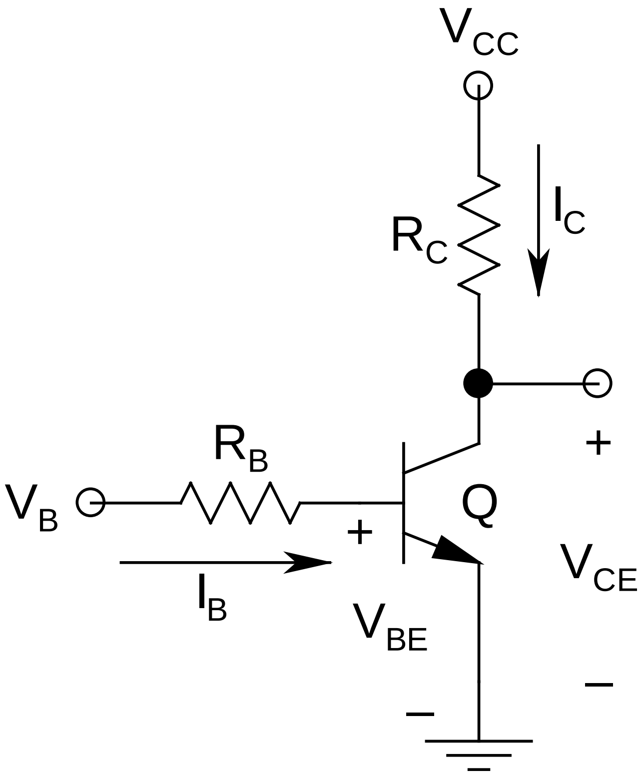
Finding the Operating Point: Load Line Analysis

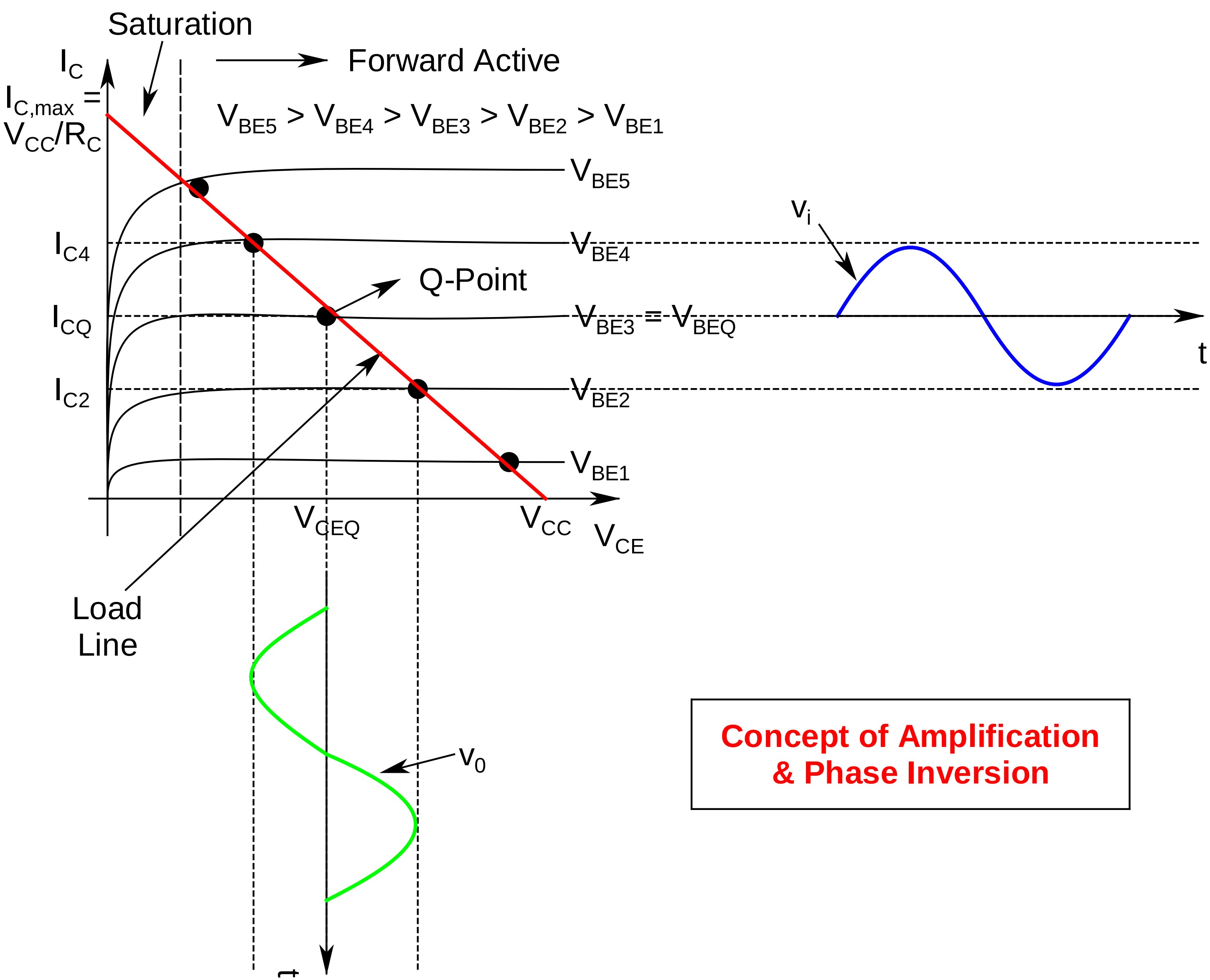
- ***Quick estimate*** in ***FA mode***:
  - $I_B = (V_B - V_{BE})/R_B$
  - $V_{BE} = 0.7$ V
  - $I_C = \beta I_B$
  - ***Independent*** of R_C, so long as ***FA operation*** is ***maintained***



