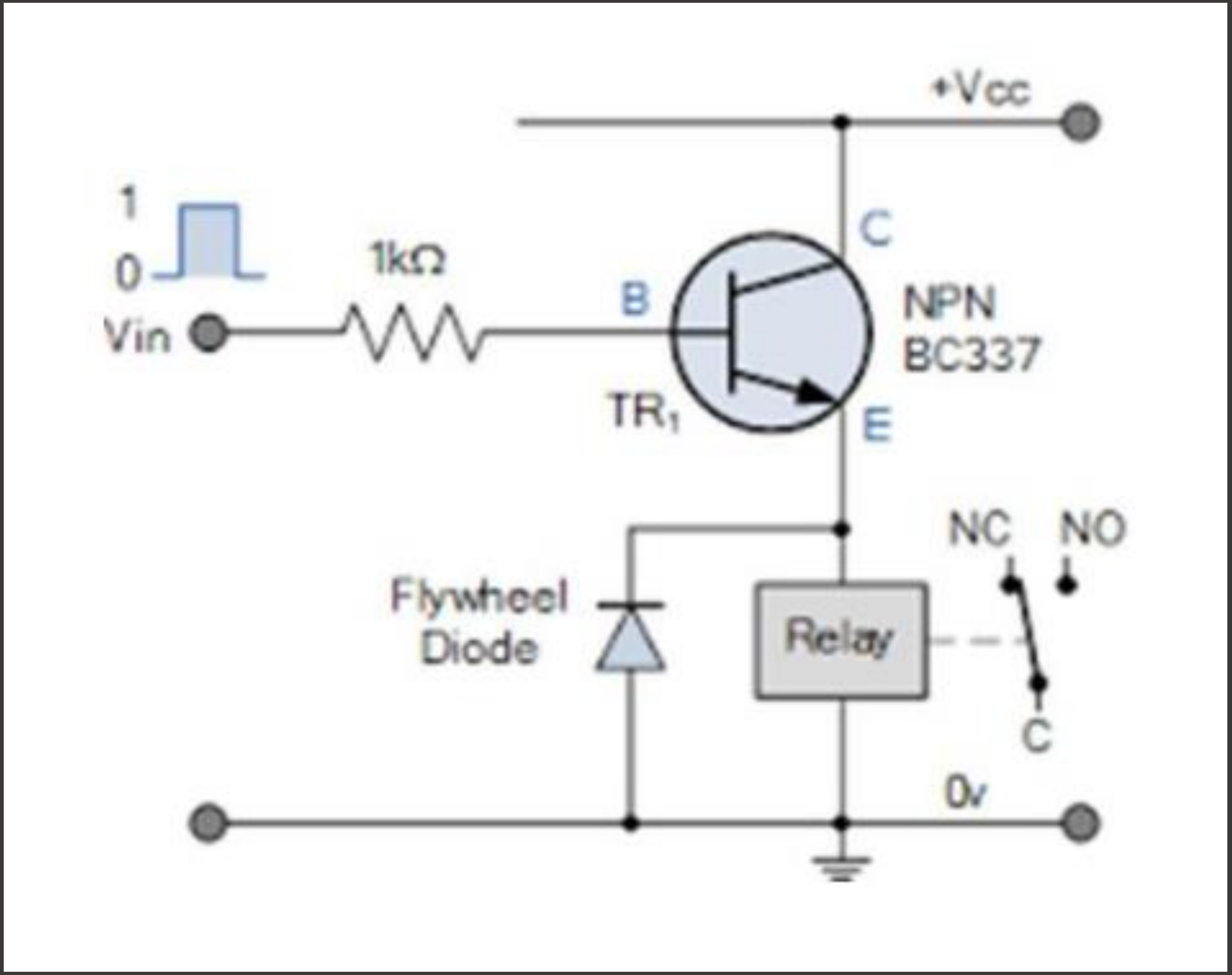
# BJT Photodiode Example



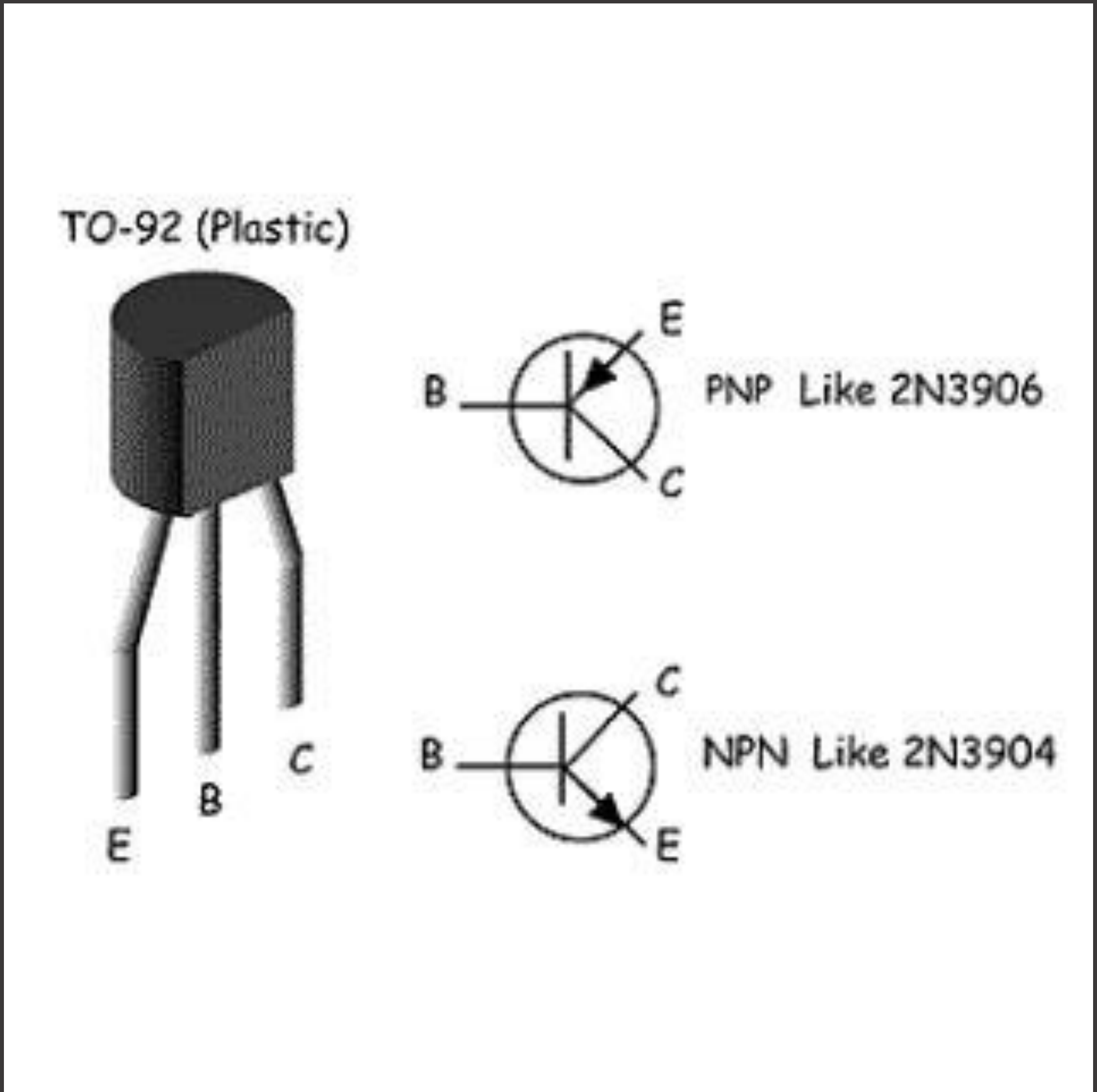
# BJT Speaker Driver Example



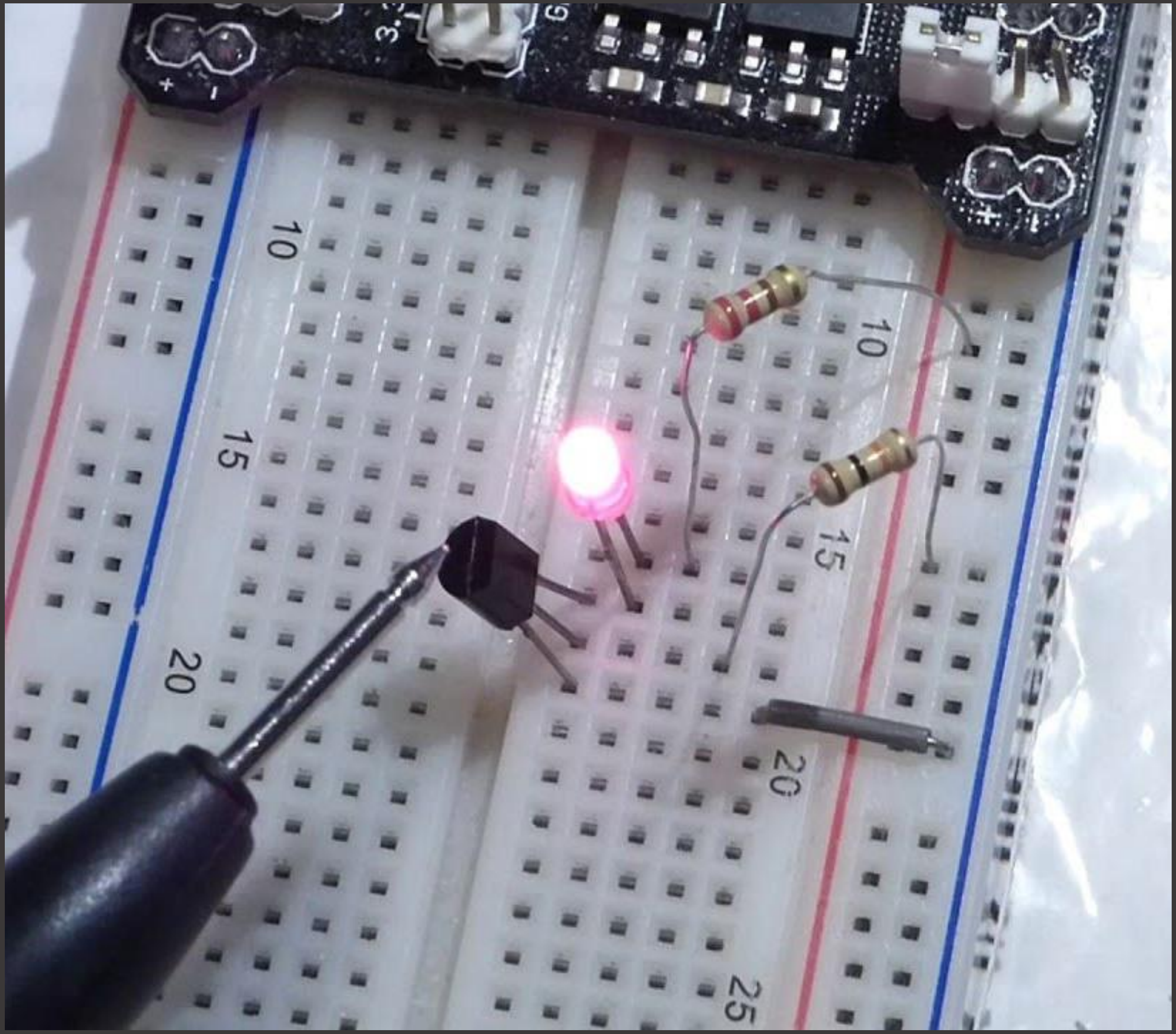
# BJT Relay Example



# Common Bipolar Pinouts



# Typical Breadboard Application



# Key Bipolar Transistor Specs

**OFF CHARACTERISTICS**

| | | | | |
|---|---|---|---|---|
| Collector – Emitter Breakdown Voltage (Note 2) ($I_C$ = 1.0 mAdc, $I_B$ = 0) | $V_{(BR)CEO}$ | 40 | – | Vdc |

