

Radio Design 101

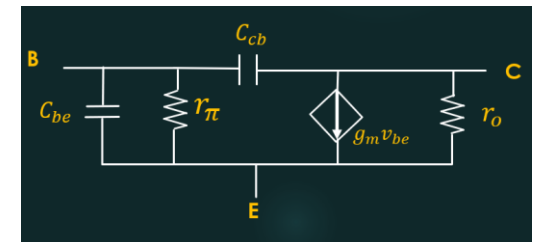
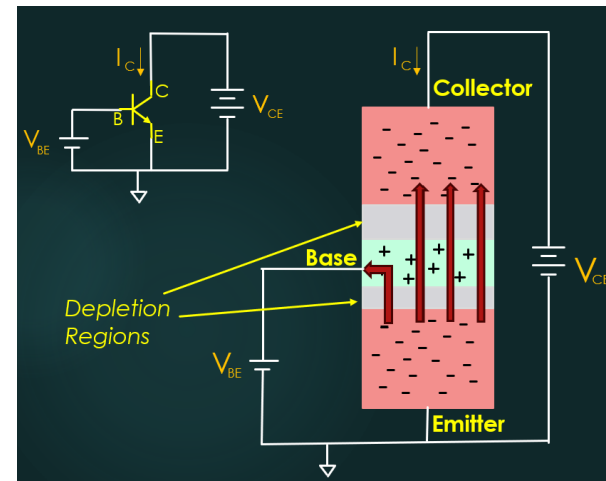
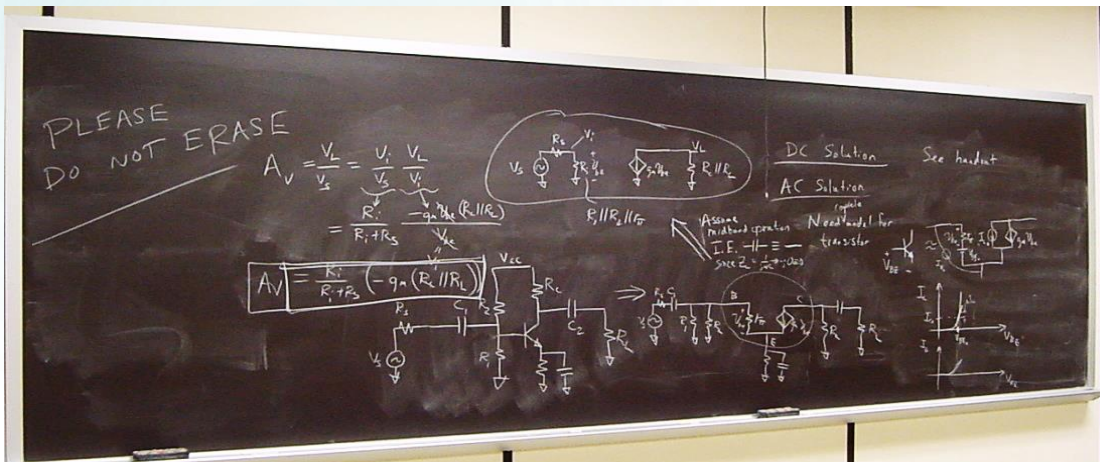
Appendix A (Episode 3 Part2) – Transistors and Amplifiers at RF

Slides downloaded from: <https://ecefiles.org/rf-design/>

Companion video at: https://youtu.be/m9X0mfg_8lQ

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This is Episode 3, Part 2, but is optional, so it is placed in the Radio Design 101 video series as Appendix A. The material here is not essential for design and construction of our FM radio receiver. Rather, it is provided for those who want more background in the analysis of small signal RF amplifiers, and the operation of transistors used in their design. We review Episode 3 (Part 1), and then show how BJT transistors are created and how they are modeled. The goal is to provide a broader foundation for those interested in different amplifier types (such as common-emitter and cascode), and in the underlying mathematics from which gains, input and output impedances, and operating frequency limitations can be understood.



Radio Design 101

Episode 3 – Part 2 (Optional ☺)

Transistors & Amplifiers @ RF

PLEASE DO NOT ERASE

$$A_V = \frac{V_L}{V_S} = \frac{V_i}{V_S} \frac{V_L}{V_i}$$
$$= \frac{R_i}{R_i + R_S} \frac{-g_m (R_C \parallel R_L)}{1 + g_m R_E}$$

DC Solution See handout

AC Solution

Assume midband operation
I.E. $\omega \gg \omega_{\beta}$
see $Z_{in} = \frac{1}{g_m} \parallel R_E$

Need model for complete transistor

The chalkboard contains several diagrams and equations. At the top left, the text 'PLEASE DO NOT ERASE' is written. Below it, the voltage gain equation is derived: $A_V = \frac{V_L}{V_S} = \frac{V_i}{V_S} \frac{V_L}{V_i}$, which simplifies to $A_V = \frac{R_i}{R_i + R_S} \frac{-g_m (R_C \parallel R_L)}{1 + g_m R_E}$. To the right, there are two circuit diagrams: one showing a signal source V_S connected to a common-emitter amplifier with input resistance R_i and output resistance R_o , and another showing a load R_L connected to the output. Below these, a larger circuit diagram shows a common-emitter amplifier with a signal source V_S , biasing network (resistors R_1, R_2), collector resistor R_C , emitter resistor R_E , and load resistor R_L . A small-signal equivalent circuit is also shown, with the input resistance R_i and output resistance R_o indicated. On the right side, there is a graph showing the relationship between current I and voltage V_{BE} , with labels I_B , I_C , and I_E . The text 'DC Solution See handout' and 'AC Solution' are written above the graph. A note says 'Assume midband operation I.E. $\omega \gg \omega_{\beta}$ see $Z_{in} = \frac{1}{g_m} \parallel R_E$ '. Another note says 'Need model for complete transistor'.

Radio Design 101 Series



Radio Design 101

MegawattKS

Public

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Shuffle

A collection of videos abstracted from a university course on radio / RF circuit design.

The goal is a working FM broadcast receiver, but the material is applicable to all wireless hardware from Amateur Radio to commercial RF integrated circuits.

While the focus is on circuit design, episodes in this series touch on a large set of topics ranging from basic circuit and system architectures to radio performance measurement and optimization. More information on the videos and the university course from which it came is available at: <https://ecefiles.org/>



Radio Design 101 - Episode 1 - Transceivers and Filters - Part 1

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Radio Design 101 - Episode 3 - RF Amplifiers

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Radio Design 101 - RF Oscillators (Episode 4)

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Radio Design 101 - RF Mixers and Frequency Conversions - Episode 5, Part 1

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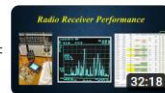
Radio Design 101 - RF Mixers, Part 2 of Episode 5

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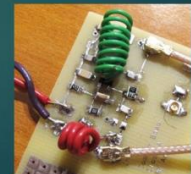
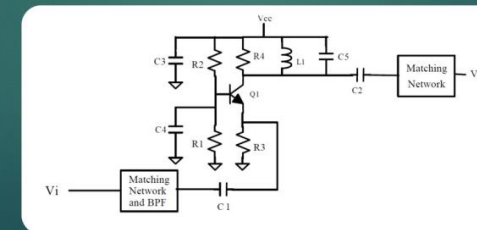
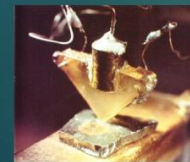
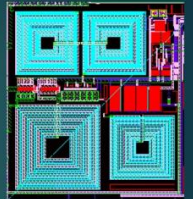


Receiver Performance - Radio Design 101 Epilogue 1

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Radio Design 101 Episode 3

RF Amplifiers



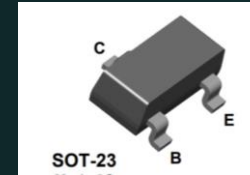
Outline of this Episode

Part 1

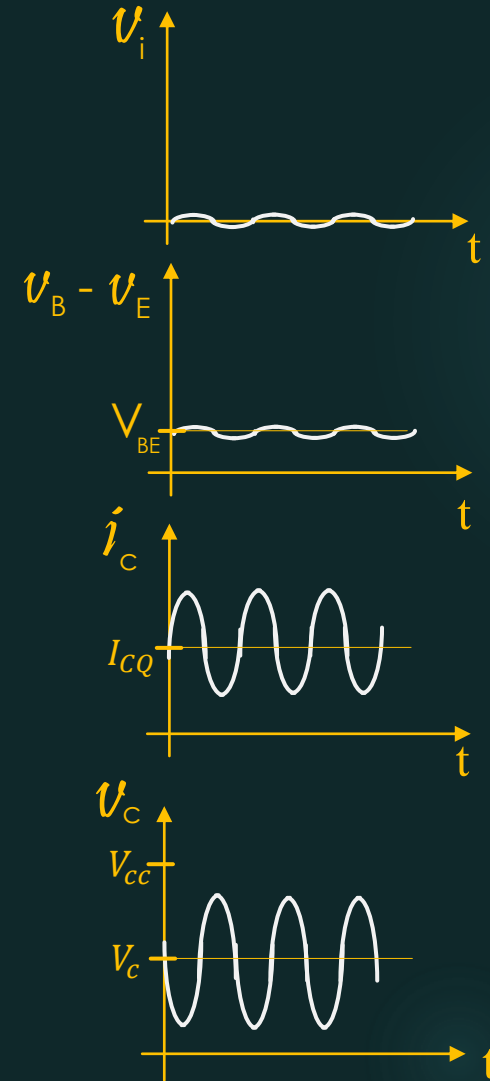
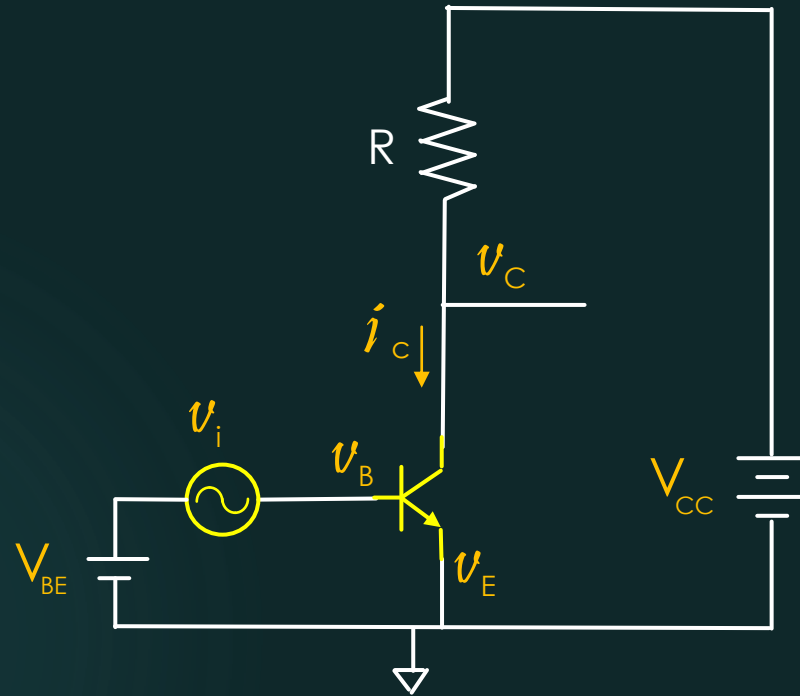
- *Triode Devices*
- *DC Biasing*
- *AC Gain and I/O Impedances*
- *Small Signal Amplifier Configurations*