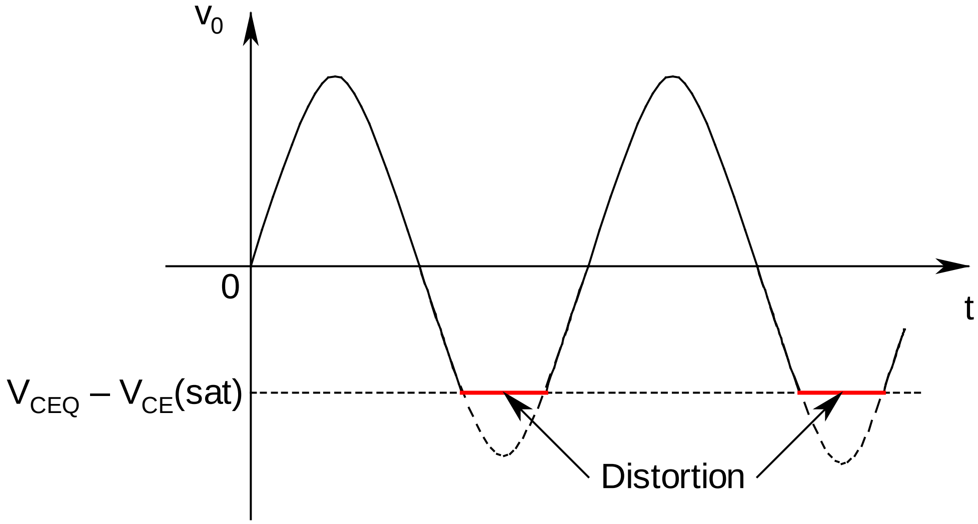
- For ***continuous variation*** of V_B, ***continuous variation*** of I_C and I_B
  - The ***output characteristics*** will ***fill up*** the ***entire quadrant***
- The ***operating point*** (***Q-point***) can ***lie anywhere*** in this ***quadrant***
- To find the ***unique*** Q-point, need to ***draw*** the ***load line***
- ***Load line equation***:
  - $I_C = (V_{CC} - V_{CE})/R_C$

- ***2 boundary points***:
  - For $I_C = 0$, $V_{CE} = V_{CC}$
  - For $V_{CE} = 0$, $I_C = V_{CC}/R_C$
- ***Joining*** these ***2 points*** by a ***straight line*** gives the ***load line***
- The ***intersection point*** of the ***load line*** with the ***output characteristic*** gives the ***Q-point***
- Gives ***infinite number*** of ***choices*** for ***possible Q-point***