Collector-emitter Breakdown Voltage

- Maximum operating C-E should be 20-50% lower

| | | | |
|---|---|---|---|
| Collector Current – Continuous | $I_C$ | 200 | mAdc |

Maximum continuous collector current

- You should be below this with some margin ~20%

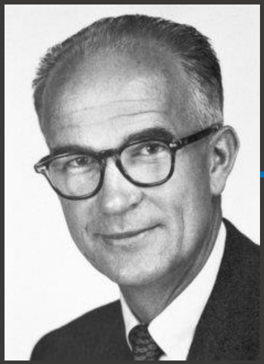
**SMALL– SIGNAL CHARACTERISTICS**

| | | | | | |
|---|---|---|---|---|---|
| Current – Gain – Bandwidth Product ($I_C$ = 10 mAdc, $V_{CE}$ = 20 Vdc, f = 100 MHz) | 2N3903<br>2N3904 | $f_T$ | 250<br>300 | –<br>– | MHz |

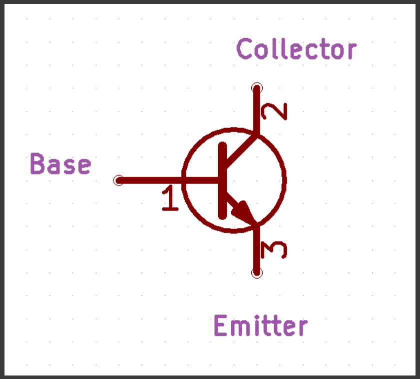
$f_T$ – frequency at which gain falls to 1

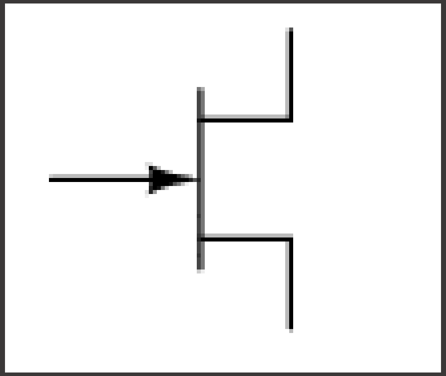
- Should be > 100x your operating frequency
- Avoid super high frequency transistors (1GHz!)