Part 2

- *Transistors, Data Sheets and Models*
- *High Frequency Model and Limitations*



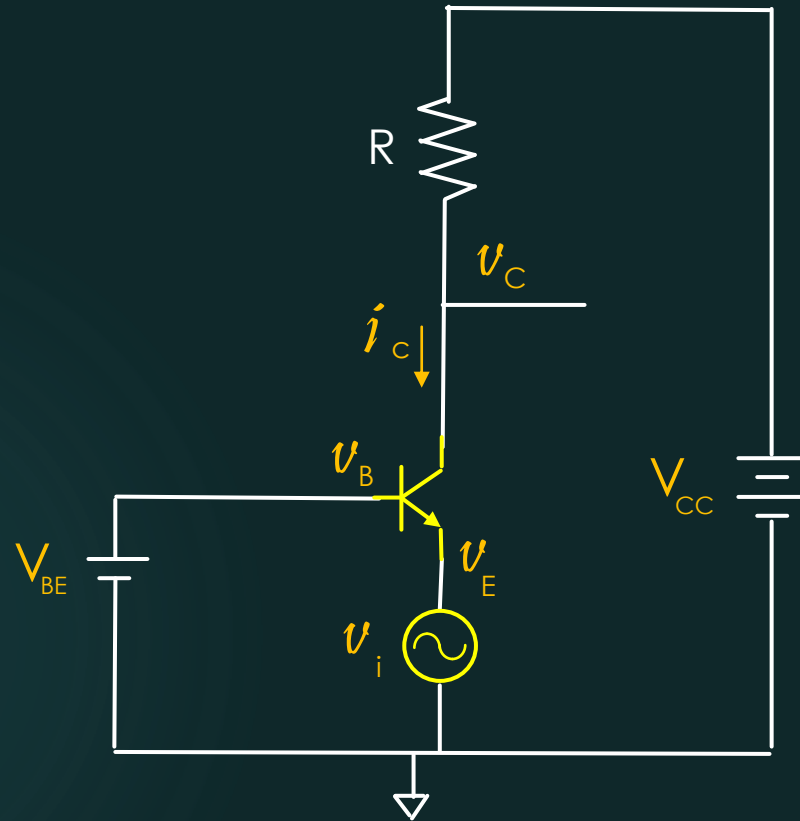
Recall Basic Amplifier Concept



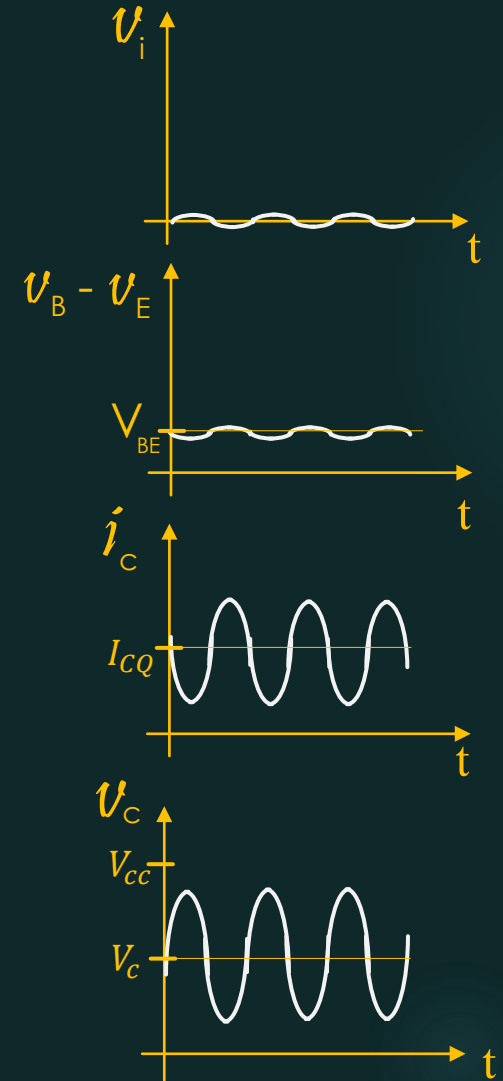
"Transconductance" $g_m \triangleq \frac{\Delta I_c}{\Delta V_{BE}}$

$$A_v = -g_m R$$

Alternative “Common-Base” Configuration

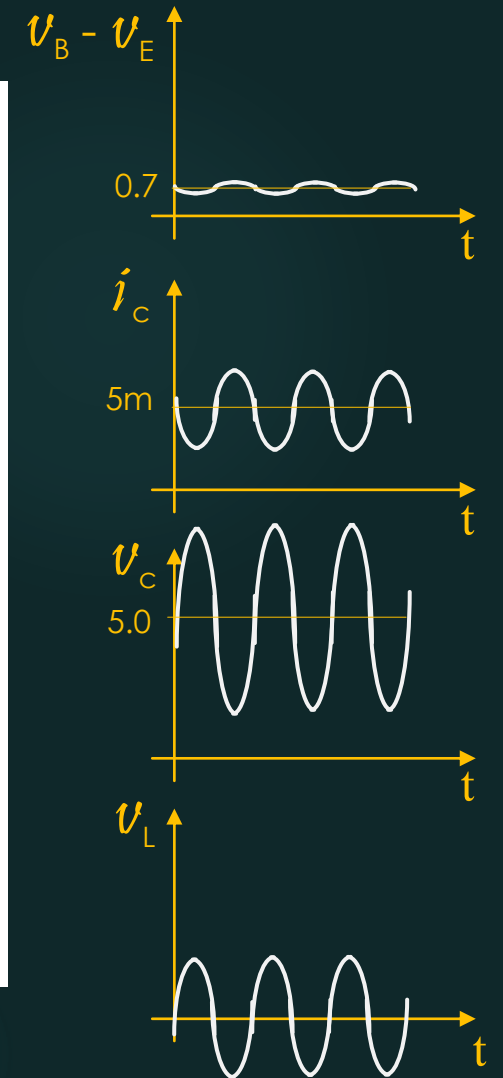
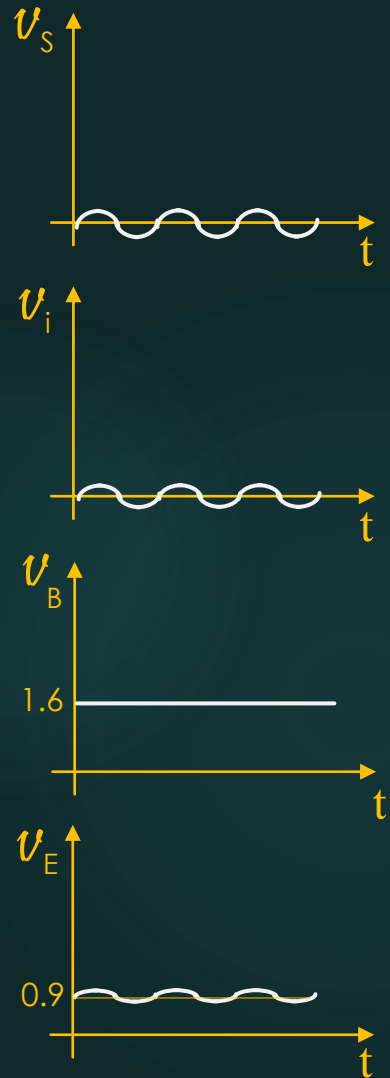
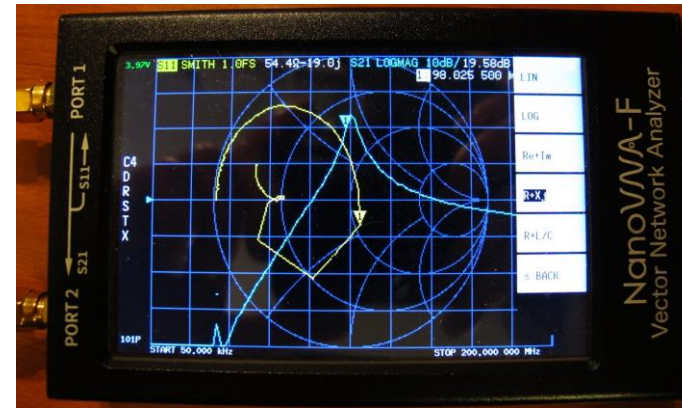
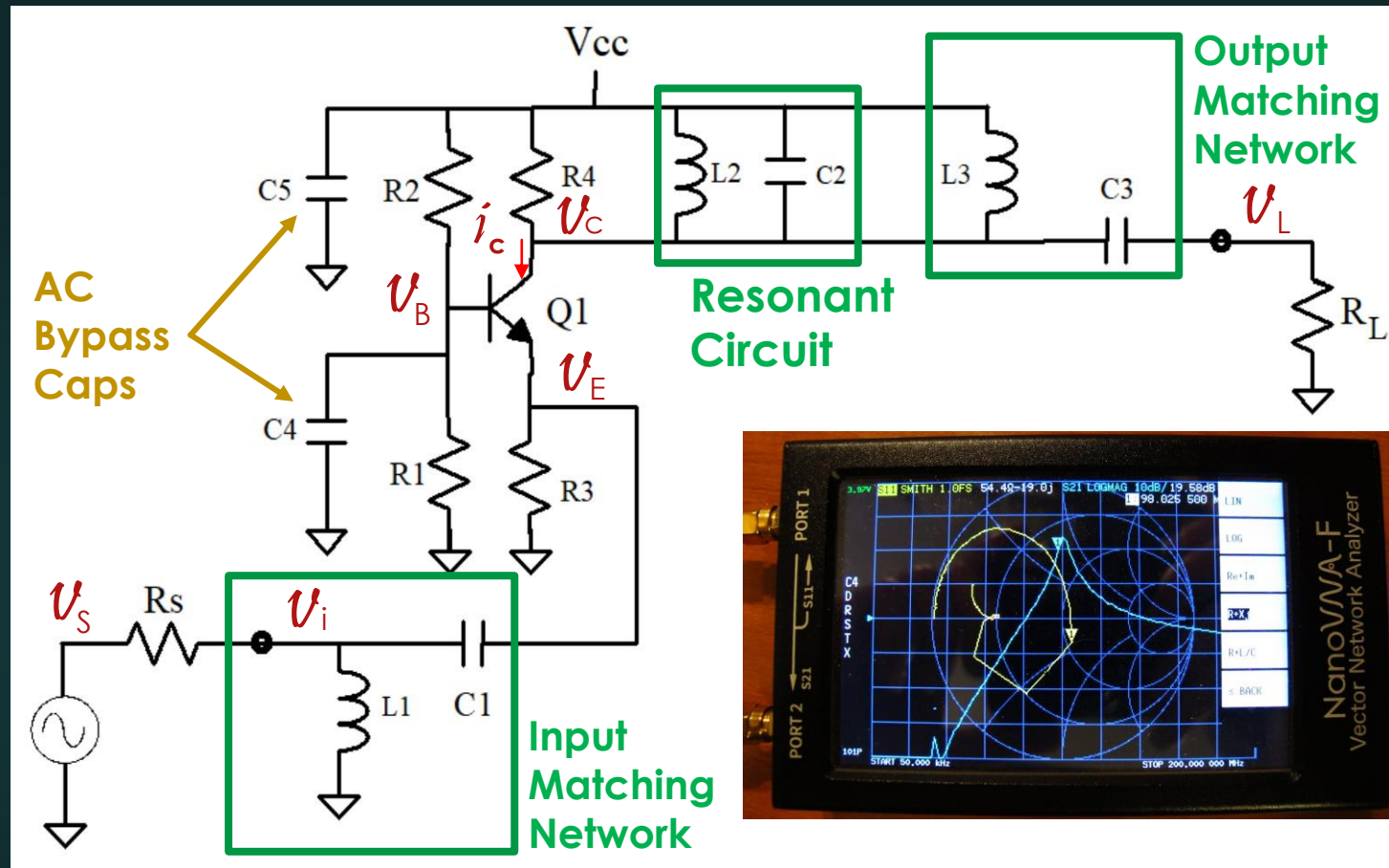


