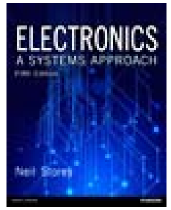
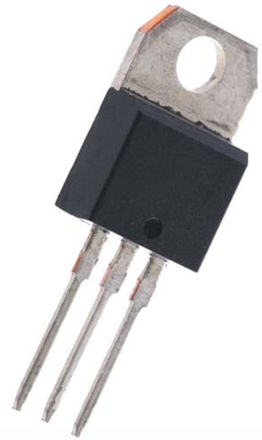
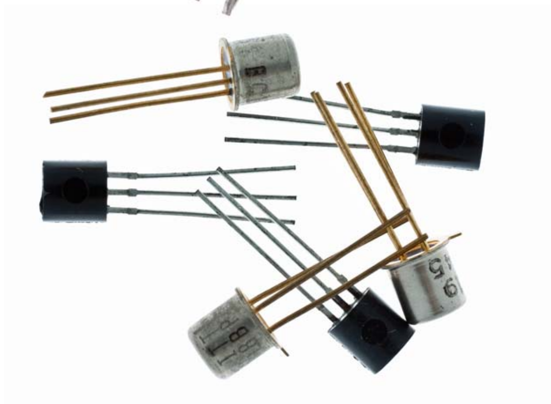


Bipolar junction transistors

Chapter 19

- Introduction
- An overview of bipolar transistors
- Bipolar transistor operation
- A simple amplifier
- Bipolar transistor characteristics
- Bipolar amplifier circuits
- Bipolar transistor applications
- Circuit examples





BJT parameters for common emitter configuration (subscript $_e$)

- **Input$_i$ Output$_o$ Forward$_f$ Reverse$_r$**

h_{FE}	DC gain	I_C / I_B	
h_{fe}	AC gain	i_c / i_b	$h_{FE} \approx h_{fe}$ (mostly)
g_m	Transconductance	$\Delta I_C / \Delta V_{BE} = i_c / v_{be}$	$\sim 40 \cdot I_C \approx 40 \cdot I_E$
h_{ie}	Small signal input resistance	$\Delta V_{BE} / \Delta I_B = v_{be} / i_b$	$\sim 1 / (40 \cdot I_B)\ \Omega \approx h_{fe} / (40 \cdot I_C)$
h_{oe}	Output admittance ($1/r_o$) where r_o = Slope in the active region	$\Delta I_C / \Delta V_{CE} = i_c / v_{ce}$	
r_e	Emitter resistance	$\Delta V_{BE} / \Delta I_C = v_{be} / i_c = 1/g_m$	$\approx v_{be} / i_e$ that is, $h_{ie} = h_{fe} \cdot r_e$
h_{re}	Early effect (V_{CE} affects bias V_{BE})	$\Delta V_{CE} / \Delta V_{BE}$	

$$h_{FE} = \frac{I_C}{I_B}$$

$$I_E = I_C + I_B = (h_{FE} + 1) \cdot I_B$$

$$but\ because\ h_{FE} >> 1,$$

$$I_E \approx h_{FE} \cdot I_B = I_C$$

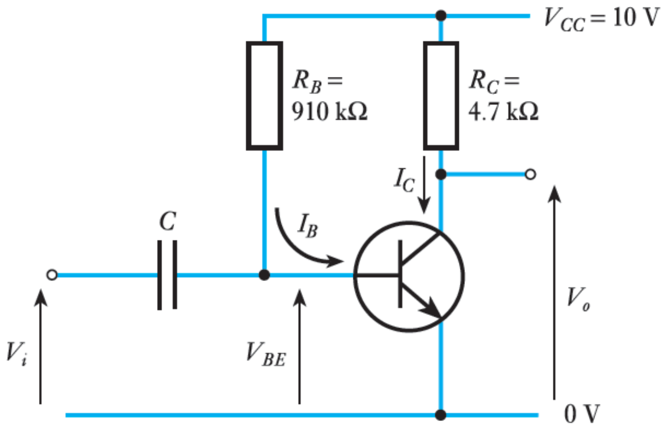
$$I_B = I_{BS} \cdot e^{40 \cdot V_{BE}} \quad \text{where } I_{BS} \text{ is constant}$$

$$I_C = h_{FE} \cdot I_B = h_{FE} \cdot I_{BS} \cdot e^{40 \cdot V_{BE}}$$

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}} = \frac{dI_C}{dV_{BE}} = 40 \cdot h_{FE} \cdot I_{BS} \cdot e^{40 \cdot V_{BE}}$$