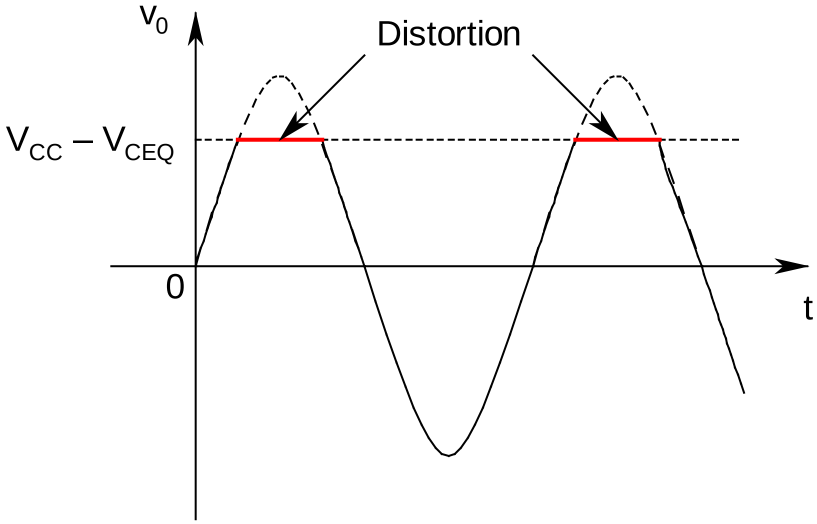
- The ***best choice*** for the ***Q-point*** is ***right at the center*** of the ***load line***
  - V_{CEQ}(best) = $V_{CC}/2$ and I_{CQ}(best) = $V_{CC}/(2R_C)$
- ***Permits the maximum possible signal swing in both directions***
- If $V_{CEQ} > V_{CC}/2$, it's ***biased more towards cutoff***
- If $V_{CEQ} < V_{CC}/2$, it's ***biased more towards saturation***
- ***Either way***, we will get a ***distorted output***



Concept of Amplification & Phase Inversion



(a) **Negative Clipping**:
Saturation Induced



(b) **Positive Clipping**:
Cutoff Induced

- Under ***application*** of an ***ac signal*** (v_i), the ***dynamic operating point*** (DOP) will ***move along the load line***
- For ***positive*** v_i, the DOP ***will move*** Q ***towards saturation*** ($V_{CE} \rightarrow 0$, $I_C \rightarrow I_{C,max}$)
  - The ***output signal*** (v_0) will be in its ***negative excursion***
  - If Q enters ***saturation***, ***negative peak*** of v_0 will get ***clipped***
  - ***Distorted output***

- For ***negative*** v_i, the DOP ***will move*** Q ***towards cutoff*** ($V_{CE} \rightarrow V_{CC}$, $I_C \rightarrow 0$)
  - The ***output signal*** (v_0) will be in its ***positive excursion***
  - If Q ***cuts off***, ***positive peak*** of v_0 will get ***clipped***
  - ***Distorted output***
- ***Golden rule of thumb for BJT biasing***:
  - ***To get maximum undistorted peak-to-peak swing of v_0, Q-point must be chosen to be at the middle of the load line***

- ***Role of R_C***:
  - Under ***FA mode***, ***R_C does not control I_C*** , however, it ***changes V_{CE}*** $(= V_{CC} - I_C R_C)$
  - If $R_C\uparrow$, $V_{CE}\downarrow \Rightarrow$ Q moves ***towards saturation***
  - If $R_C\downarrow$, $V_{CE}\uparrow \Rightarrow$ Q moves ***towards cutoff***
  - Thus, ***different values of R_C*** can produce ***different Q-points*** (***in terms of V_{CE}***)
- ***DC Power Dissipation***:
  - $P_D = V_{BEQ} \times I_{BQ} + V_{CEQ} \times I_{CQ}$

    $\approx V_{CEQ} \times I_{CQ}$ (***under FA mode***)