$$A_v = g_m R$$

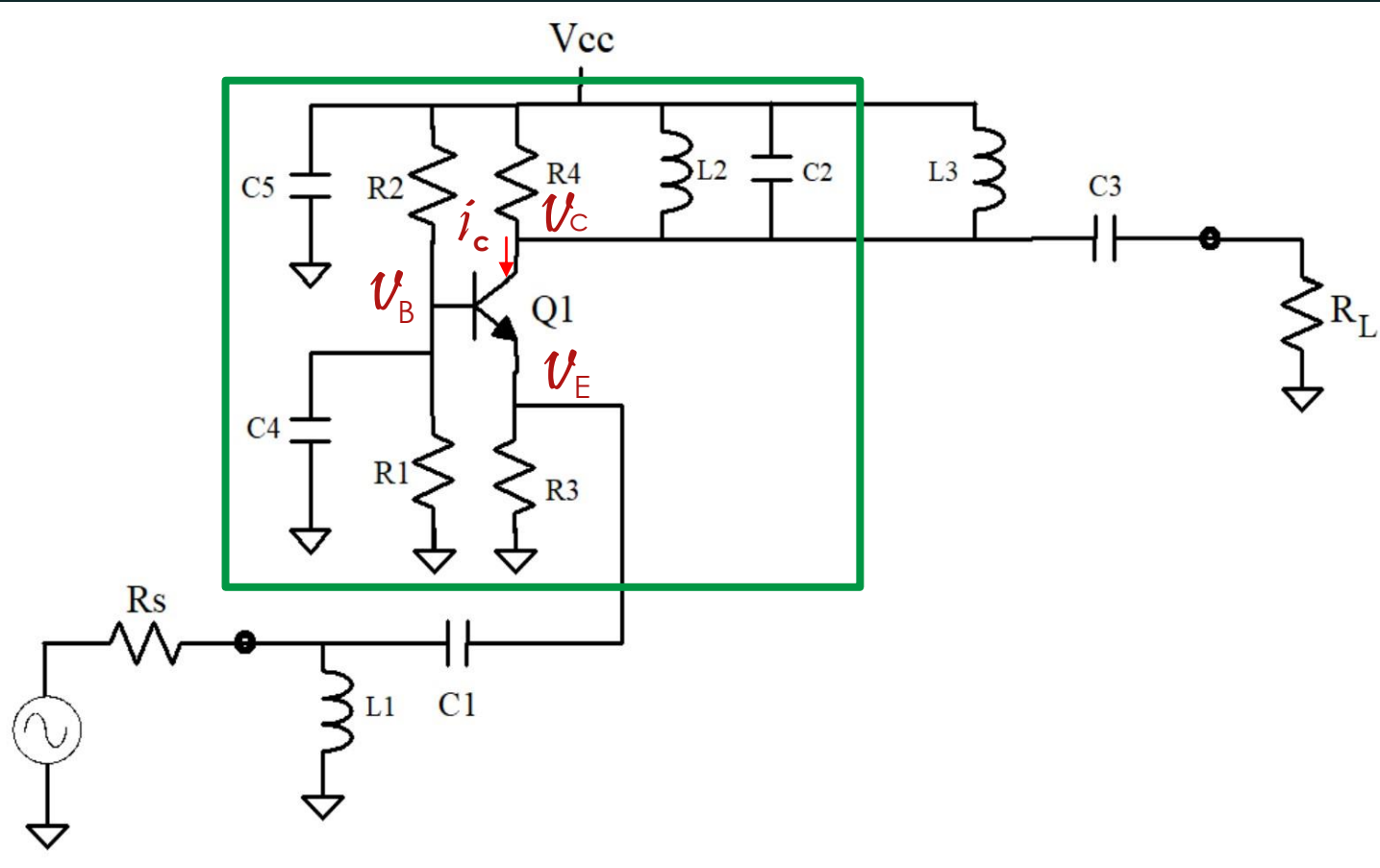


Practical Common-Base RF Amplifier

DC+AC Solution (From Part 1)



Core Amplifier Circuit Analysis



Analysis Method

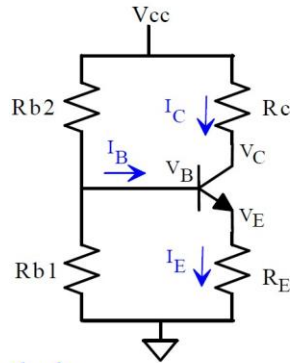
Based on superposition theory and linearized device models

- Solve DC bias to get I_c and g_m
- Solve AC small signal circuit to find gain (and R_i , R_o), and AC voltages, currents
- Add two solutions to get full waveforms, if designed

Practical BJT Biasing (From Part 1)

DC Biasing of Class A BJT Amplifiers

A traditional "4-resistor bias circuit" is shown below.



Bias circuit analysis

Assume the transistor is operating in the active region, and that Beta or h_{FE} is "large". Then, I_B will be approximately zero (relative to the current in R_{b1} , R_{b2}), and we can use the simple voltage divider formula at the base to get,

$$V_B \approx V_{cc} \frac{R_{b1}}{R_{b1} + R_{b2}}$$

If the transistor is in the active region, the BE junction is forward biased and $V_{BE_{on}} \approx 0.7V$. Hence,

$$V_E \approx V_B - 0.7$$

The emitter current is then,

$$I_E = \frac{V_E}{R_E}$$

and the collector current is,

$$I_C \approx I_E$$

Finally, the collector voltage can be found from the IR drop in R_C as,

$$V_C = V_{cc} - I_C R_C *$$

Note that these equations are reasonably independent of the transistor gain h_{FE} , provided the current through R_{b1} and R_{b2} is $\gg I_B$. Hence, the bias voltages and currents should not change significantly with changes in h_{FE}

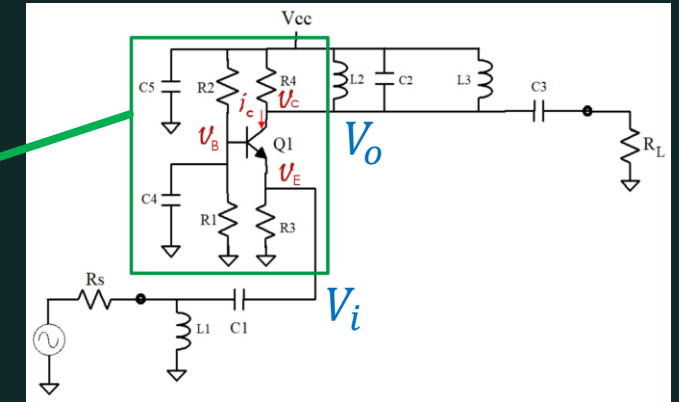
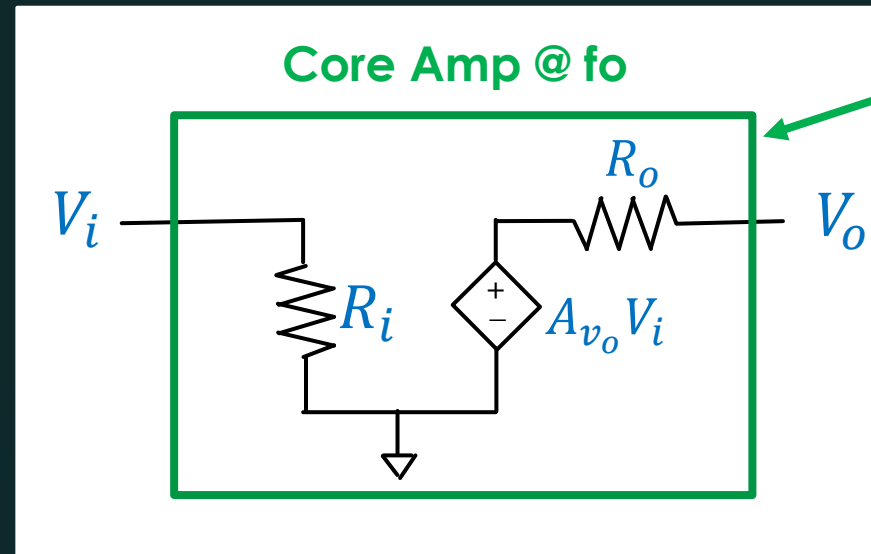
Note also that the bias current and DC voltages will be relatively insensitive to small variations in V_{BE} caused by temperature or manufacturing, provided that V_E is greater than about 0.5 to 1 volt.

* For an RF amplifier with LC across R_C , V_C will be equal to V_{cc}

AC Small Signal Model Of Voltage Amplifier Core

Simplified **equivalent circuit (VCVS type)**

Based on Thevenin's theorem



- R_i , R_o , and A_{v_o} depend on amplifier device, circuit configuration, and biasing.
- In general, we should use Z_i , Z_o , and complex frequency-dependent gain ...

SS Amplifier Configurations Review

(Low Frequency Formulas)

Configuration	Representative Circuit	Approx. Formulas	$A_{V_{no-load}}$	R_i	R_o
Common Emitter		$A_{V_{no-load}} = -g_m (R_c \parallel r_o)$ $R_i = r_\pi \parallel R_{b1} \parallel R_{b2}$ where $r_\pi = h_{fe}/g_m$ $R_o = R_c \parallel r_o$	High	Med	Med
Common Base		$A_{V_{no-load}} = +g_m (R_c \parallel r_o)$ $R_i = 1/g_m \parallel R_E \parallel r_\pi$ $R_o = R_c \parallel r_o$	High	Low	Med
Common Collector (Emitter follower)		$A_{V_{no-load}} \approx 1$ $R_i = R_{b1} \parallel R_{b2} \parallel r_\pi (1 + g_m R_E)^*$ $R_o = 1/g_m^{**}$	Unity	High	Low

* Assumes unloaded output

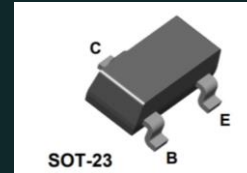
** Assumes low source R

Where do these formulas come from ?