# BJT vs FET as a Switch

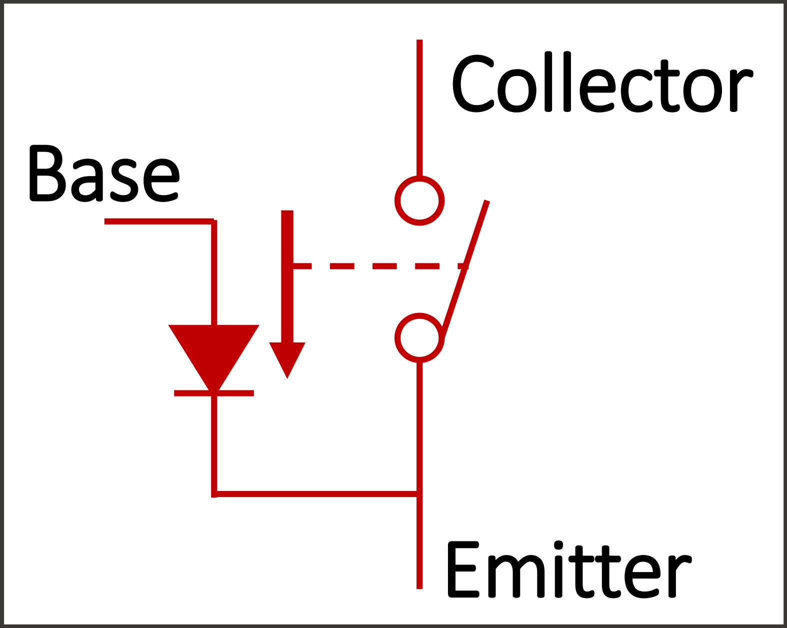


W. Shockley
1947
Nobel Prize 1956

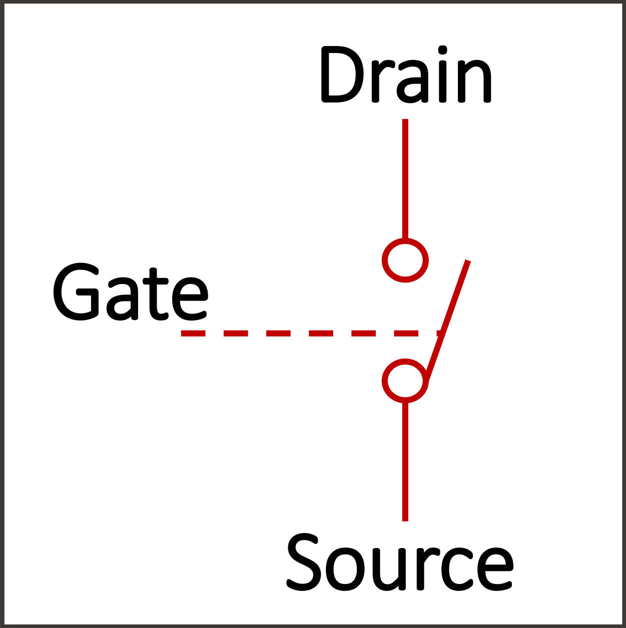


J. E. Lilienfeld
1925

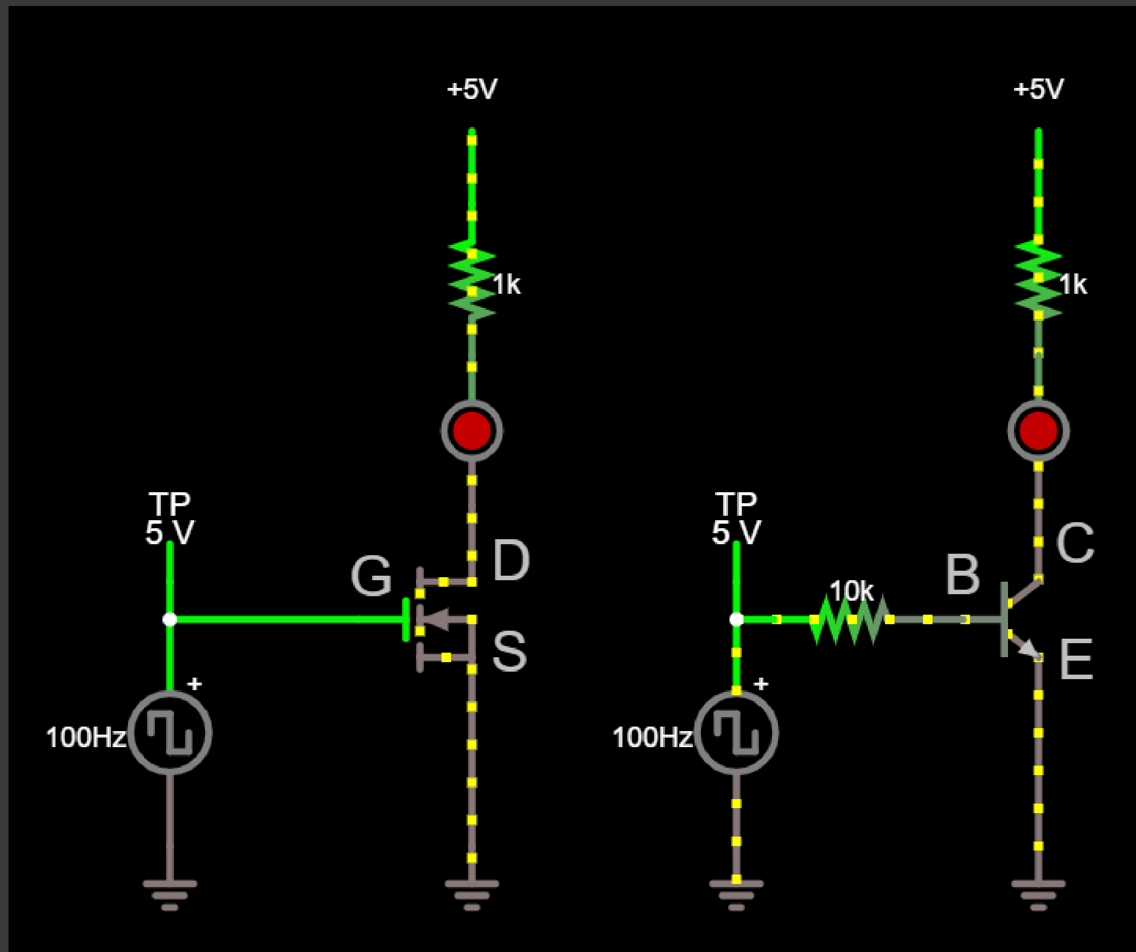



Current Controlled



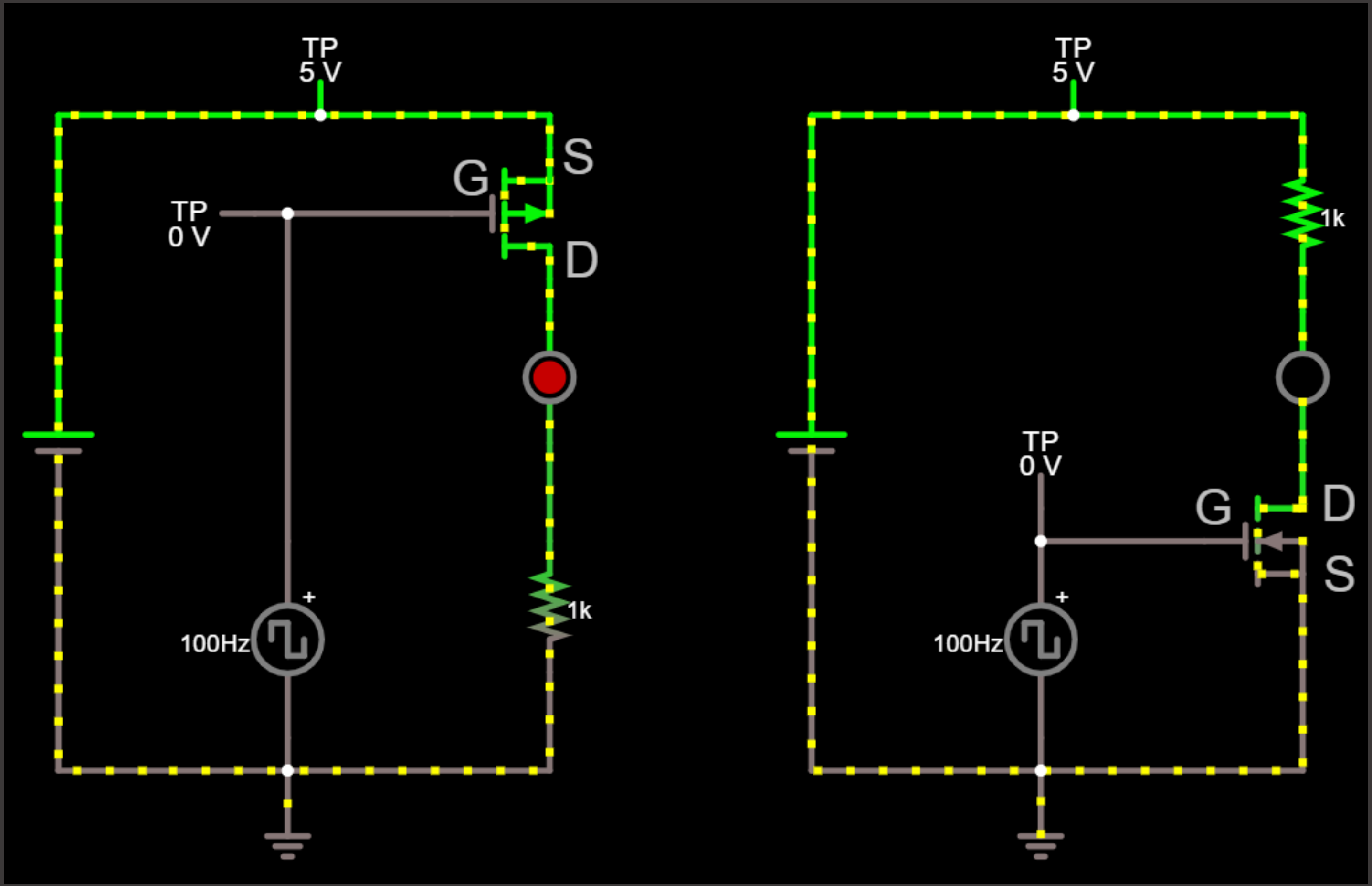

Voltage Controlled

# FET vs BJT in Operation



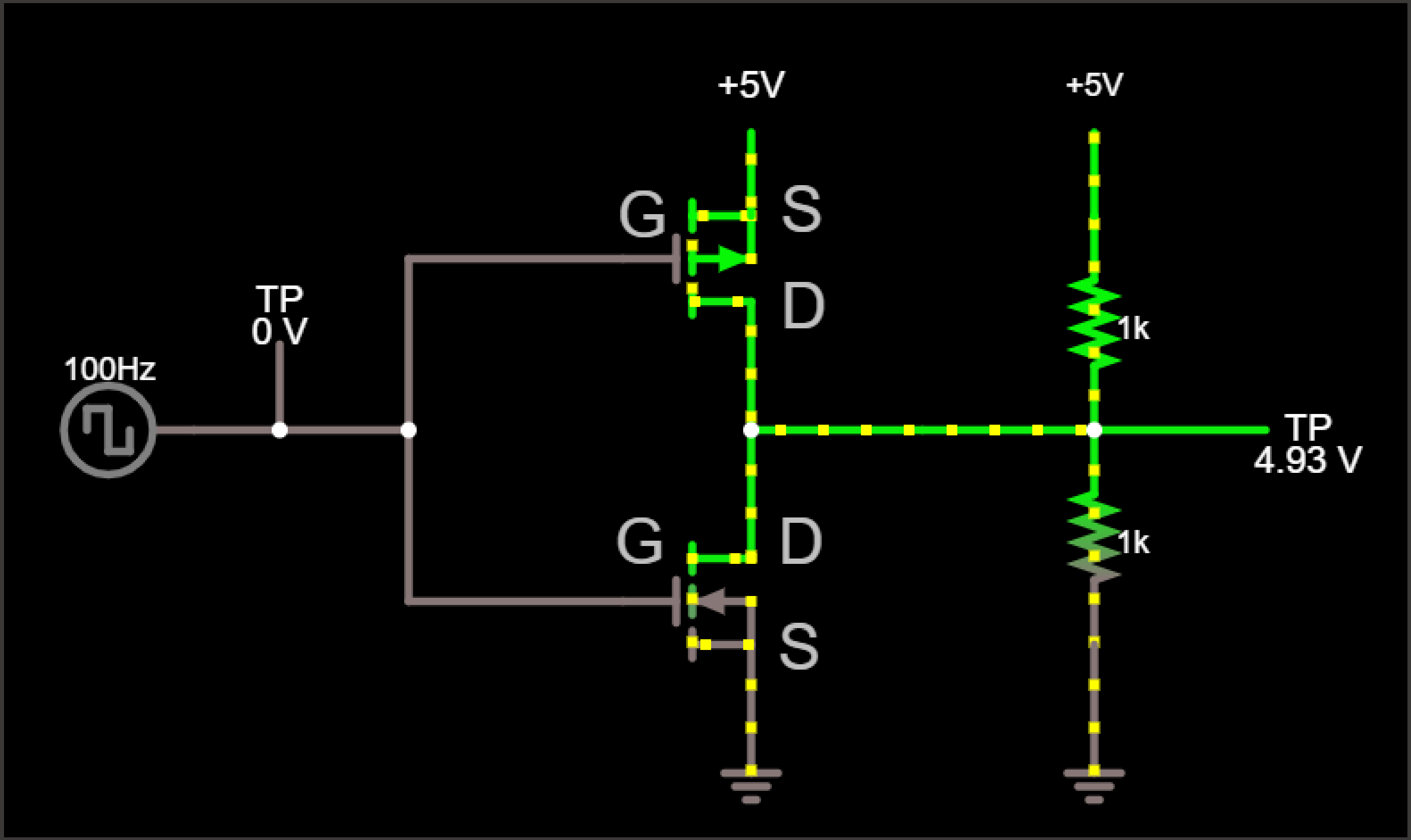

http://falstad.com/circuit/circuitjs.html?cct=$+1+0.000005+3.9121283998153213+59+5+43%0Av+80+384+80+288+0+2+100+2.5+2.5+0+0.5%0Aw+80+288+160+288+0%0A162+208+176+208+240+2+default-led+1+0+0+0.01%0Ar+208+112+208+176+0+1000%0Aw+208+240+208+272+0%0Ag+80+384+80+400+0%0A368+80+272+80+240+0+0%0Aw+80+272+80+288+0%0Aw+320+272+320+288+0%0A368+320+272+320+240+0+0%0Ag+320+384+320+400+0%0Aw+448+240+448+272+0%0Ar+448+112+448+176+0+1000%0A162+448+176+448+240+2+default-led+1+0+0+0.01%0Aw+448+304+448+384+0%0Av+320+384+320+288+0+2+100+2.5+2.5+0+0.5%0At+416+288+448+288+0+1+-4.999808758737633+1.049998087170923e-9+100%0Ar+336+288+400+288+0+10000%0Aw+400+288+416+288+0%0Aw+336+288+320+288+0%0AR+448+112+448+64+0+0+40+5+0+0+0.5%0Ag+448+384+448+400+0%0Aw+208+304+208+384+0%0Ag+208+384+208+400+0%0AR+208+112+208+64+0+0+40+5+0+0+0.5%0Af+160+288+208+288+32+1.5+1%0A

# MOSFETs: NMOS vs PMOS



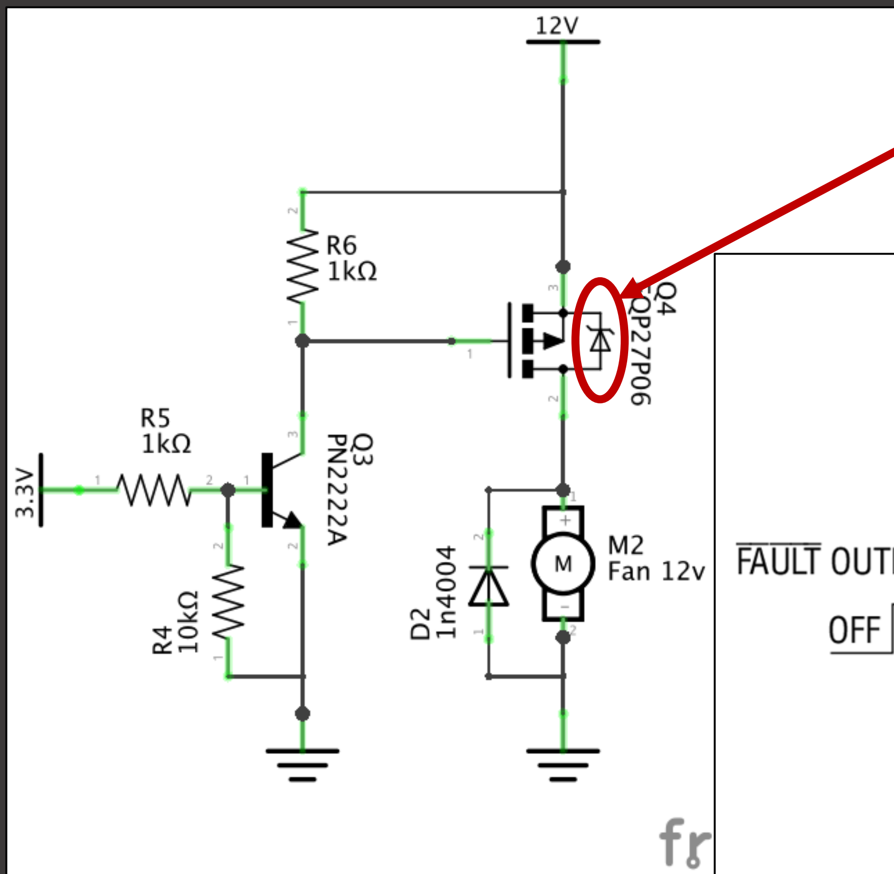

http://falstad.com/circuit/circuitjs.html?cct=$+1+0.000005+3.9121283998153213+59+5+43%0Av+432+416+432+320+0+2+100+2.5+2.5+3.141592653589793+0.5%0Aw+560+432+432+432+0%0Aw+560+336+560+432+0%0Aw+432+320+512+320+0%0A162+560+208+560+272+2+default-led+1+0+0+0.01%0Ar+560+128+560+192+0+1000%0Aw+560+192+560+208+0%0Aw+560+272+560+304+0%0Av+320+432+320+112+0+0+40+5+0+0+0.5%0Aw+320+112+448+112+0%0Aw+320+432+432+432+0%0A368+448+112+448+80+0+0%0Ag+432+448+432+464+0%0Aw+432+448+432+432+0%0A368+432+304+432+272+0+0%0Aw+432+304+432+320+0%0Aw+432+416+432+432+0%0Aw+448+112+560+112+0%0Aw+80+112+192+112+0%0Aw+64+448+64+432+0%0Ag+64+448+64+464+0%0A368+80+112+80+80+0+0%0Aw+-48+432+64+432+0%0Aw+-48+112+80+112+0%0Av+-48+432+-48+112+0+0+40+5+0+0+0.5%0Aw+192+272+192+320+0%0Aw+192+192+192+208+0%0Ar+192+320+192+384+0+1000%0A162+192+208+192+272+2+default-led+1+0+0+0.01%0Aw+192+384+192+432+0%0Aw+192+432+64+432+0%0Aw+192+112+192+128+0%0Aw+560+128+560+112+0%0Af+512+320+560+320+32+1.5+0.02%0Av+64+416+64+320+0+2+100+2.5+2.5+3.141592653589793+0.5%0Aw+64+416+64+432+0%0Af+144+160+192+160+33+1.5+0.02%0Aw+192+128+192+144+0%0Aw+192+176+192+192+0%0Aw+144+160+64+160+0%0Aw+64+320+64+160+0%0A368+48+160+16+160+0+0%0Aw+48+160+64+160+0%0Ax+144+151+162+154+4+24+G%0Ax+198+141+214+144+4+24+S%0Ax+199+191+216+194+4+24+D%0Ax+569+310+586+313+4+24+D%0Ax+570+345+586+348+4+24+S%0Ax+507+312+525+315+4+24+G%0A

