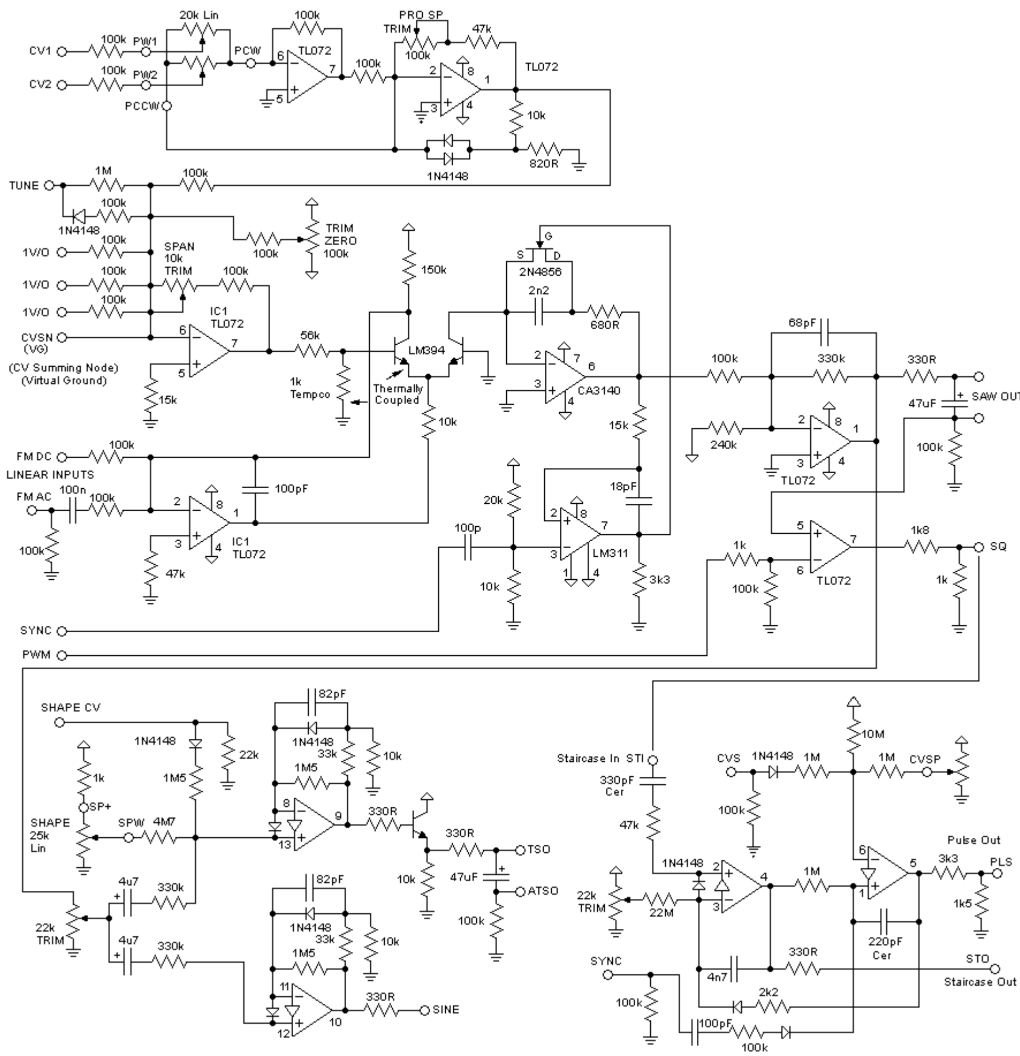
EE 140 | Op Amps Are Everywhere | CTN | 1