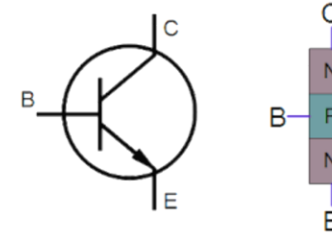
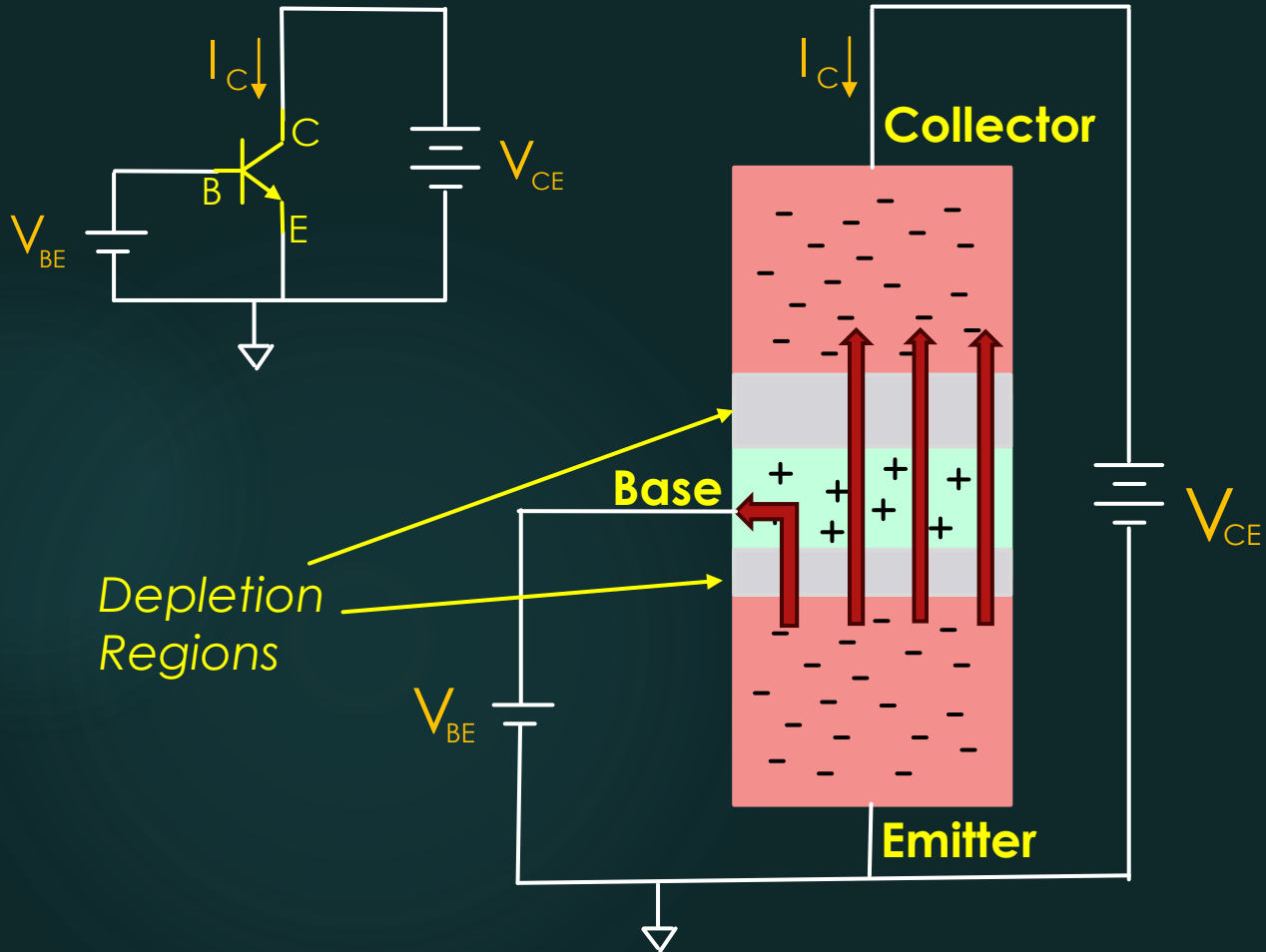
Let's find out ...

Outline

- *Triode Devices*
- *DC Biasing*
- *AC Gain and I/O Impedances*
- *Small Signal Amplifier Configurations*
- *Transistors, Data Sheets and Models*
- *High Frequency Model and Limitations*



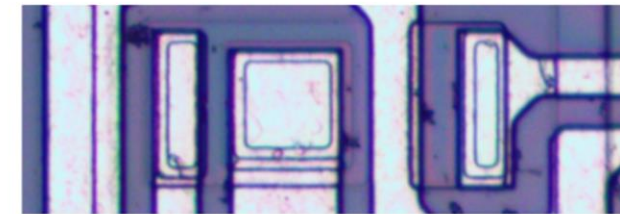
BJT Transistor Structure and Physics



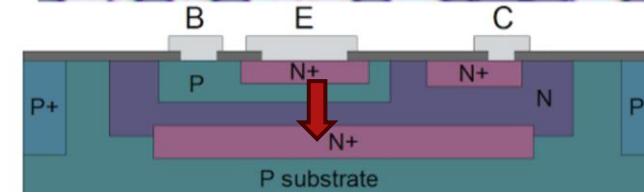
Ken Shirriff's blog

Computer history, restoring vintage computers, IC reverse engineering, and whatever

Reverse engineering a counterfeit 7805 voltage regulator



Top View



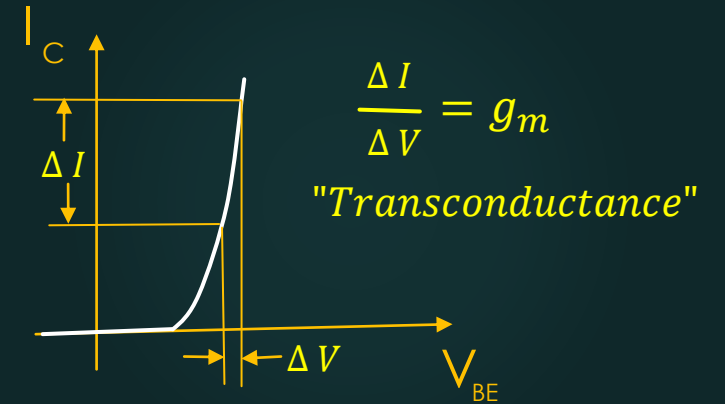
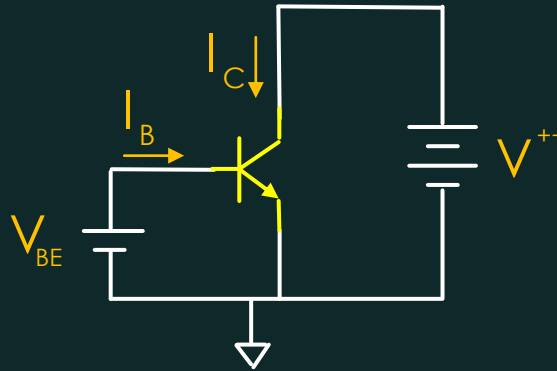
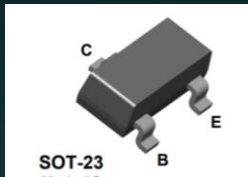
Side View

Structure of a NPN transistor inside the 7805 voltage regulator.

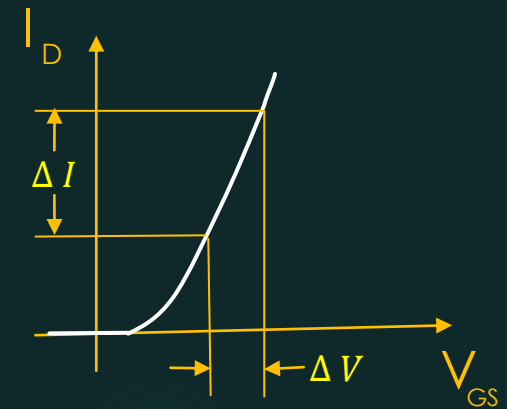
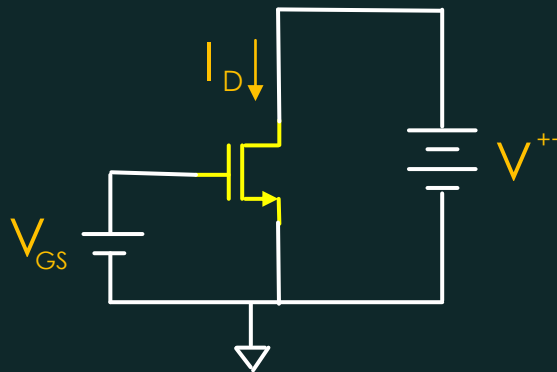
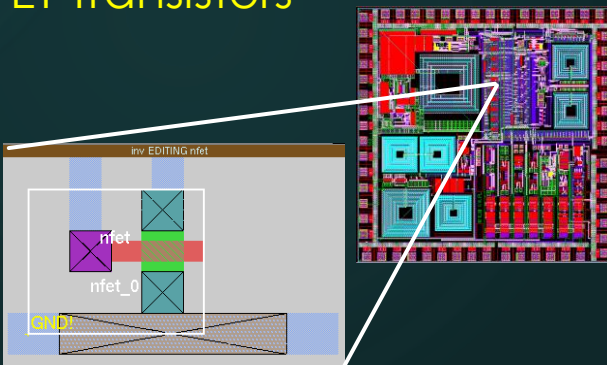
BJTs vs MOSFETs

Similarities and Differences

Bipolar Junction Transistor



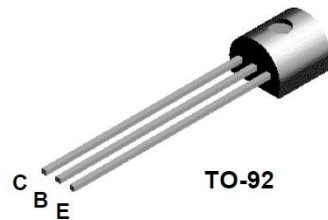
MOSFET Transistors



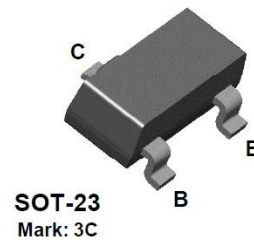
Example BJT Datasheet



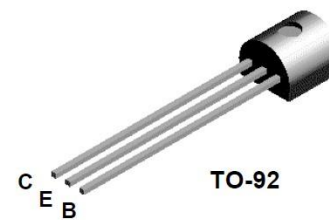
MPS5179



MMBT5179



PN5179



MPS5179 / MMBT5179 / PN5179

NPN RF Transistor

This device is designed for use in low noise UHF/VHF amplifiers with collector currents in the 100 μ A to 30 mA range in common emitter or common base mode of operation, and in low frequency drift, high output UHF oscillators. Sourced from Process 40.