# CMOS Output

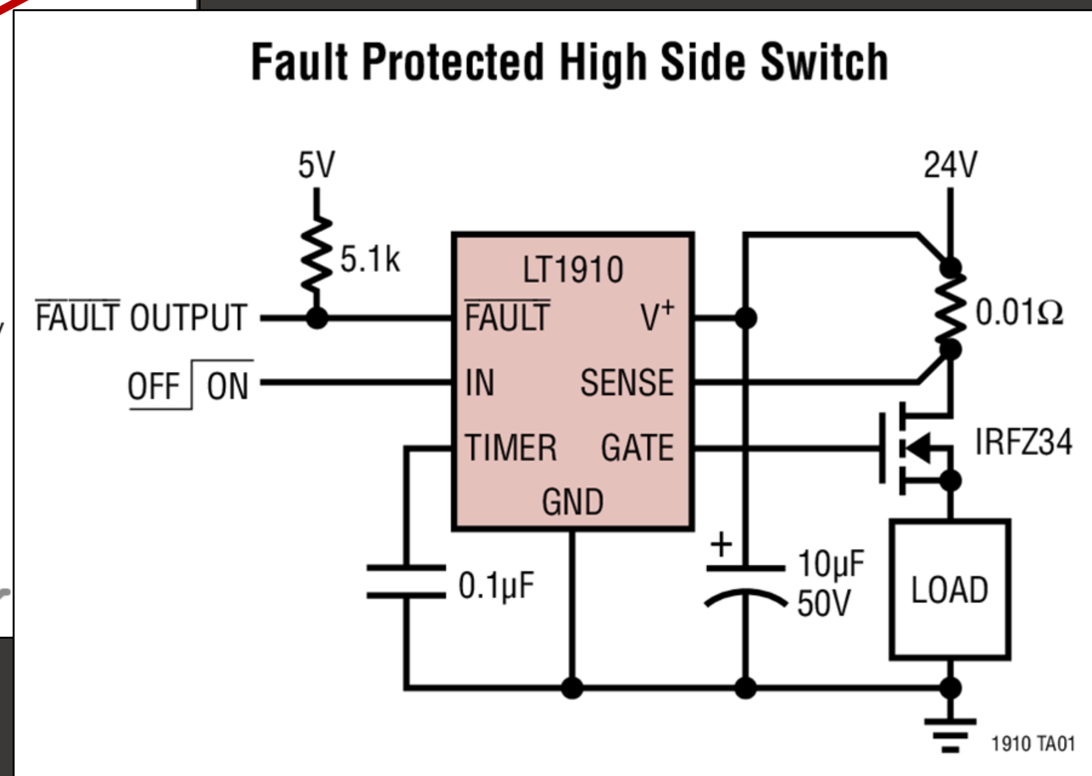



http://falstad.com/circuit/circuitjs.html?cct=$+1+0.000005+3.9121283998153213+59+5+43%0Ar+432+272+432+352+0+1000%0Ag+304+352+304+400+0%0A368+432+272+512+272+0+0%0Aw+304+272+304+320+0%0Af+256+336+304+336+32+1.5+0.02%0Af+256+208+304+208+33+1.5+0.02%0A368+128+272+128+224+0+0%0Ax+244+189+262+192+4+24+G%0Ax+319+195+335+198+4+24+S%0Ax+321+237+338+240+4+24+D%0AR+304+192+304+144+0+0+40+5+0+0+0.5%0Aw+304+224+304+272+0%0Aw+304+272+368+272+0%0Aw+256+208+176+208+0%0Aw+176+336+256+336+0%0Aw+176+272+128+272+0%0Aw+128+272+96+272+0%0AR+96+272+64+272+0+2+100+2.5+2.5+0+0.5%0Ar+432+192+432+272+0+1000%0Ag+432+352+432+400+0%0AR+432+192+432+144+0+0+40+5+0+0+0.5%0Aw+368+272+432+272+0%0Aw+176+208+176+272+0%0Aw+176+272+176+336+0%0A

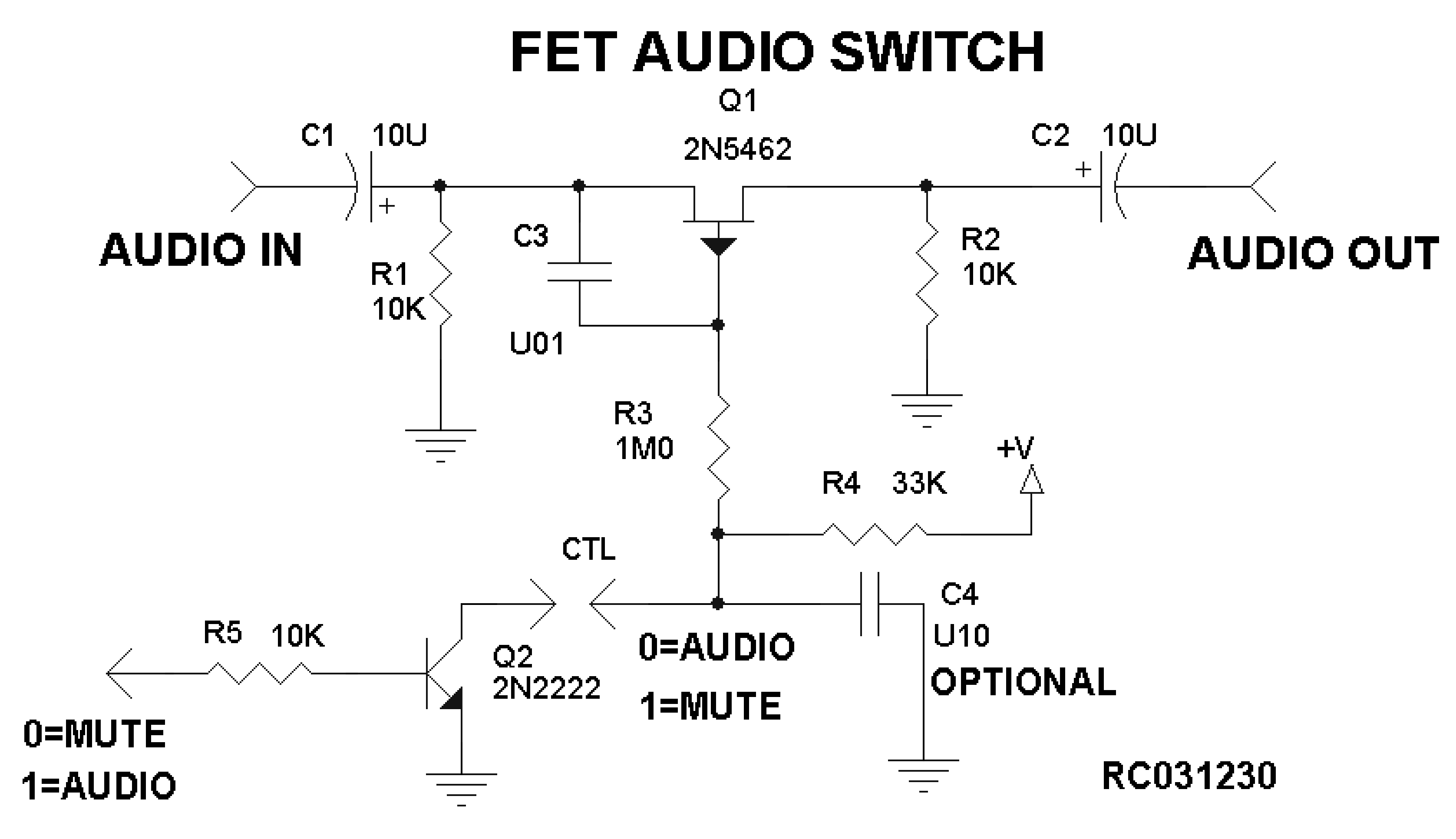
# MOSFET Examples




Note the “body diode” which is intrinsic to all MOSFETs



# FET Example



FET AUDIO SWITCH
Q1
2N5462
C1
10U
C2
10U
AUDIO IN
AUDIO OUT
C3
U01
R1
10K
R2
10K
R3
1M0
R4
33K
+V
CTL
C4
U10
OPTIONAL
R5
10K
Q2
2N2222
0=AUDIO
1=MUTE
0=MUTE
1=AUDIO
RC031230

# Key MOSFET Specs

| Characteristic | | Symbol | Min | Max | Unit |
|---|---|---|---|---|---|
| **OFF CHARACTERISTICS** | | | | | |
| Drain–Source Breakdown Voltage | ($V_{GS}$ = 0, $I_D$ = 10 μAdc) | $V_{(BR)DSS}$ | 60 | – | Vdc |

## Drain-Source Breakdown Voltage

- Maximum operating D-S should be 20-50% lower

| | | | | | |
|---|---|---|---|---|---|
| **ON CHARACTERISTICS** (Note 1) | | | | | |
| Gate Threshold Voltage | ($V_{DS}$ = $V_{GS}$, $I_D$ = 1.0 mAdc) | $V_{GS(th)}$ | 0.8 | 3.0 | Vdc |