Some Observations

- Q should be ***biased*** such that it is in the ***FA*** mode of operation
  - Behaves like a ***constant and ideal current source with infinite output resistance***, since I_C is ***independent*** of V_{CE}
  - ***Ideal region to bias a BJT***
- For ***very high*** R_C, $I_{C,max}$ ***very small***
  - ***Load line may not have any intersection point in the FA region at all***

- ***Q-point moves to saturation region***
- ***Ceases to become a constant current source***, since in ***saturation***, I_C becomes a ***strong function*** of V_{CE}
- ***Disastrous way of biasing a BJT***

• ***Similar situation*** will arise if R_C is ***very small***

- $I_{C,max}$ will become ***very large*** and ***Q-point will move towards cutoff***
- ***Another disastrous way of biasing a BJT***

- **Example**: Let $V_{CC} = V_B = 5$ V, $R_B = 430$ kΩ, and $\beta = 100$
  - ➢ $I_B = (V_B - V_{BE})/R_B = (5 - 0.7)/(430\ \text{k}\Omega) = 10$ μA (assuming ***FA*** mode of operation with $V_{BE} = 0.7$ V)
  - ➢ $I_C = \beta I_B = 1$ mA
  - ➢ V_{CE} will ***depend*** on our ***choice*** of R_C
  - ➢ R_C for ***best biasing*** (BB) (V_{CE}(BB) = $V_{CC}/2$):
    - $R_C(\text{BB}) = V_{CC}/(2I_C) = 2.5$ kΩ
  - ➢ R_C that puts Q at OS (VCE(OS) = 0.7 V):
    - $R_C(\text{OS}) = [V_{CC} - V_{CE}(\text{OS})]/I_C = 4.3$ kΩ

- ***Any value of R_C higher than 4.3 kΩ would push Q in saturation***
- Choose R_C = 20 kΩ:
  - Assuming ***FA*** operation is maintained, V_{CE} comes out to be –15 V!
  - ***Golden rule***:
    - ***Potential at any point in a circuit can never go beyond the positive and negative extremes of the power supply voltages, unless there is a power source within the circuit***
  - Thus, V_{CE} = –15 V is ***absurd***
  - Hence, Q is ***no more*** in the ***FA*** mode of operation, rather it has been pushed into ***saturation***