Absolute Maximum Ratings* TA = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	12	V
V_{CBO}	Collector-Base Voltage	20	V
V_{EBO}	Emitter-Base Voltage	2.5	V
I_C	Collector Current - Continuous	50	mA

Tabular Data

NPN RF Transistor (continued)

MPS5179 / MMBT5179 / PN5179

Electrical Characteristics TA = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{CEO(sus)}$	Collector-Emitter Sustaining Voltage*	$I_C = 3.0 \text{ mA}, I_B = 0$	12		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	$I_C = 1.0 \text{ }\mu\text{A}, I_E = 0$	20		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	$I_E = 10 \text{ }\mu\text{A}, I_C = 0$	2.5		V
I_{CBO}	Collector Cutoff Current	$V_{CB} = 15 \text{ V}, I_E = 0$ $V_{CB} = 15 \text{ V}, T_A = 150^\circ\text{C}$		0.02 1.0	μA μA
ON CHARACTERISTICS					
h_{FE}	DC Current Gain	$I_C = 3.0 \text{ mA}, V_{CE} = 1.0 \text{ V}$	25	250	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	$I_C = 10 \text{ mA}, I_B = 1.0 \text{ mA}$		0.4	V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	$I_C = 10 \text{ mA}, I_B = 1.0 \text{ mA}$		1.0	V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	$I_C = 5.0 \text{ mA}, V_{CE} = 6.0 \text{ V},$ $f = 100 \text{ MHz}$	900	2000	MHz
C_{cb}	Collector-Base Capacitance	$V_{CB} = 10 \text{ V}, I_E = 0,$ $f = 0.1 \text{ to } 1.0 \text{ MHz}$		1.0	pF
h_{fe}	Small-Signal Current Gain	$I_C = 2.0 \text{ mA}, V_{CE} = 6.0 \text{ V},$ $f = 1.0 \text{ kHz}$	25	300	
$rb'C_c$	Collector Base Time Constant	$I_C = 2.0 \text{ mA}, V_{CB} = 6.0 \text{ V},$ $f = 31.9 \text{ MHz}$	3.0	14	ps
NF	Noise Figure	$I_C = 1.5 \text{ mA}, V_{CE} = 6.0 \text{ V},$ $R_S = 50\Omega, f = 200 \text{ MHz}$		5.0	dB
FUNCTIONAL TEST					
G_{pe}	Amplifier Power Gain	$V_{CE} = 6.0 \text{ V}, I_C = 5.0 \text{ mA},$ $f = 200 \text{ MHz}$	15		dB
P_O	Power Output	$V_{CB} = 10 \text{ V}, I_E = 12 \text{ mA},$ $f \geq 500 \text{ MHz}$	20		mW

NOTE:
Current gain
 $\beta \equiv h_{FE}$

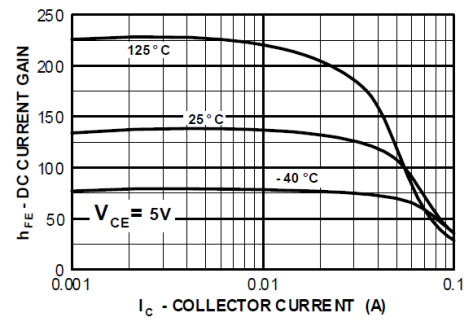
Graphs

NPN RF Transistor (continued)

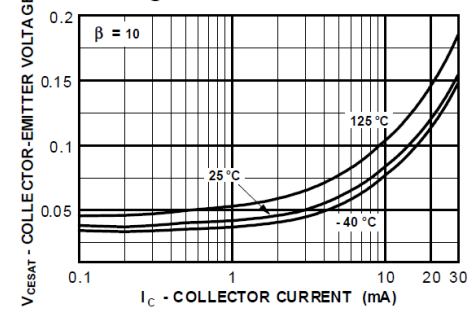
MPS5179 / MMBT5179 / PN5179

Typical Characteristics

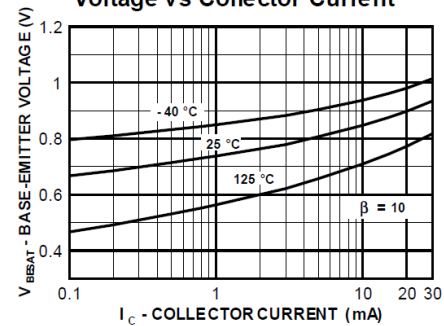
DC Current Gain vs Collector Current



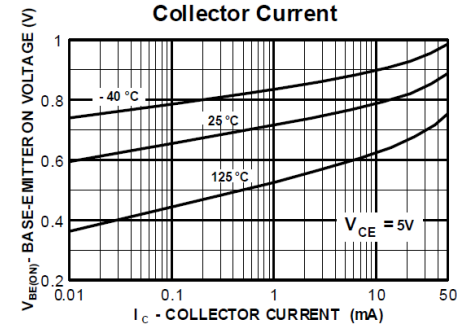
Collector-Emitter Saturation Voltage vs Collector Current



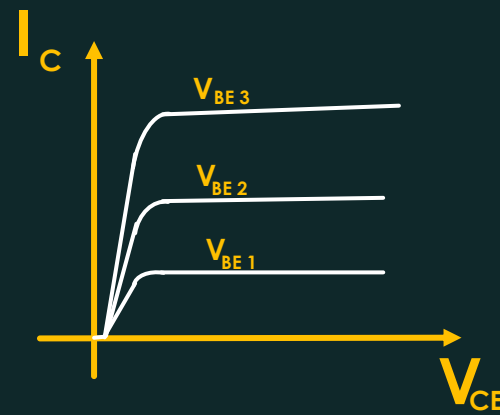
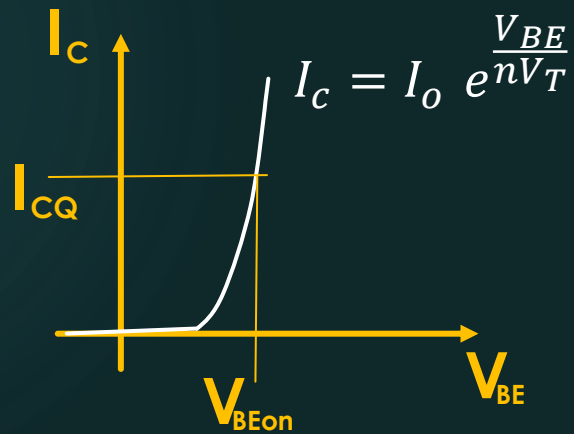
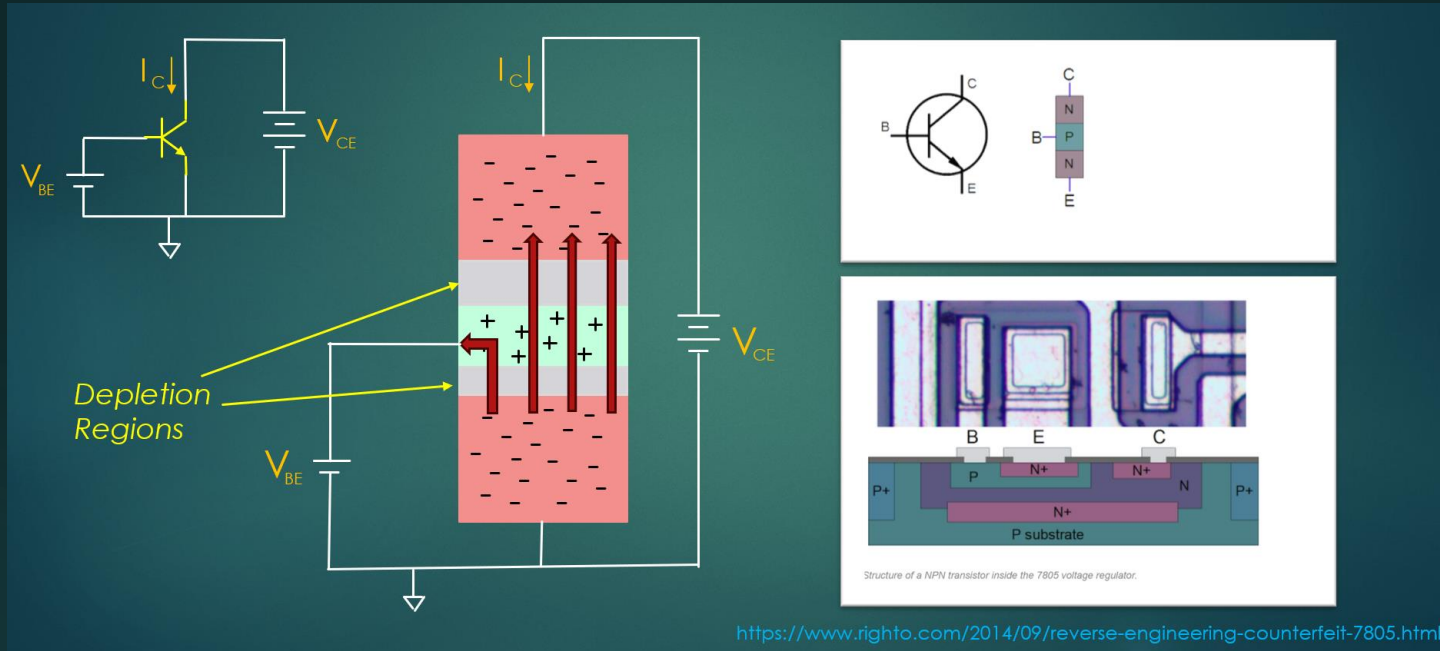
Base-Emitter Saturation Voltage vs Collector Current