## Gate threshold voltage

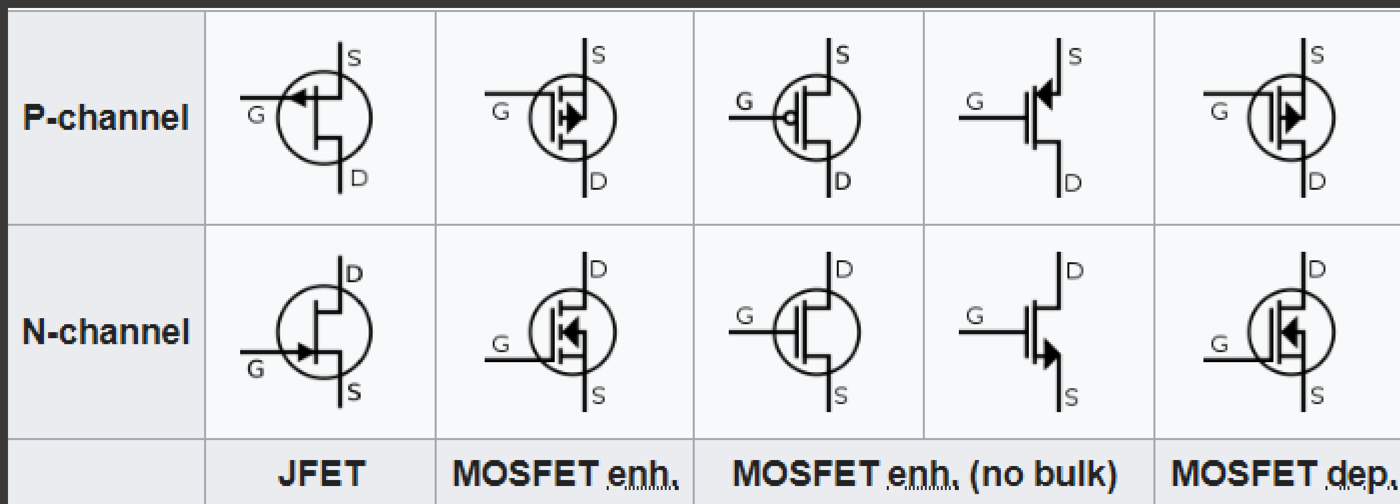
- You should be well above/below this

| | | | | | |
|---|---|---|---|---|---|
| Static Drain–Source On–Resistance | | $r_{DS(on)}$ | | | Ω |
| | ($V_{GS}$ = 10 Vdc, $I_D$ = 0.5 Adc) | | – | 5.0 | |
| | ($V_{GS}$ = 4.5 Vdc, $I_D$ = 75 mAdc) | | – | 6.0 | |
| Drain–Source On–Voltage | | $V_{DS(on)}$ | | | Vdc |
| | ($V_{GS}$ = 10 Vdc, $I_D$ = 0.5 Adc) | | – | 2.5 | |
| | ($V_{GS}$ = 4.5 Vdc, $I_D$ = 75 mAdc) | | – | 0.45 | |

## On-Voltage

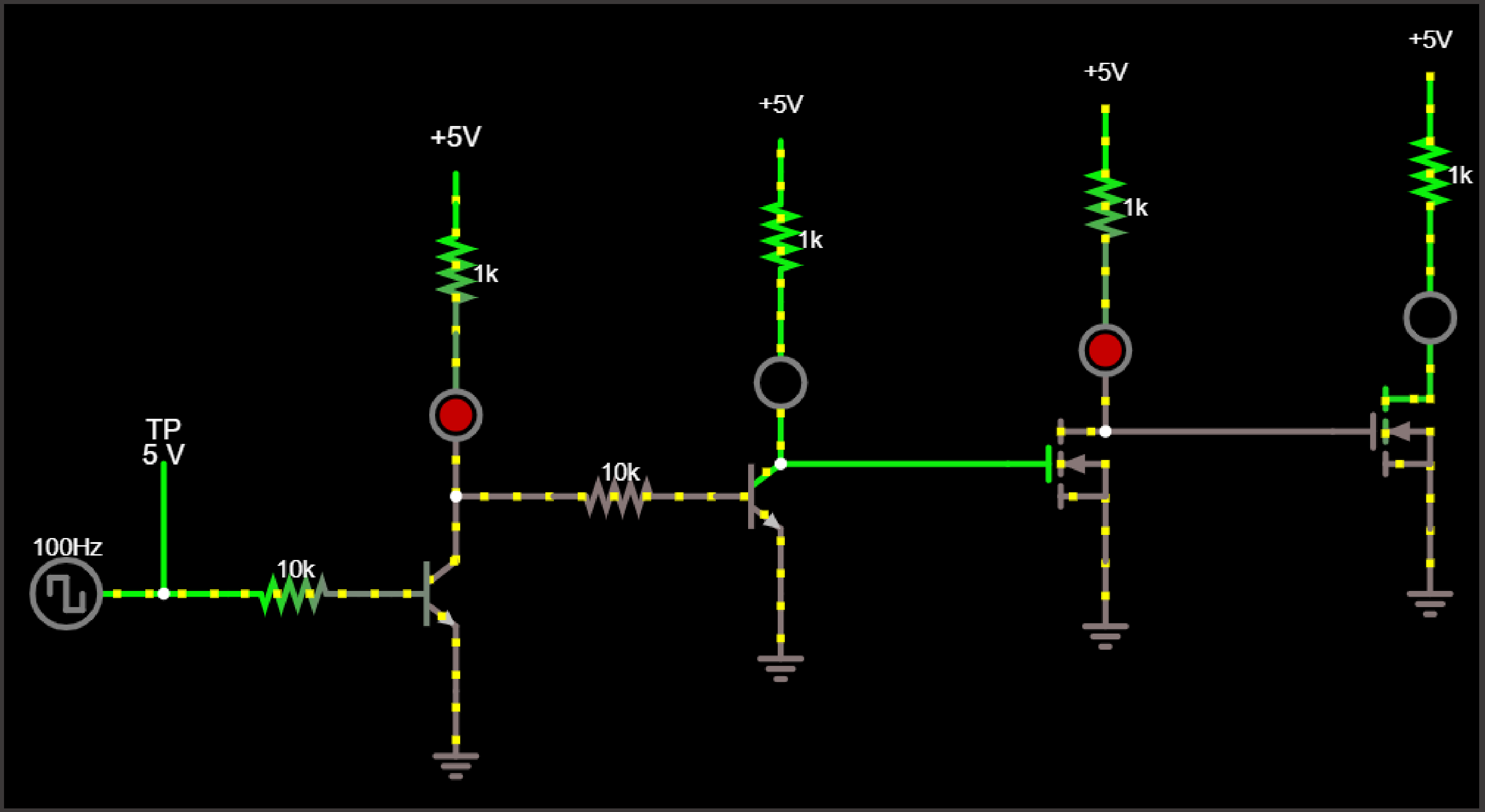
- Should be low enough

# MOSFET Schematic Symbols




- There are many, many variations on these
- FETs of the same type (P vs N) behave similar to each other
- Be aware but don't fret over it too much

# “Common Emitter/Source” Inverts

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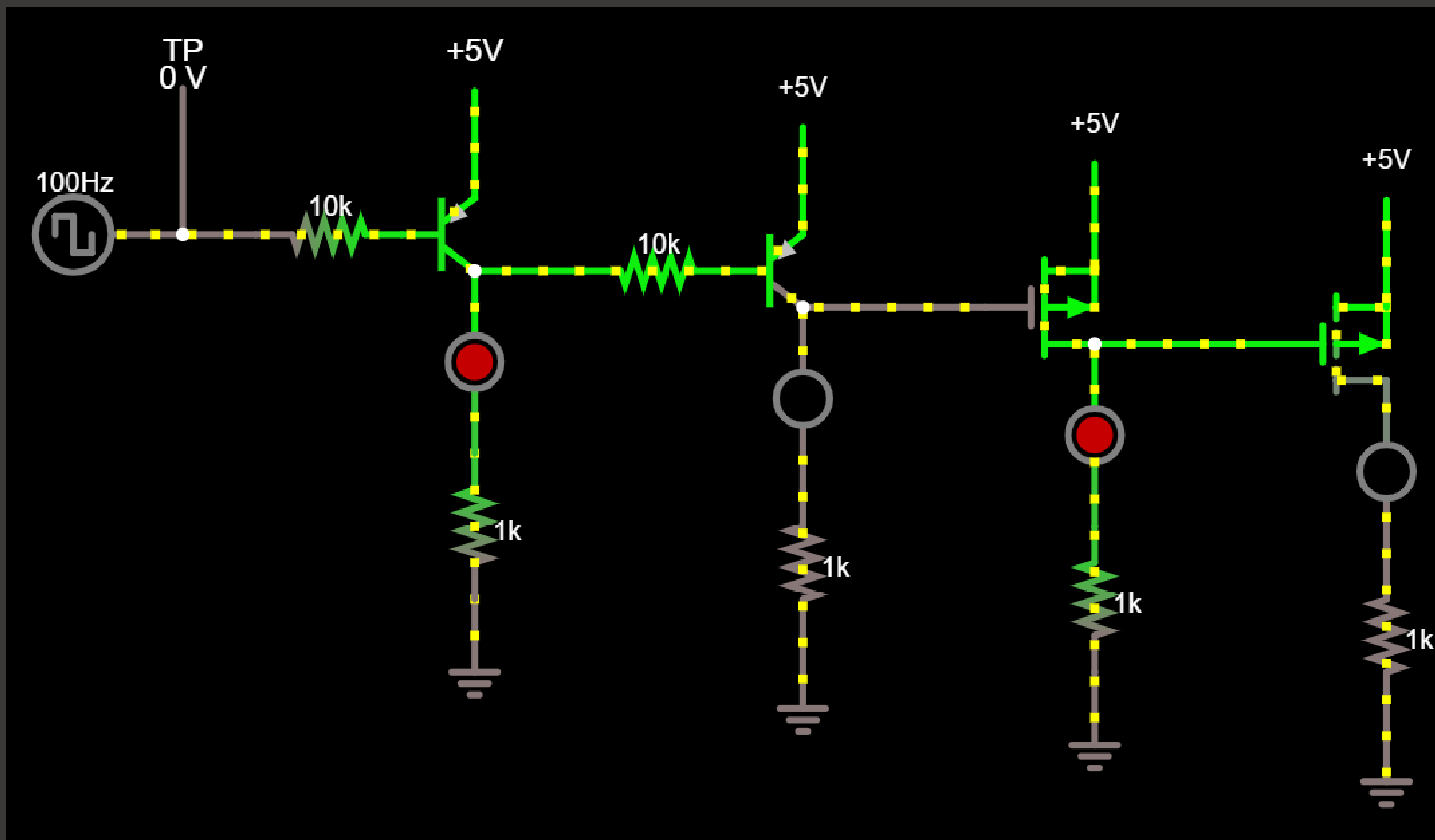
# Same on the High Side