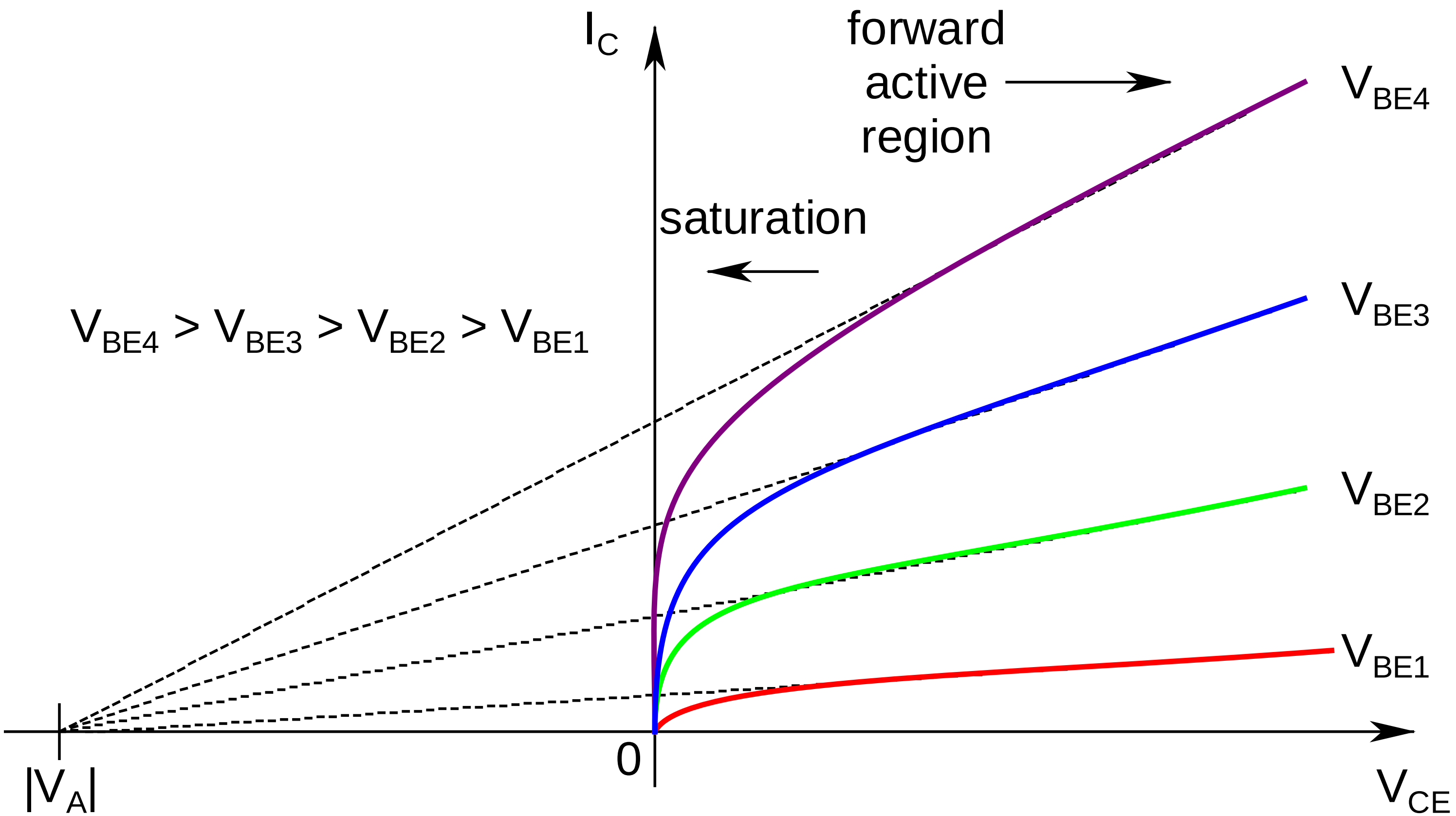
- Whether it is in ***soft saturation*** (SS) or ***hard saturation*** (HS), would ***depend*** on the ***degree of saturation*** (DoS)
- ***For HS, DoS must be ≥ 2*** ($\beta sat \leq \beta$)
- Assume ***HS***: $V_{BE}(HS) = 0.8$ V, $V_{CE}(HS) = 0.1$ V
  - $I_{B,sat} = [V_{CC} - V_{BE}(HS)]/R_B = (5 - 0.8)/(430\ k\Omega) = 9.77\ \mu A$
  - $I_{C,sat} = [V_{CC} - V_{CE}(HS)]/R_C = (5 - 0.1)/(20\ k\Omega) = 245\ \mu A$
  - $\beta_{sat} = I_{C,sat}/I_{B,sat} = 245/9.77 = 25$
  - $DoS = \beta/\beta_{sat} = 4$ (> 2)
  - ***Assumption verified, and analysis is correct***!

➢ **Ex.**: Find the values of R_C that would put Q at the edge of: i) HS, and ii) SS

Base Width Modulation Effect

- In ***FA*** mode, as $|V_{BC}|\uparrow$, BC ***depletion region width***$\uparrow \Rightarrow$ ***neutral base width***$\downarrow$
  - ***Electrons spend less time in base*** $\Rightarrow$ ***chance of recombination***$\downarrow$
  - ***More electrons make it to the collector*** $\Rightarrow I_C\uparrow$ as $V_{CE}\uparrow$
  - Known as the ***Base Width Modulation Effect*** (or ***Early Effect***, after inventor **J.M. Early**)

- The ***current-voltage characteristic***, including ***Early Effect***, is modeled as:
  - $I_C = I_S[\exp(V_{BE}/V_T)](1 + V_{CE}/V_A)$
  - V_A: ***Early Voltage*** (~130 V for ***npn***, and ~52 V for ***pnp***)
  - V_A is a ***negative number***, but taken to be a ***positive quantity***
- Imparts a ***positive slope*** in the ***output characteristics*** in the ***FA region***
  - Introduces an ***output resistance***, and makes the current source ***non-ideal***!



All characteristics merge at $|V_A|$ in the negative V_{CE} axis

Note: If $V_A \to \infty$, all characteristics become horizontal in the FA region