Base-Emitter ON Voltage vs Collector Current



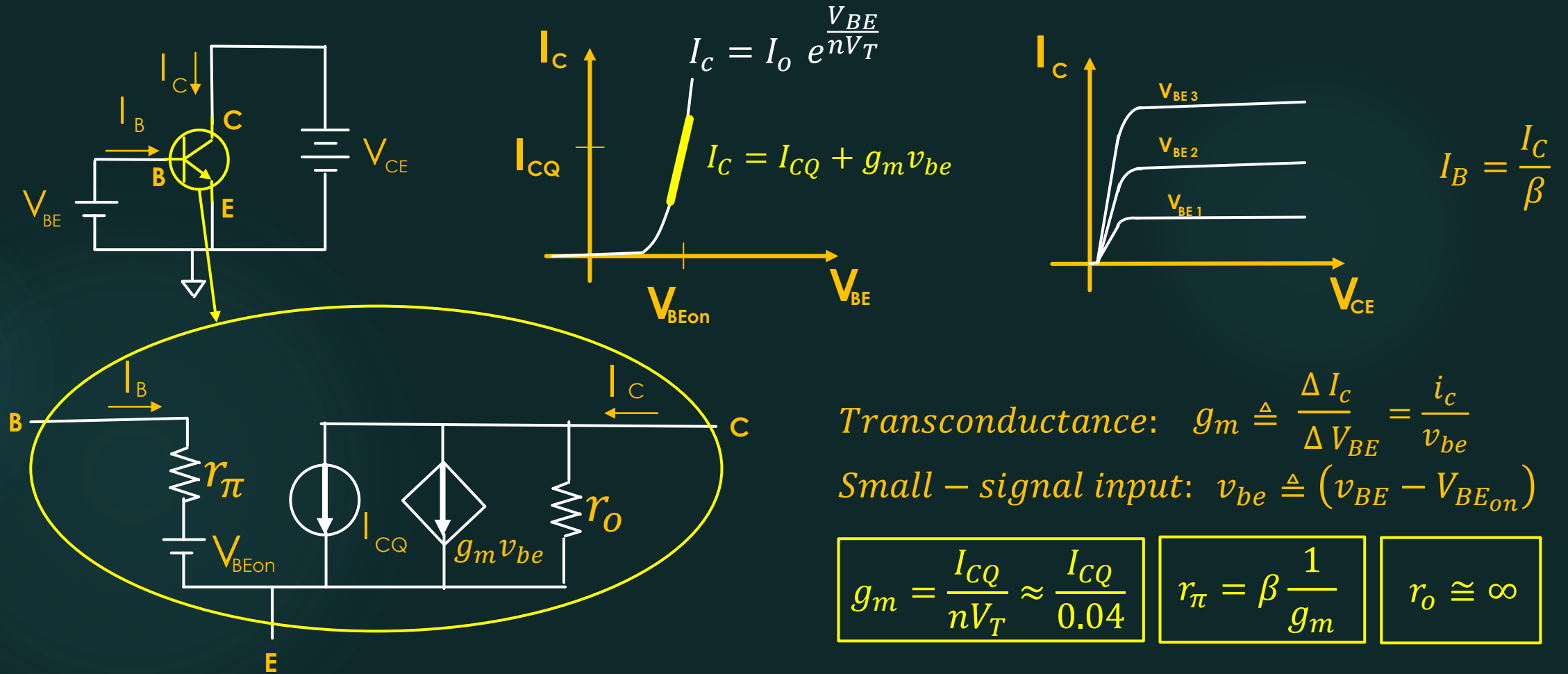
IV Curves



$$I_B = \frac{I_C}{\beta}$$

BJT Linearized Circuit Model

(at DC, low, and mid frequencies)



NOTE: Circuit model is a Taylor Series expansion of $I_C(V_{BE})$ around bias point V_{BEon}, I_{CQ}

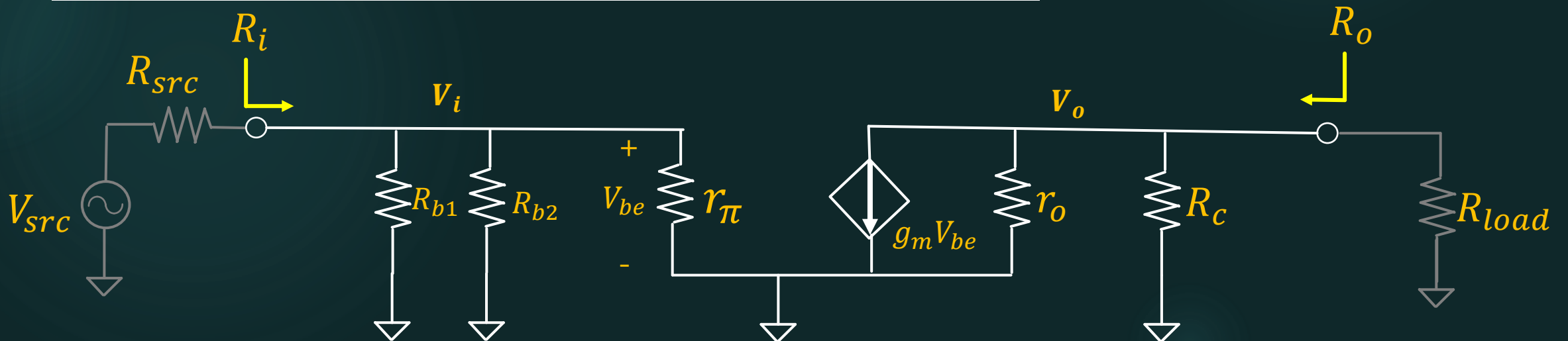
BJT Amp Small Signal AC Analysis At “Midband” Frequencies

Configuration	Representative Circuit	Approx. Formulas	$A_{V_{no-load}}$	R_i	R_o
Common Emitter		$A_{V_{no-load}} = -g_m (R_c \parallel r_o)$ $R_i = r_\pi \parallel R_{b1} \parallel R_{b2}$ where $r_\pi = h_{fe}/g_m$ $R_o = R_c \parallel r_o$	High	Med	Med

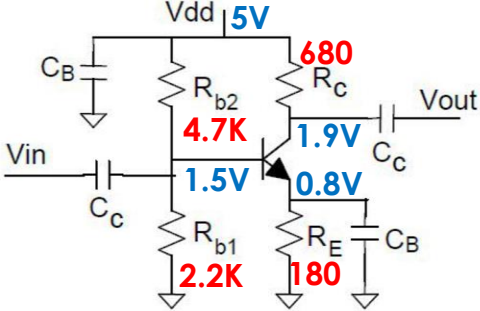
$$V_o|_{R_{load}=\infty} = -g_m v_{be} (R_c \parallel r_o)$$

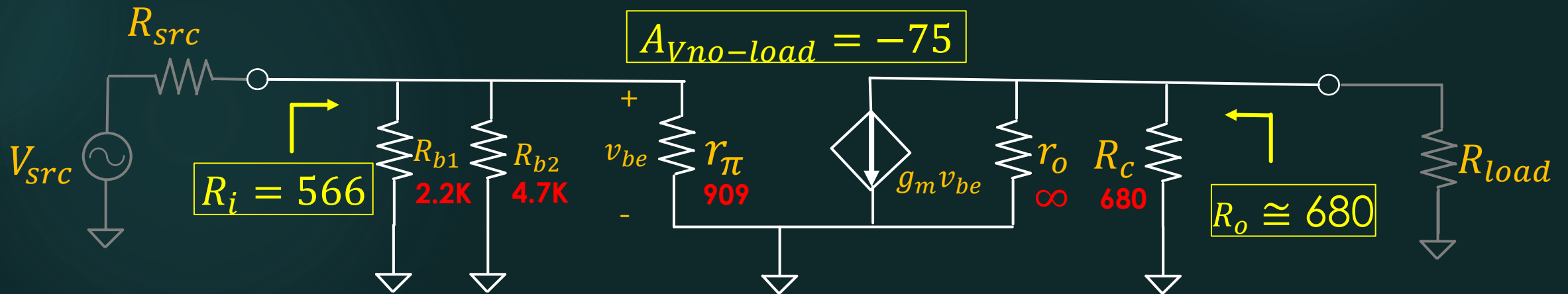
$$V_{be} \equiv V_i$$

$$\Rightarrow \left. \frac{V_o}{V_i} \right|_{R_{load}=\infty} = -g_m (R_c \parallel r_o)$$



Example Values

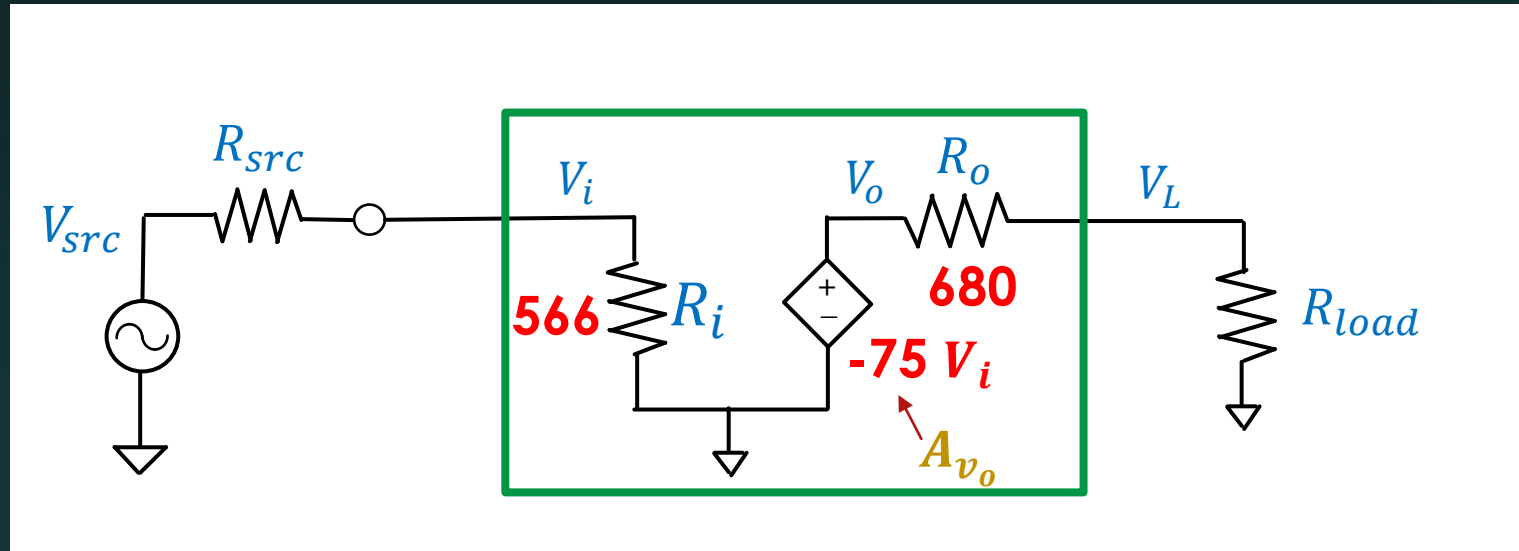
Configuration	Representative Circuit	Approx. Formulas	$A_{V_{no-load}}$	R_i	R_o
Common Emitter		$I_C = 4.5 \text{ mA} \Rightarrow g_m = 0.11 \text{ A/V}$ $r_\pi = \frac{100}{0.11} = 909$ $r_o \cong \infty$	$A_{V_{no-load}} = -g_m (R_C \parallel r_o)$ “High” 75	Med 566	Med 680
		$R_i = r_\pi \parallel R_{b1} \parallel R_{b2}$ where $r_\pi = h_{fe}/g_m$ $R_o = R_C \parallel r_o$ $h_{fe} \cong \beta = \frac{I_C}{I_B}$			



$|A_{V_{loaded}}| < 75$ Why?