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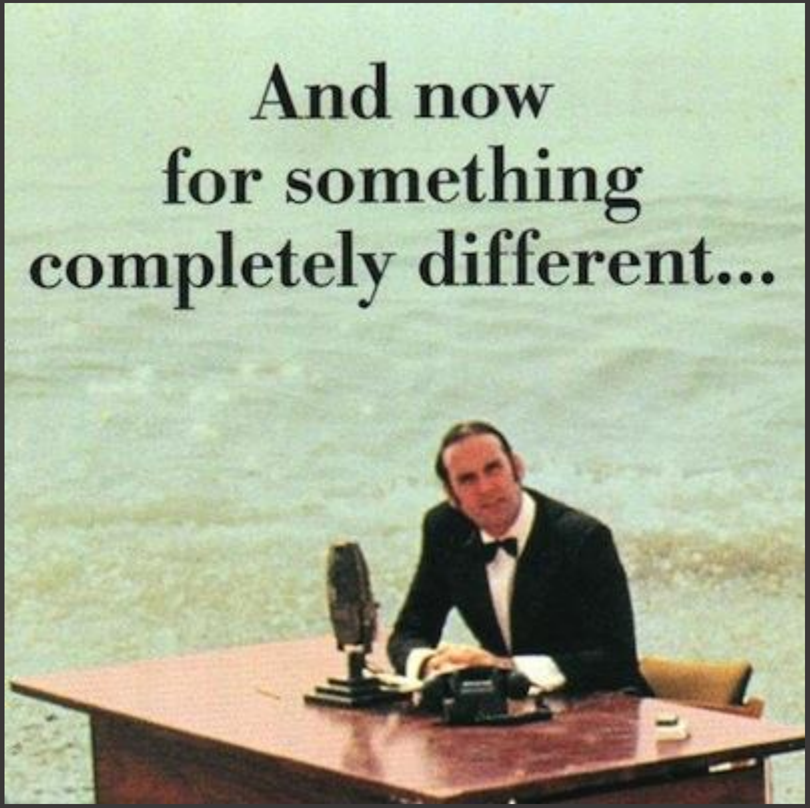
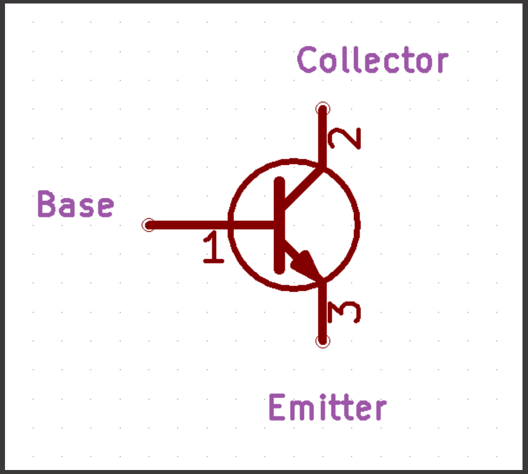
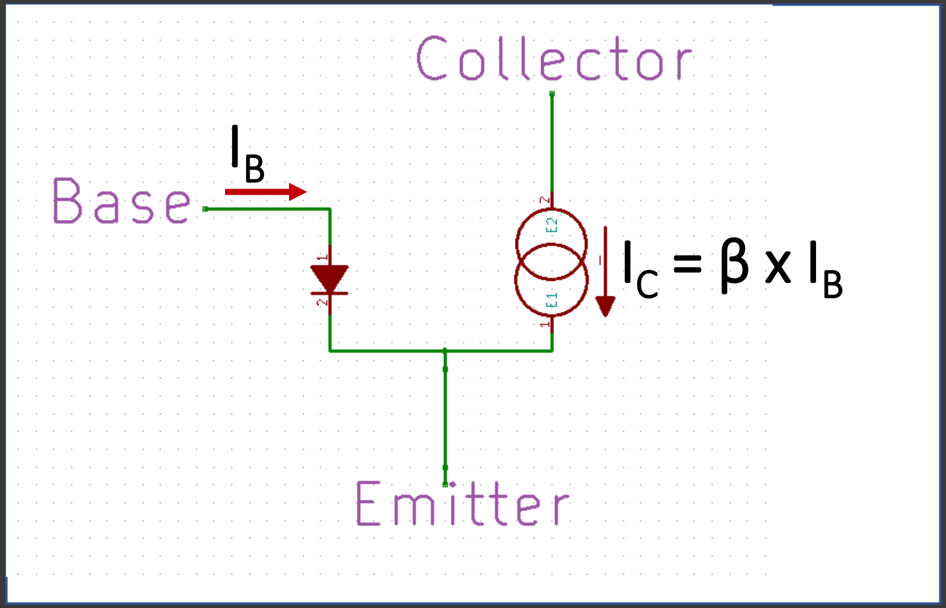



# Transistors as Amplifiers

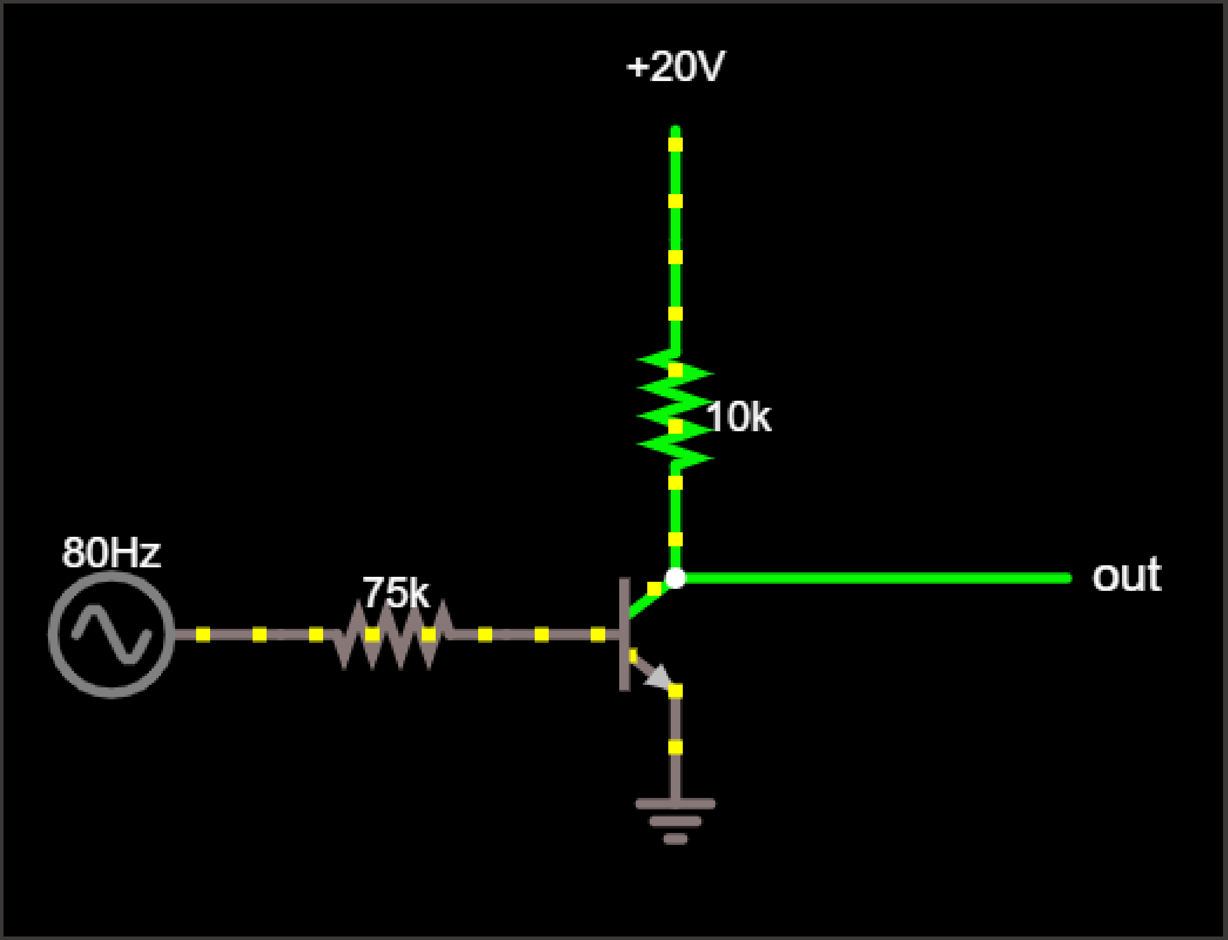
# A More Accurate NPN Model




β (aka $h_{fe}$) is the "current gain" of the device

# A Bad Common Emitter Amplifier

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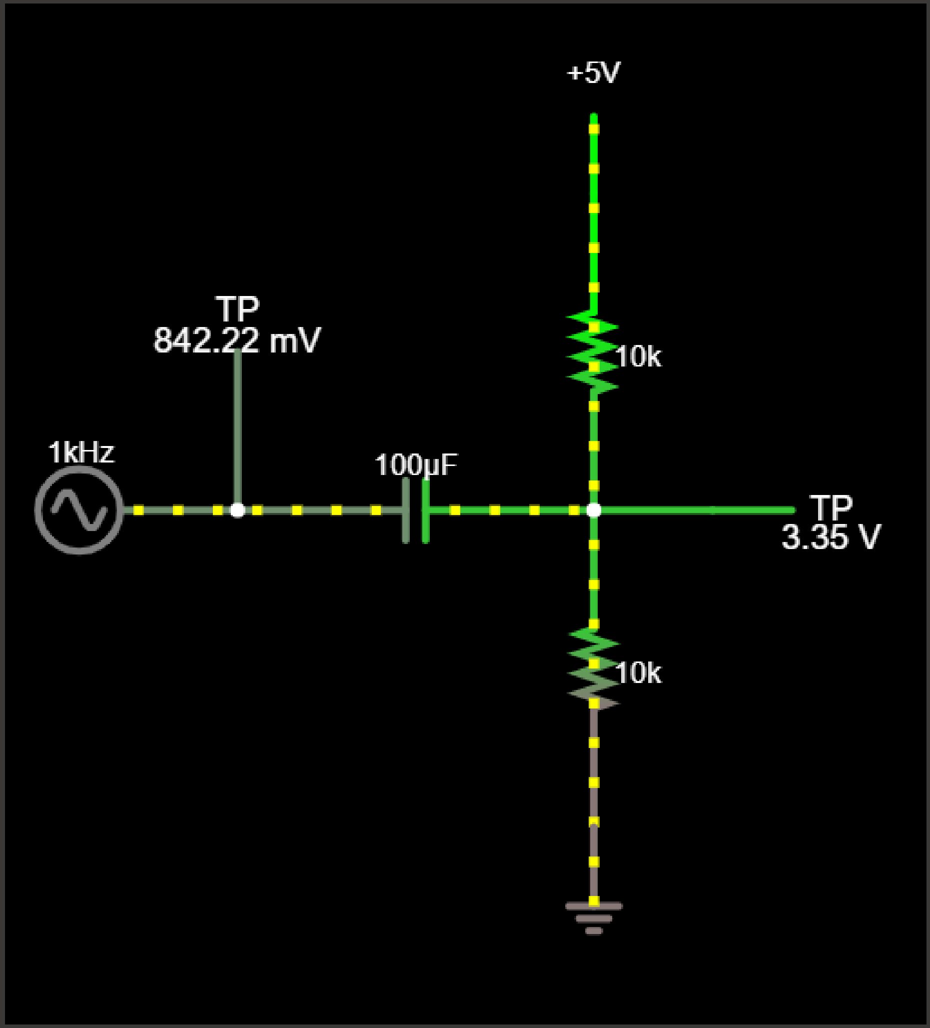
# A Bias Tee