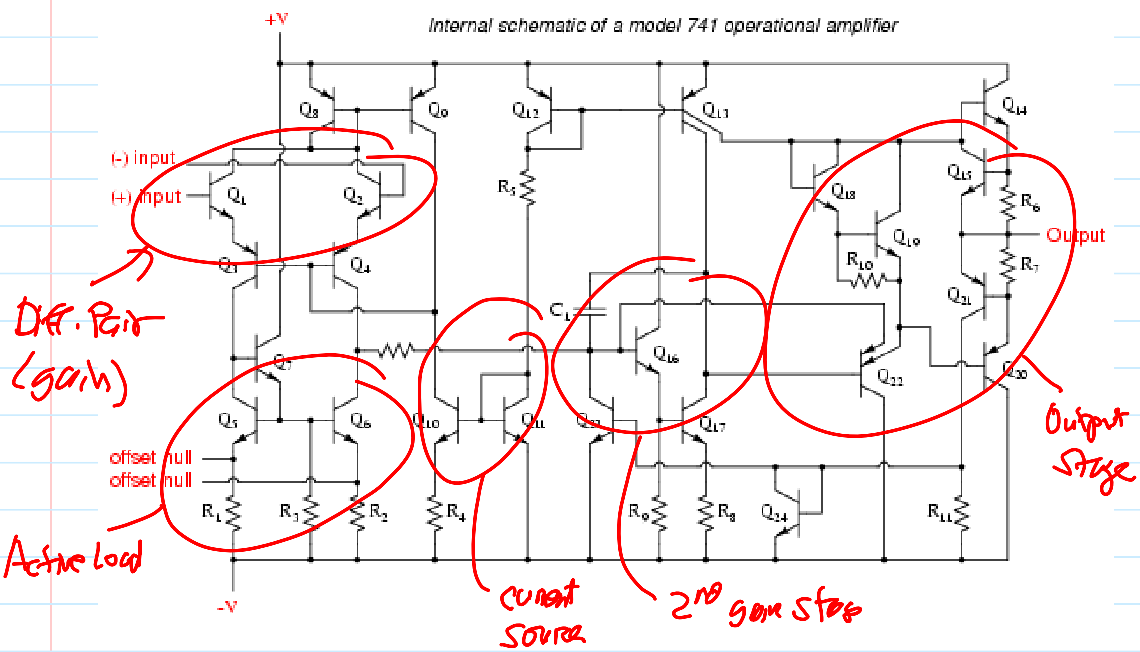
- Op amps are everywhere in practical circuits: (e.g., for solid-state guitar amplifiers, instrumentation, measurement tools, etc.)



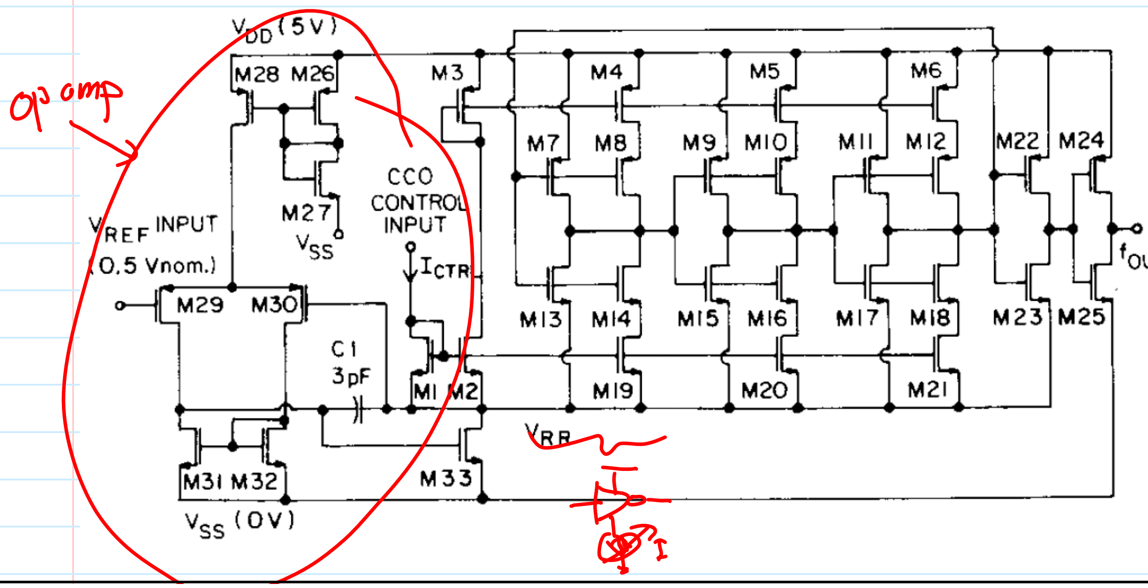
- Op amps that can be used to build practical board-level circuits are often implemented via bipolar junction transistor technology