A_V loaded

NOTE: Voltage amplifier model below can be derived from previous one using Thevenin's Theorem

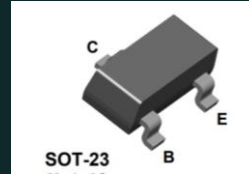


Then:

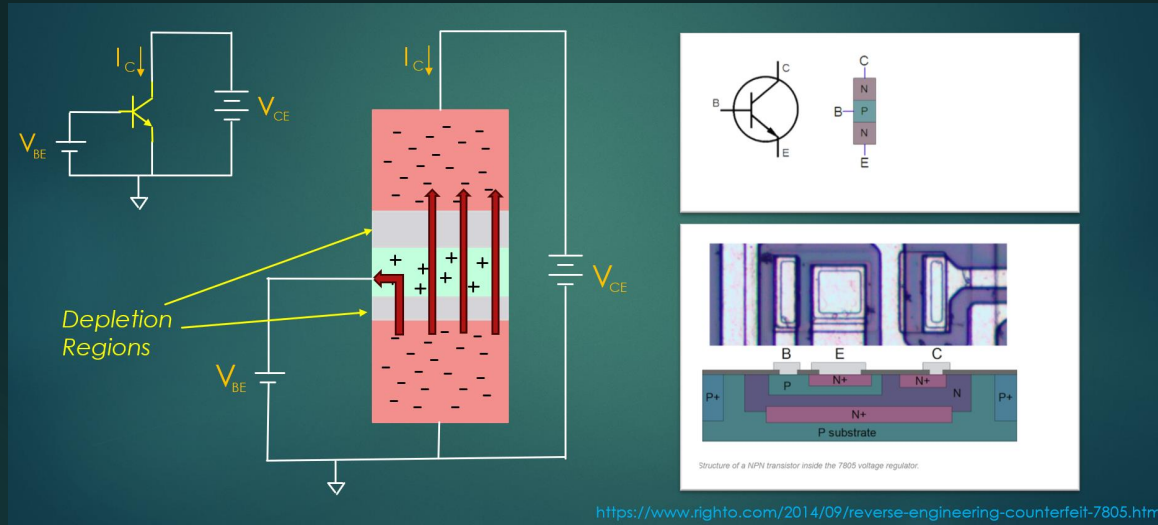
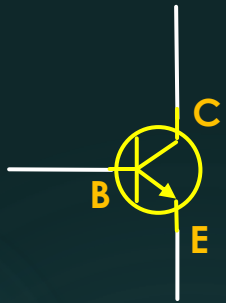
$$A_V \text{ loaded} \triangleq \frac{V_L}{V_{src}} = \left(\frac{V_i}{V_{src}} \right) \left(\frac{V_o}{V_i} \right) \left(\frac{V_L}{V_o} \right) = \left(\frac{R_i}{R_i + R_{src}} \right) (A_{v_o}) \left(\frac{R_{load}}{R_{load} + R_o} \right)$$

Outline

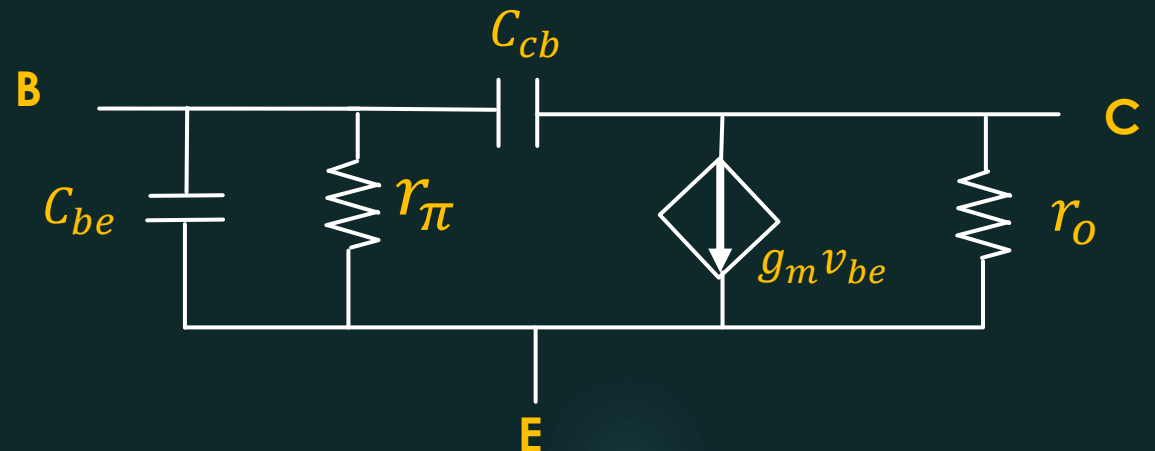
- *Triode Devices*
- *DC Biasing*
- *AC Gain and I/O Impedances*
- *Small Signal Amplifier Configurations*
- *Transistors, Data Sheets and Models*
- *High Frequency Model and Limitations*



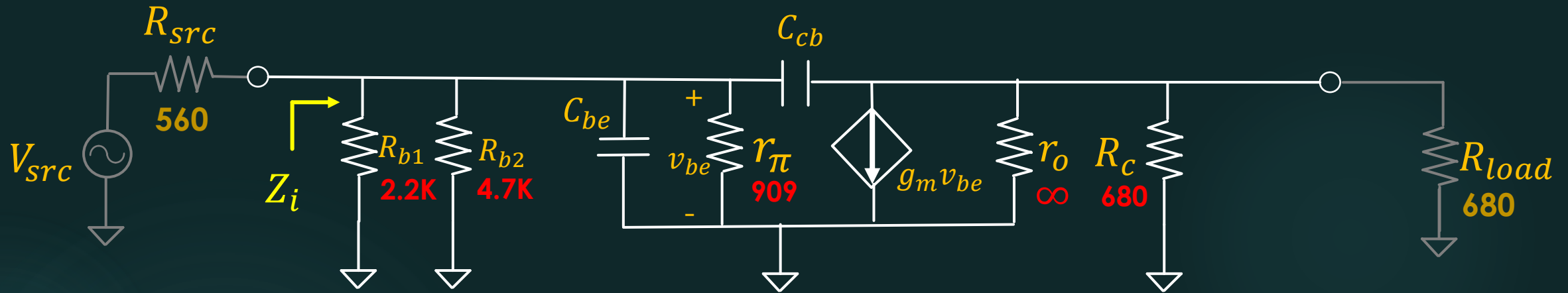
Small Signal AC Model at RF



- Emitter, Base, and Collector are (semi) conducting regions
- They are separated by insulating “depletion” regions
- This is the basic structure of a capacitor !



Effects on Circuit Operation



- C_{be} and C_{cb} create lowpass filtering
 - C_{cb} is magnified by “Miller Effect” ☹️
- $$C_{in} = C_{be} + (1 + |A_{Vloaded}|)C_{cb} \approx (13 + 37)pF @ 4.5 mA$$
- $$\Rightarrow Z_i \approx -j32 \Omega @ 100 MHz !$$
- Solutions to this problem at RF include:
 - Use CB or Cascode configurations instead of typical CE amp
 - Use LC circuits for resonance and matching for good *power* gain
 - Incorporate parasitic C into matching network design

Finding C_{be} and C_{cb}

NPN RF Transistor (continued)

Electrical Characteristics TA = 25°C unless otherwise noted

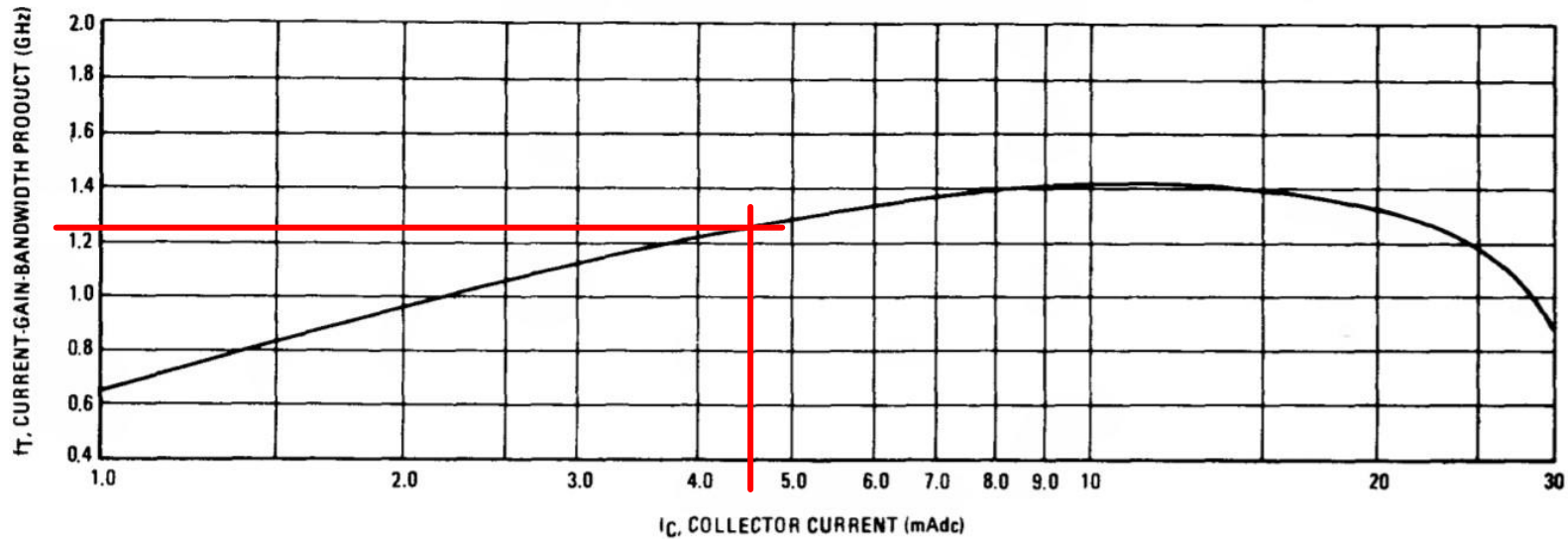
Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{CE(sus)}$	Collector-Emitter Sustaining Voltage*	$I_C = 3.0 \text{ mA}, I_B = 0$	12		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	$I_C = 1.0 \text{ }\mu\text{A}, I_E = 0$	20		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	$I_E = 10 \text{ }\mu\text{A}, I_C = 0$	2.5		V
I_{CBO}	Collector Cutoff Current	$V_{CB} = 15 \text{ V}, I_E = 0$ $V_{CB} = 15 \text{ V}, T_A = 150^\circ\text{C}$		0.02 1.0	μA μA
ON CHARACTERISTICS					
h_{FE}	DC Current Gain	$I_C = 3.0 \text{ mA}, V_{CE} = 1.0 \text{ V}$	25	250	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	$I_C = 10 \text{ mA}, I_B = 1.0 \text{ mA}$		0.4	V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	$I_C = 10 \text{ mA}, I_B = 1.0 \text{ mA}$		1.0	V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	$I_C = 5.0 \text{ mA}, V_{CE} = 6.0 \text{ V},$ $f = 100 \text{ MHz}$	900	2000	MHz
C_{cb}	Collector-Base Capacitance	$V_{CB} = 10 \text{ V}, I_E = 0,$ $f = 0.1 \text{ to } 1.0 \text{ MHz}$		1.0	pF
h_{fe}	Small-Signal Current Gain	$I_C = 2.0 \text{ mA}, V_{CE} = 6.0 \text{ V},$ $f = 1.0 \text{ kHz}$	25	300	
$rb'C_c$	Collector Base Time Constant	$I_C = 2.0 \text{ mA}, V_{CB} = 6.0 \text{ V},$ $f = 31.9 \text{ MHz}$	3.0	14	ps
NF	Noise Figure	$I_C = 1.5 \text{ mA}, V_{CE} = 6.0 \text{ V},$ $R_S = 50\Omega, f = 200 \text{ MHz}$		5.0	dB
FUNCTIONAL TEST					
G_{pe}	Amplifier Power Gain	$V_{CE} = 6.0 \text{ V}, I_C = 5.0 \text{ mA},$ $f = 200 \text{ MHz}$	15		dB
P_O	Power Output	$V_{CB} = 10 \text{ V}, I_E = 12 \text{ mA},$ $f \geq 500 \text{ MHz}$	20		mW