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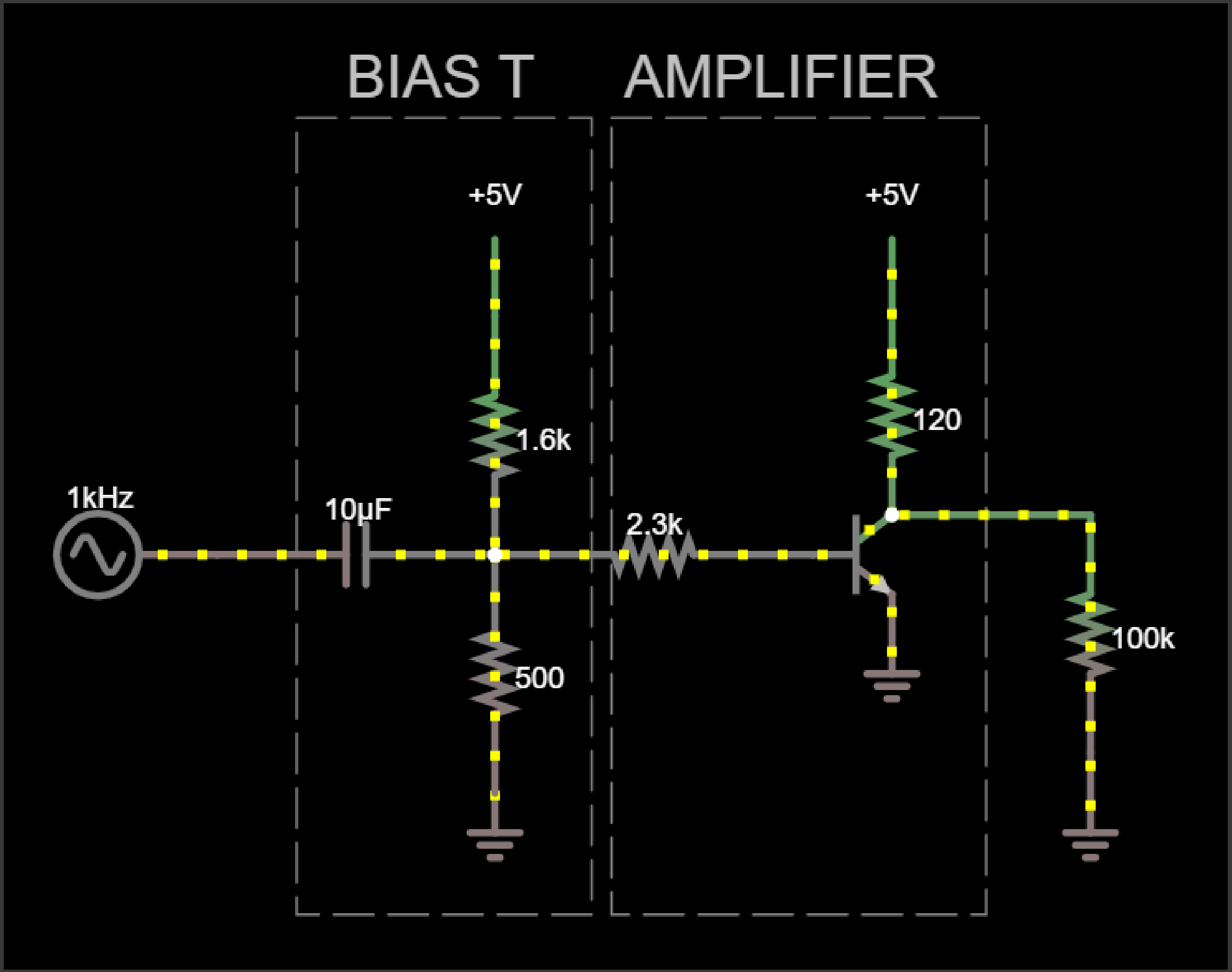
# A Mediocre CE Amplifier

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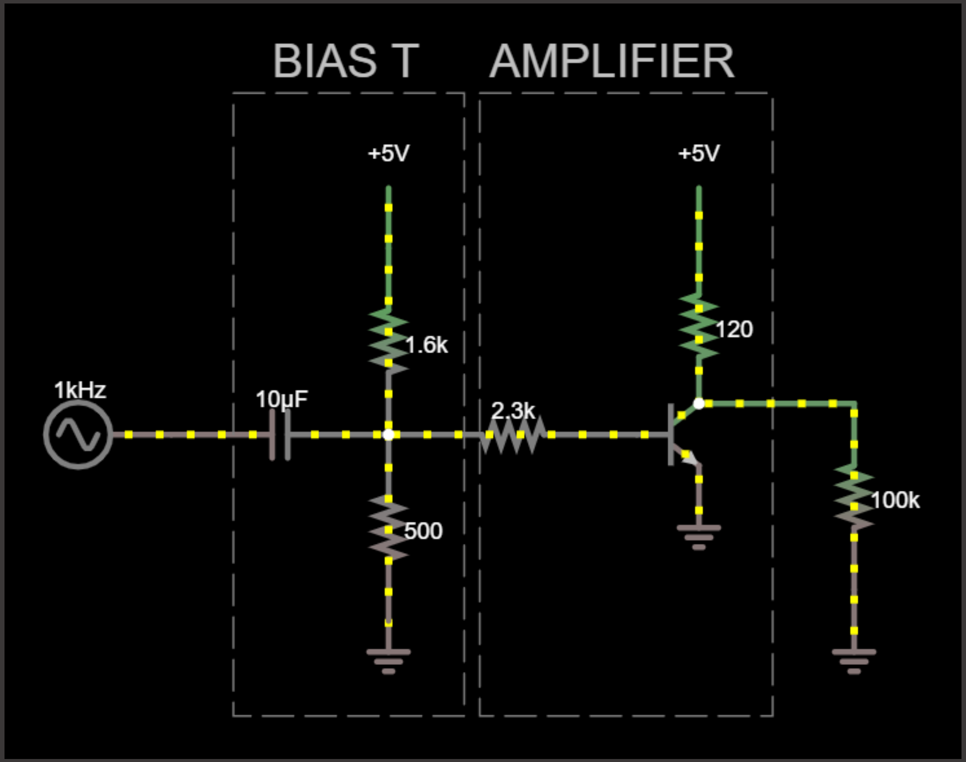
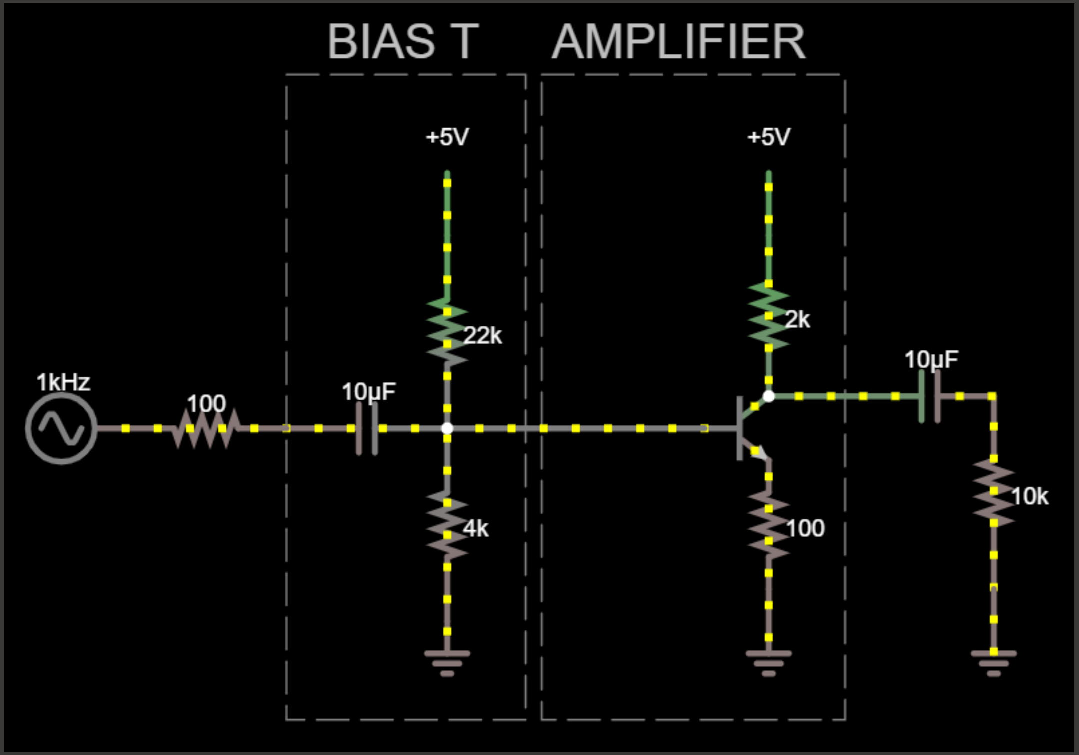
# Problems with this amplifier




Problems

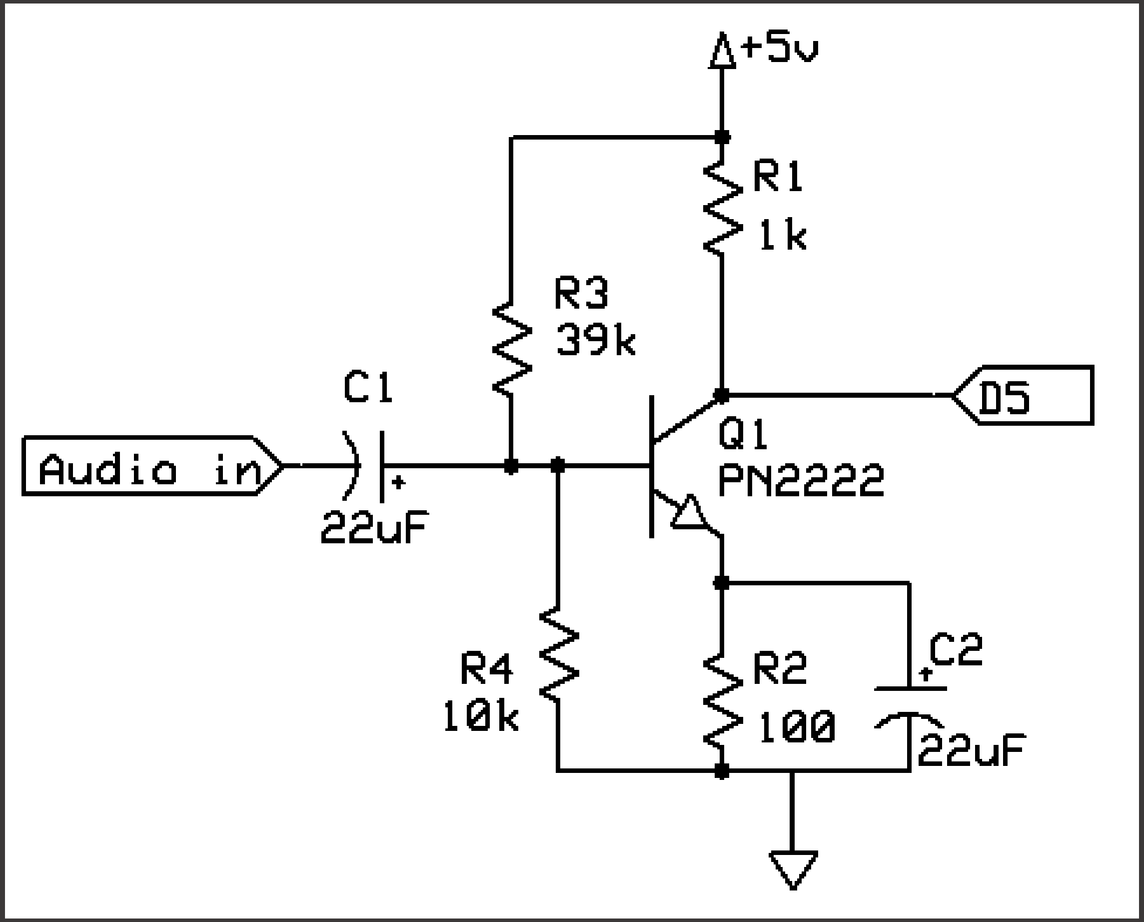
- Gain will vary too much with β ($h_{fe}$) variation
- Linearity isn't very good
- Input dynamic range is poor
- Circuit needs fine-tuning per transistor used