EE 140 | Op Amps Are Everywhere | CTN | 2

- e.g., the 741 op amp, which has been a workhorse instrumentation op amp for decades



- Today, application specific integrated circuits (ASICs) for mixed analog/digital signal applications (e.g., A/D converters) utilize many op amps on the die level
  - ↳ such ASICs generally utilize CMOS op amps



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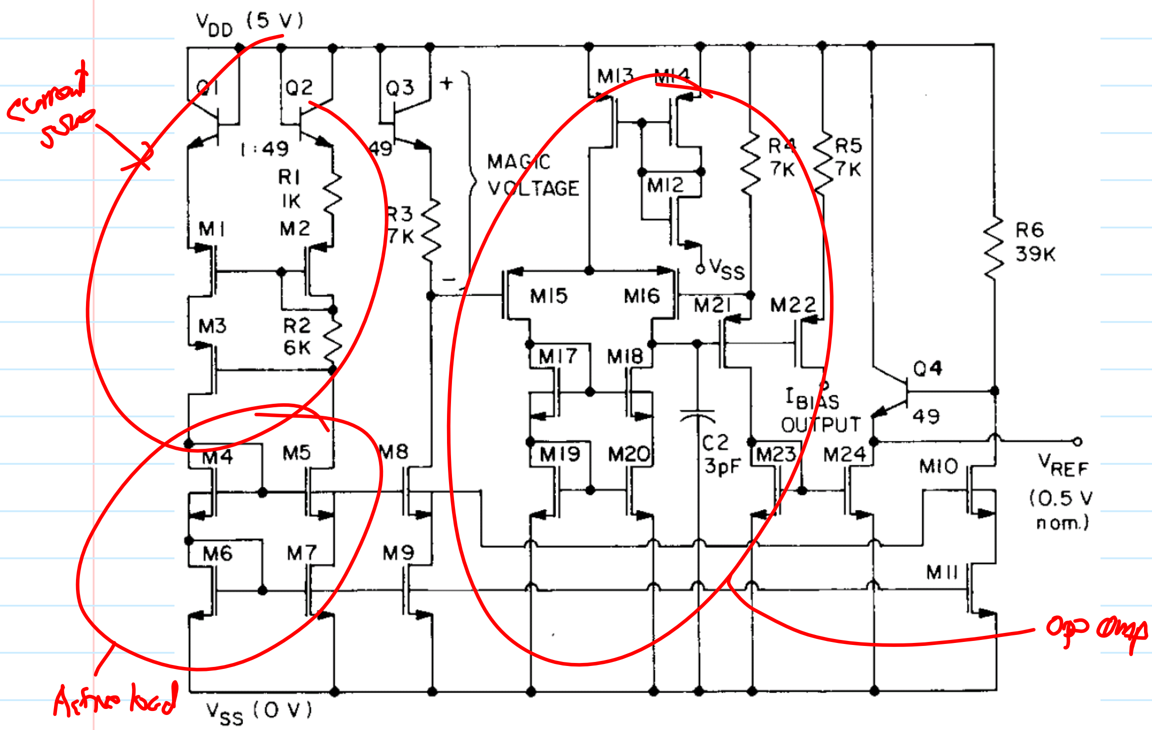
- **Below**: bandgap reference using a CMOS op amp