MPS5179 / MMBT5179 / PN5179

Finding C_{be}

2N5179

FIGURE 6 – CURRENT-GAIN-BANDWIDTH PRODUCT



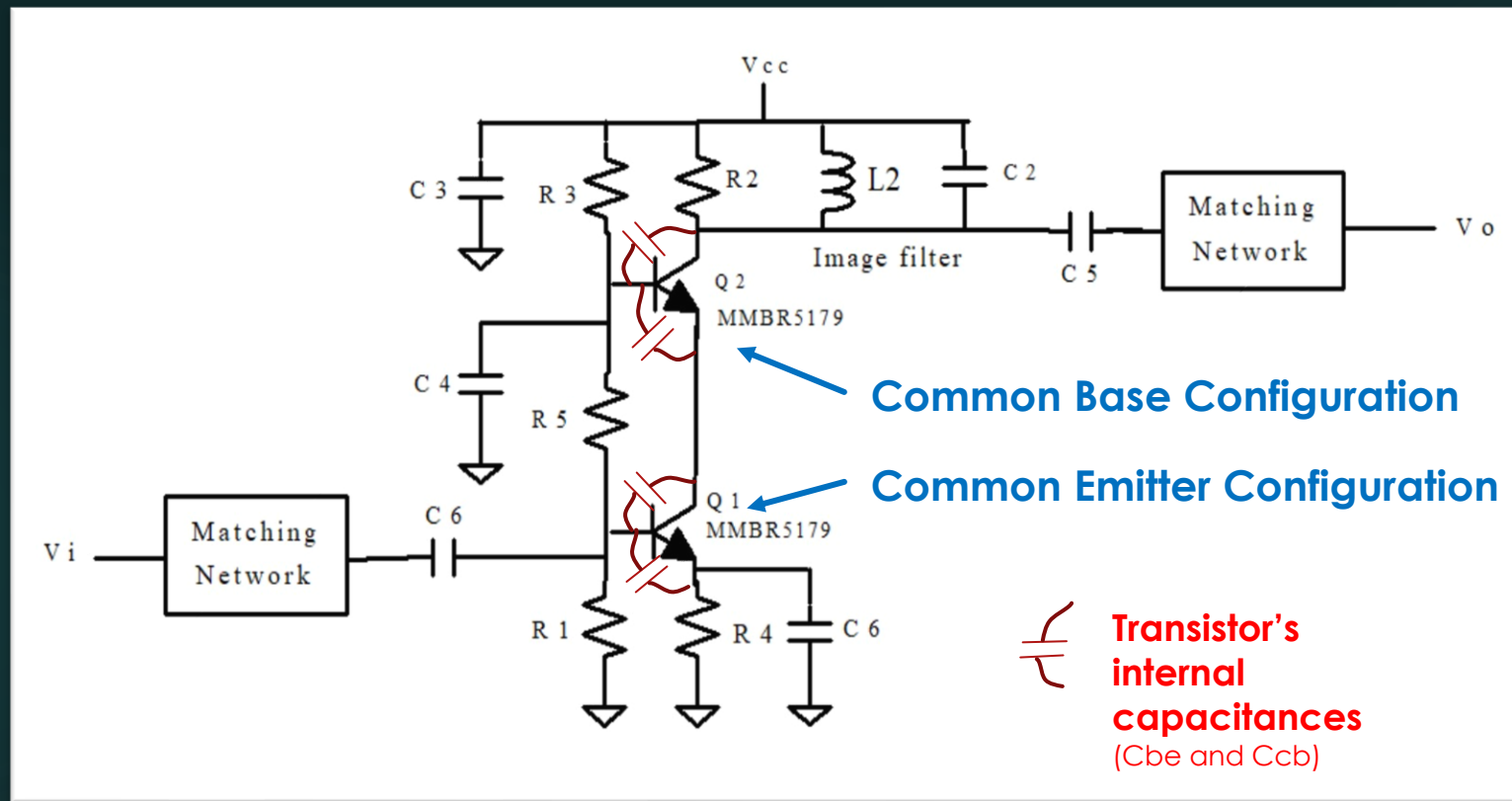
$$g_m = \frac{I_c}{nV_T}$$

$$C_{be} \approx \frac{1}{2\pi \frac{1}{g_m} f_T} - C_{cb}$$

$$r_\pi = \frac{1}{g_m} h_{fe}$$

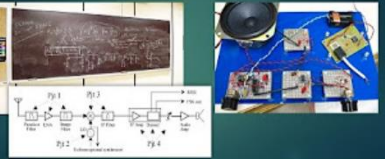
Cascode Amplifier Solution

(Details coming in Part 3 ?)



For More Information

New Radio Design 101 series
Abstracted from a senior-design University class



Radio Design 101

MegawattKS

Public

12 videos 29,214 views Updated today

Play all Shuffle

A collection of videos abstracted from a university course on radio / RF circuit design.

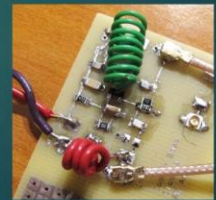
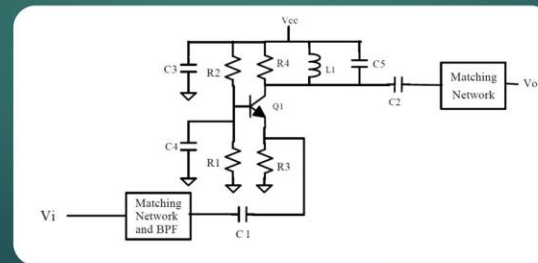
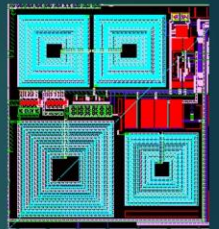
The goal is a working FM broadcast receiver, but the material is applicable to all wireless hardware from Amateur Radio to commercial RF integrated circuits.

While the focus is on circuit design, episodes in this series touch on a large

- Radio Design 101 - Episode 1 - Transceivers and Filters - Part 1**
MegawattKS • 17K views • 2 years ago
26:14
- Radio Design 101 - Episode 1 - Transceivers and Filters - Part 2**
MegawattKS • 9.9K views • 2 years ago
30:43
- Radio Design 101 - Episode 2 - Impedance Matching - Part 1**
MegawattKS • 8K views • 2 years ago
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- Radio Design 101 - Episode 2 - Impedance Matching - Part 2**
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- Radio Design 101 - Episode 3 - RF Amplifiers**
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- Radio Design 101 - RF Oscillators (Episode 4)**
MegawattKS • 16K views • 2 years ago
38:23
- Radio Design 101 - RF Mixers and Frequency Conversions**

Radio Design 101 Episode 3

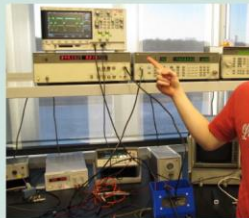
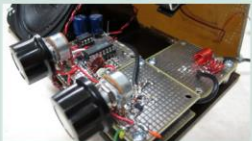
RF Amplifiers



For More Information

<https://ecefiles.org/rf-circuits-course-notes/>

RF Circuits Course Notes



Designing and Building Transmitters and Receivers in a Single Semester

This page was created to document a senior design course taught by the author for 20 years at Kansas State University. It is related to the "Radio Design 101" series of videos on YouTube, but goes into more depth (at the expense of being less polished in presentation)

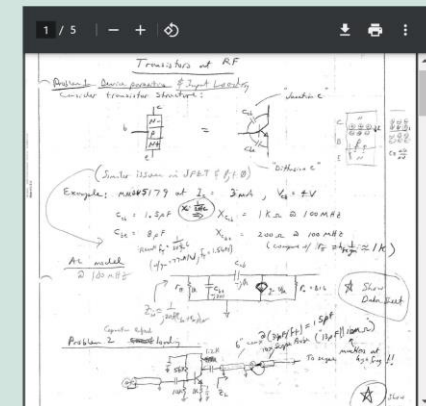
Lectures and Class Handouts

Each link below leads to lecture notes (hand written and a bit rough) plus course handouts (typed and much nicer) on the associated topic.

- [Syllabus, Parts List, and Typical Assignments](#)
- [Prototyping Boards](#)
- [Course Introduction](#)
- [Electronic Amplifier Design](#)
- [Transistors at RF](#)
- [Resonant Circuits](#)
- [Component Parasitics](#)
- [Impedance Matching and Power Gain](#)
- [Transmission Lines and Smith Charts](#)
- [Two Port Linear Circuit Modeling and S-Parameters](#)
- [RF Test Equipment](#)
- [Oscillators, Varactors, and VCOs plus Crystals and TCXOs](#)
- [Transmitters, Antennas, FCC Rules, and Midterm Exam](#)
- [Mixers and Frequency Downconversion](#)
- [Toroids, Transformers, and Cores](#)
- [Filters](#)
- [IF Amp, Demod, and Audio Amp](#)
- [Final Receiver Assembly](#)
- [Student Notes and Circuit/Measurement Pics](#)

RF Circuits Course Section 3

Transistors at RF



003_TransistorsAtRF-1

Download



Recall inductor impedance is given by $Z_L(j\omega) = j\omega L = jX_L$ where $X_L = 2\pi fL$.



*Thanks For
Watching !*

PLEASE
DO NOT ERASE

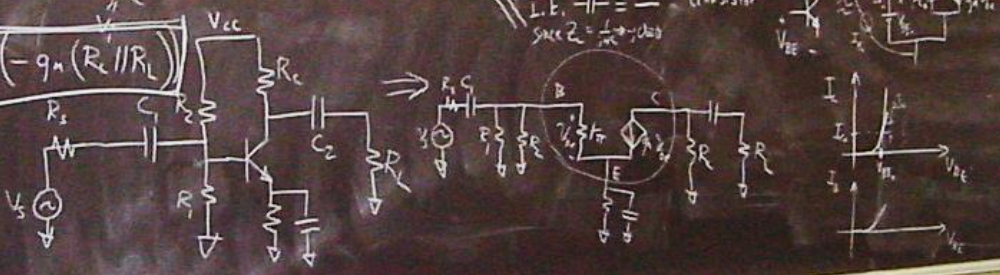
$$A_v = \frac{V_L}{V_s} = \frac{V_i}{V_s} \frac{V_L}{V_i}$$

$$= \frac{R_i}{R_i + R_s} \frac{-g_m (R_c || R_L)}{1 + g_m R_s}$$



DC Solution See handout
AC Solution

$$A_v = \frac{R_i}{R_i + R_s} (-g_m (R_c || R_L))$$



Assume midband operation
I.E. $\beta \gg 1$
Since $Z_i = \beta r_{\pi}$