# Emitter Resistor

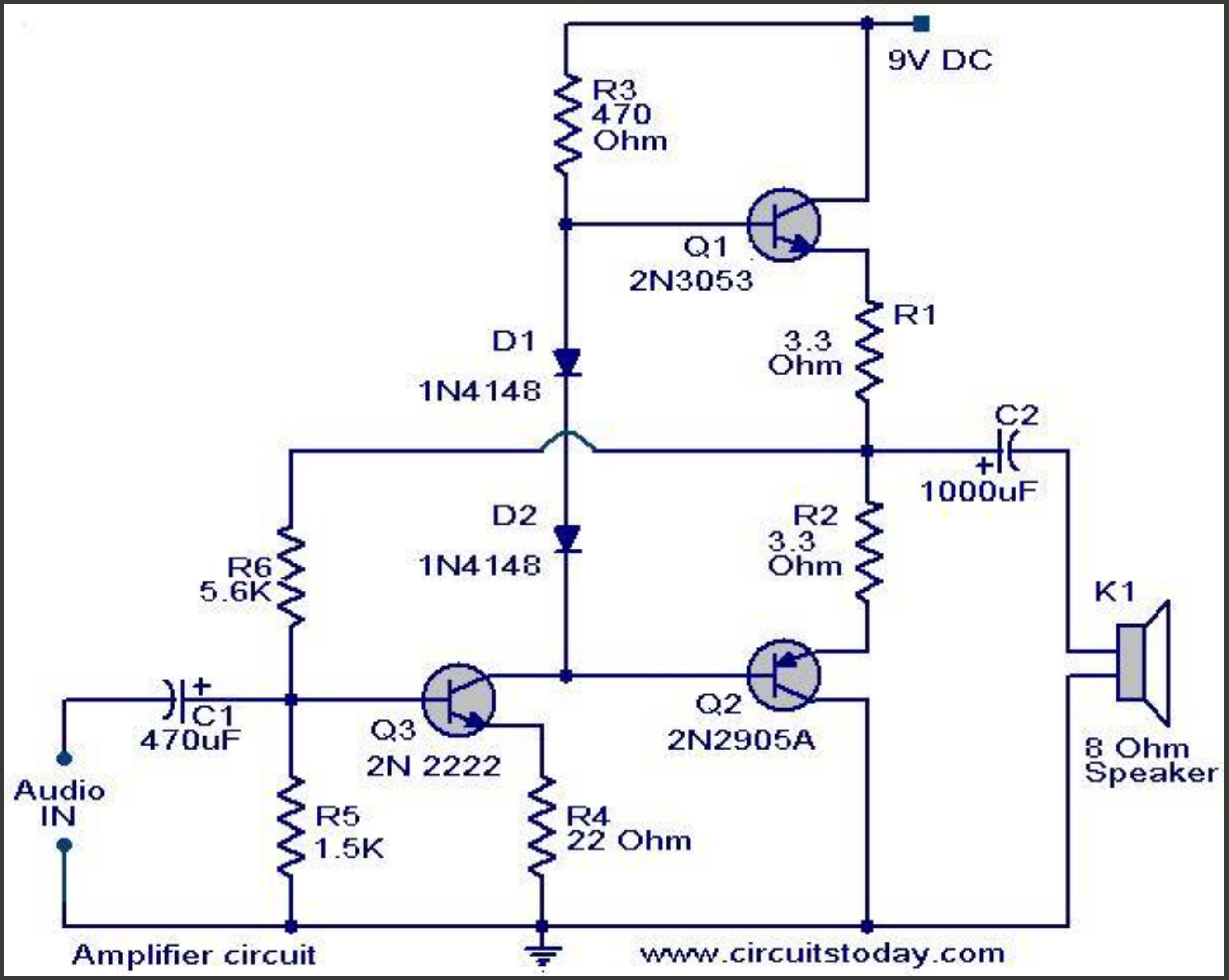



- Gain ~= -Rc/Re
- Improved distortion
- Improved dynamic range
- Less sensitive to individual transistor characteristics

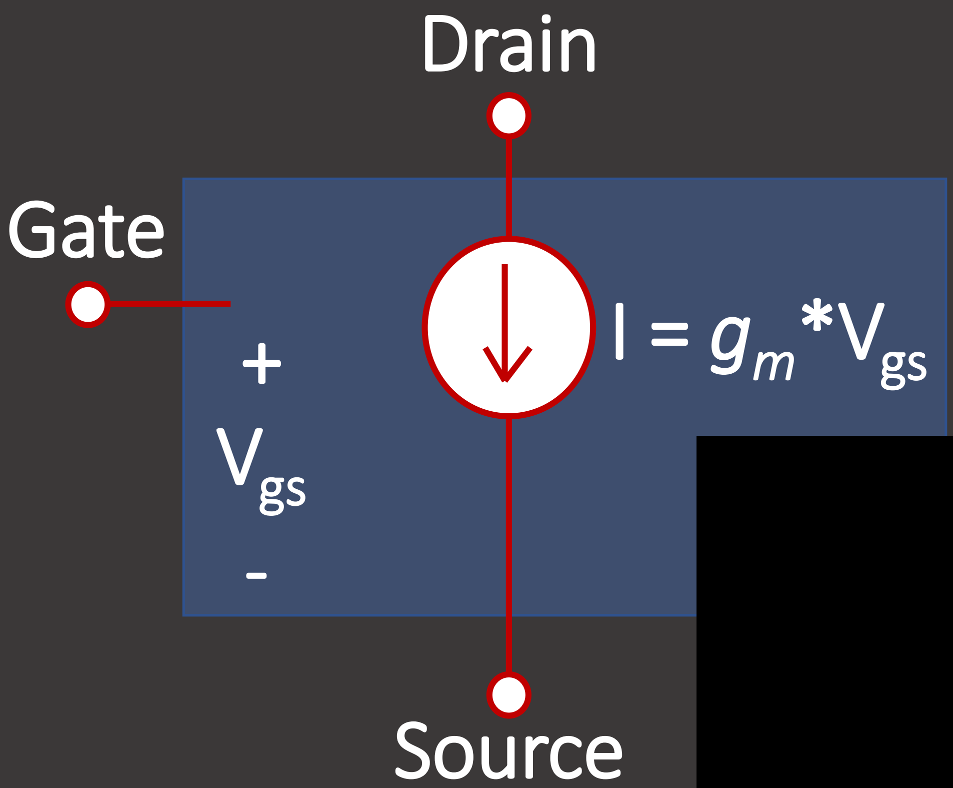
# Example circuits

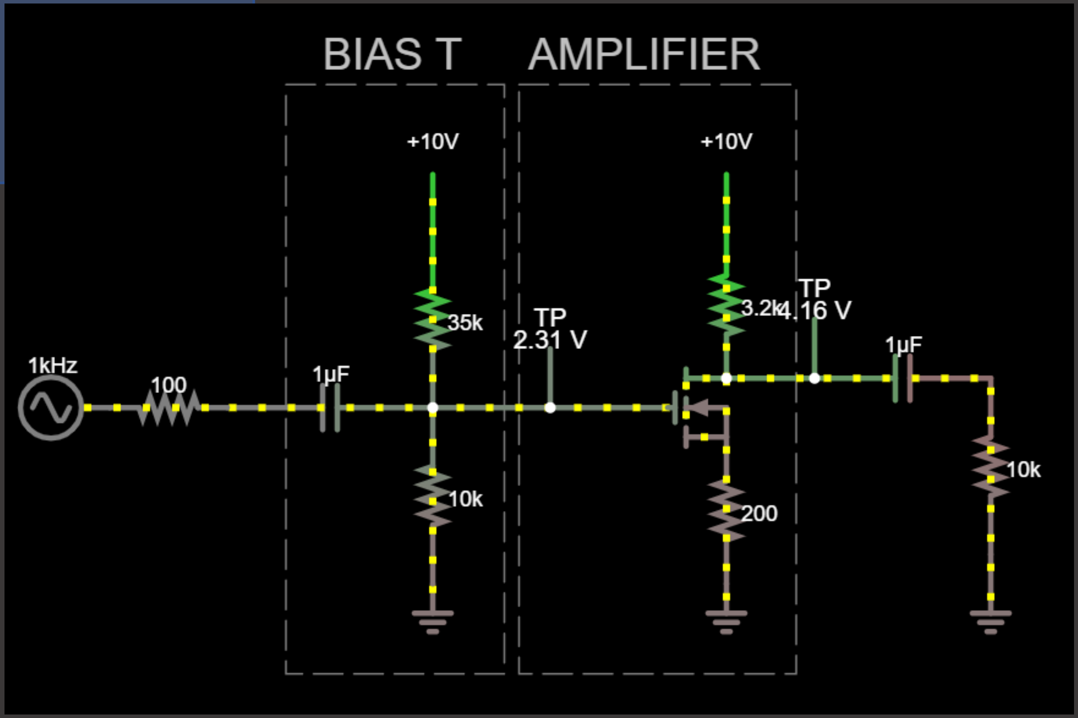


# Example circuits



# A more accurate FET model



# FETs vs BJTs – Which is best?

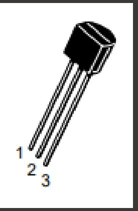
| Questionable generalizations! | **Bipolar (BJT)** | **FET (MOSFET)** |
|---|---|---|
| Speed | ✗ | ✓ |
| Gate/base current | ✗ | ✓ |
| On-state voltage drop | ✓ | ✗ |
| Low voltage circuits, esp when controlling high current | ✓ | ✗ |
| Ease of selection/application | (?) ✓ | (?) ✗ |

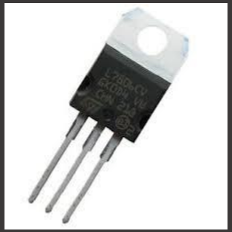
Practical guidance/tendencies:
- Low power, low voltage -> bipolar
- High current -> FET
- High efficiency switching supplies -> FET

# Go-to Transistors

Bipolar – the workhorse for enthusiasts

- 2N3904 – NPN, 40V, 200mA, 300MHz $f_T$
- 2N3906 – PNP, -40V. 200mA, 250MHz $f_T$
- TIP120 – NPN, 60V, 5A



MOSFETs

- Probably don’t want to stock FETs
- Wanna play? 2N7000, 2N7002 - NMOS