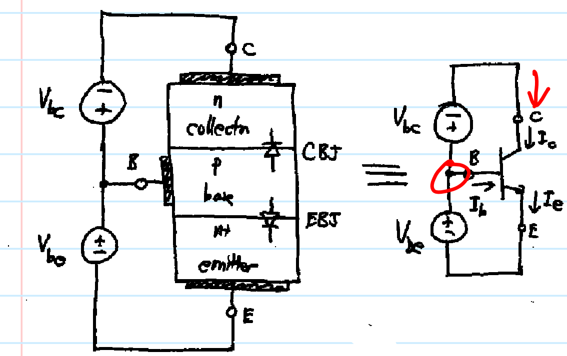
- Again, this course will focus mainly on the innards of op amps
- **Focus**: CMOS, with some BJT coverage so you can work with practical board-level circuits, as well
- The first step towards analyzing and designing op amps is to understand the transistor technologies upon which they are based

EE 140 | BJT Modeling | CTN | 4

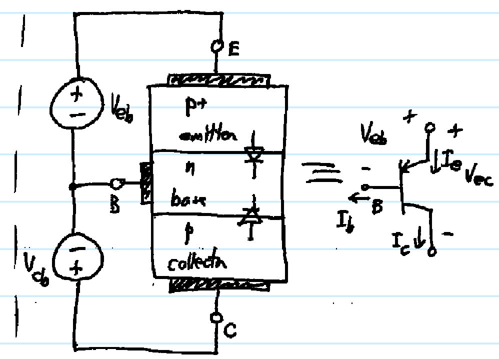
Modeling the Bipolar Junction Transistor (BJT)

→ physically, BJT's are just back-to-back pn junctions

npn bipolar Xsistor



pnp bipolar Xsistor

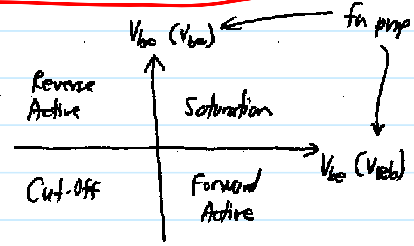


Regions of Bipolar Xsistor Operation

→ Key: R ≙ reverse-biased, F ≙ forward-biased

EBJ	CBJ	Mode
R	R	Cut-off (both diodes off)
F	R	Forward Active (widely used in analog amplifier ckts)
R	F	Reverse Active
F	F	Saturation

⇒ can also think of this in a convenient graphical sense:
→ for npn (pnp):



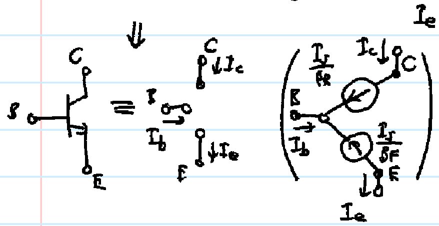
① Cut-Off Region – (npn transistor)

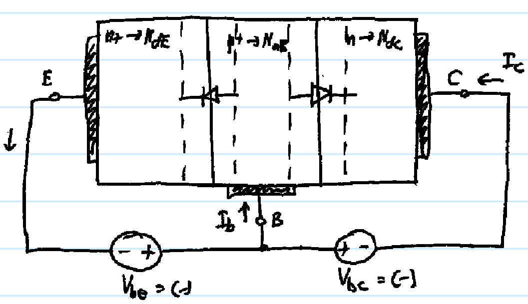
⇒ both diodes reverse-biased

⇒ no current flows:

$I_b = 0,\ I_c = 0,\ I_e = 0$

⇓

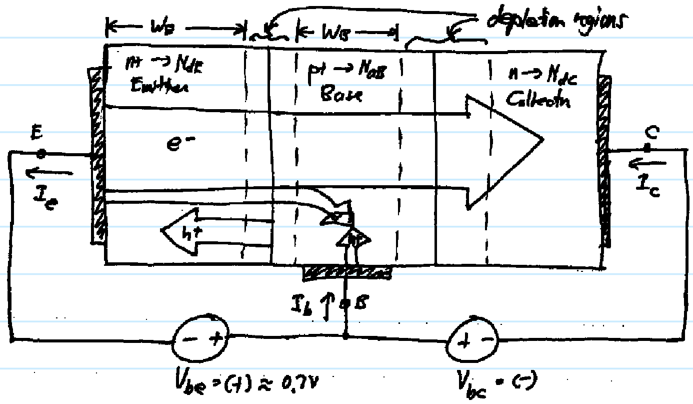


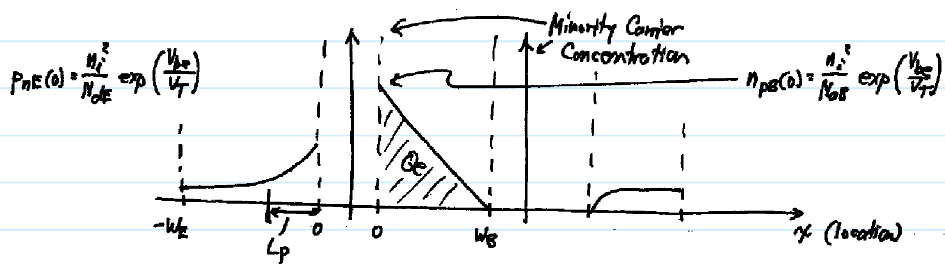


EE 140 | BJT Forward-Active | CTN | 5

② Forward-Active Region - (npn transistor)

⇒ BEJ Forward-Biased (i.e., diode on), BCJ Reverse-Biased (i.e., diode off)





Forward biasing of the BEJ generates three current components:

① e⁻'s injected from emitter to base: $I_{nB} = -A J_{nB}^{diff}$

② h⁺'s injected from base to emitter: $I_{pE} = A J_{pE}^{diff}$

③ recombination of e⁻'s & h⁺'s in base: I_{rB}

$I_c = I_{nB} = ①$

$I_e = I_{nB} + I_{pE} + I_{rB} = ① + ② + ③$

$I_b = I_{pE} + I_{rB} = ② + ③$

$$I_{nB} = -A J_{nB}^{diff} = -A q \underbrace{D_{nB}}_{\text{diffusion constant for } e^-\text{'s in B}} \underbrace{\frac{dn_{pB}(x)}{dx}}_{\text{slope}} = -qAD_{nB}\frac{[n_{pB}(W_B) - n_{pB}(0)]}{W_B} = \boxed{qAD_{nB}\frac{n_i^2}{N_{aB}W_B}\exp\left(\frac{V_{be}}{V_T}\right) = ①} \ *$$

$$\left[\begin{array}{l} n_{pB}(W_B) = \frac{n_i^2}{N_{aB}}\exp\left(\frac{V_{bc}}{V_T}\right) \approx 0 \\ n_{pB}(0) = \frac{n_i^2}{N_{aB}}\exp\left(\frac{V_{be}}{V_T}\right) \end{array}\right]$$

$I_c = I_S \exp\left(\frac{V_{be}}{V_T}\right)$

$$I_{pE} = A J_{pE}^{diff} = A q \underbrace{D_{pE}}_{\text{diffusion constant for } h^+\text{'s in E}} \underbrace{\frac{dp_{nE}(x)}{dx}}_{\text{slope}} = qAD_{pE}\frac{[p_{nE}(0) - p_{nE}(-W_E)]}{W_E} = \boxed{qAD_{pE}\frac{n_i^2}{N_{dE}W_E}\exp\left(\frac{V_{be}}{V_T}\right) = ②} \ *$$

$$\left[\begin{array}{l} p_{nE}(0) = \frac{n_i^2}{N_{dE}}\exp\left(\frac{V_{be}}{V_T}\right) \\ p_{nE}(-W_E) \approx 0 \end{array}\right]$$

could also replace by diffusion length, L_p (for h⁺ in n-type material)