$$g_m = \qquad = 40 \cdot I_C \approx 40 \cdot I_E$$

Last time: bipolar transistor-no feedback

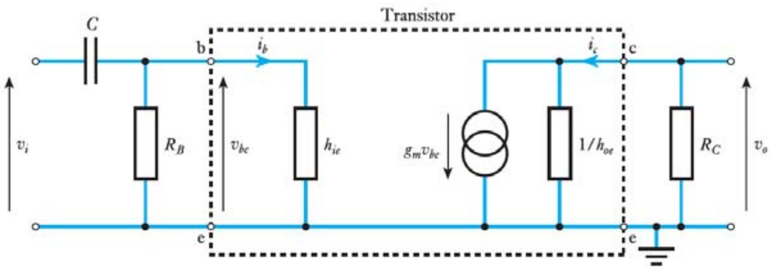


DC-large signal

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C = h_{FE} I_B$$

$$V_o = V_{CC} - I_C R_C$$



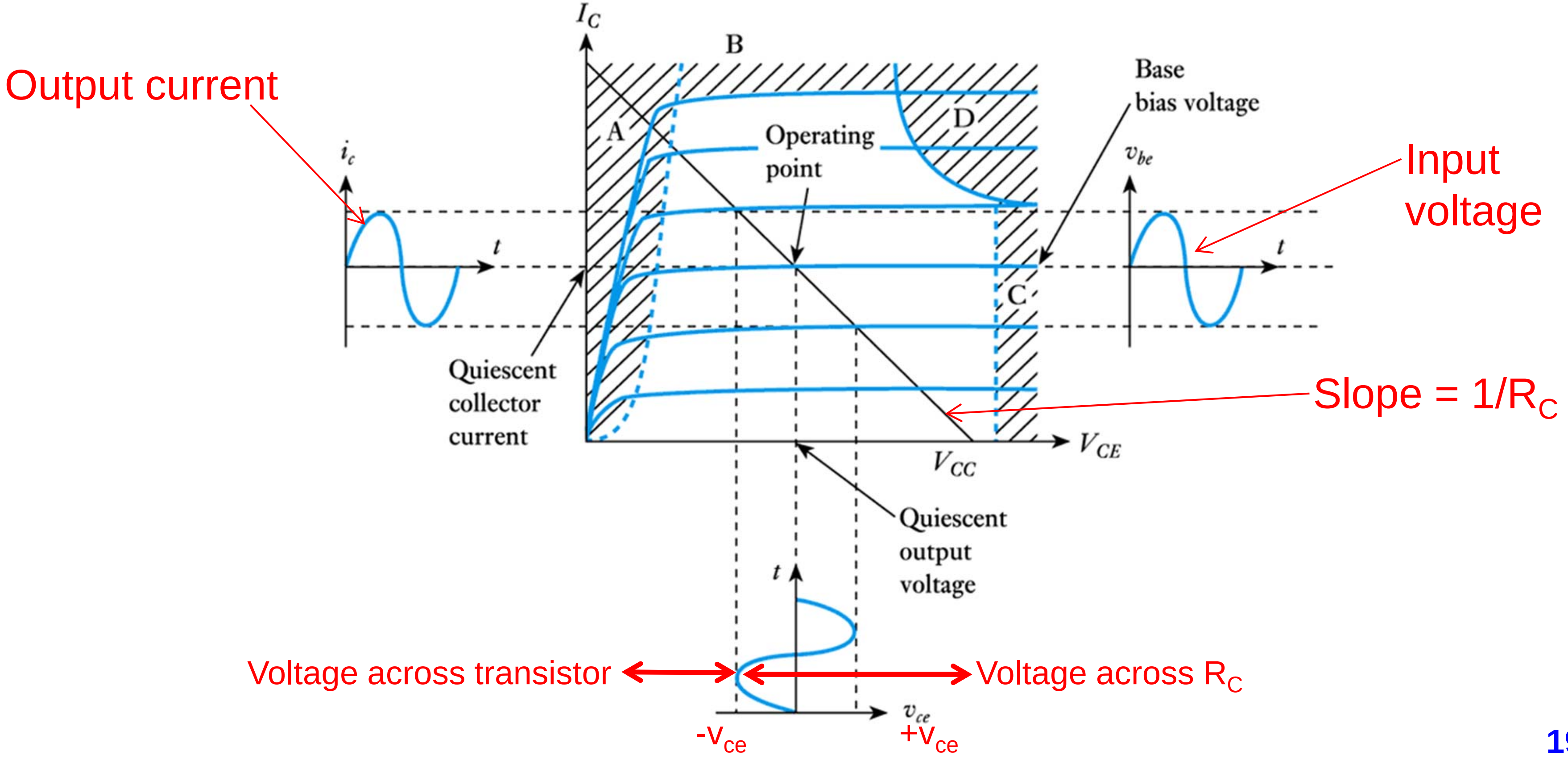
AC-small signal

$$\frac{v_o}{v_i} = -g_m \cdot \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \frac{v_o}{v_i} \approx -g_m \cdot R_C$$

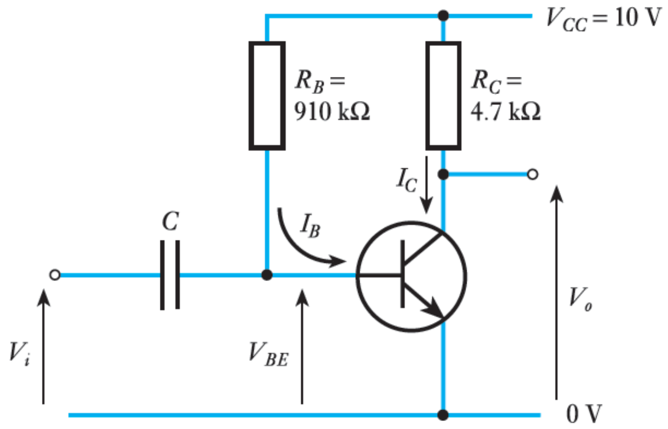
$$r_i = \frac{h_{ie}}{\frac{h_{ie}}{R_B} + 1} \qquad R_B >> h_{ie} \Rightarrow r_i \approx h_{ie}$$

$$r_o = \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow r_o = R_C$$

- Choice of operating point in a simple amplifier



Problems with this circuit

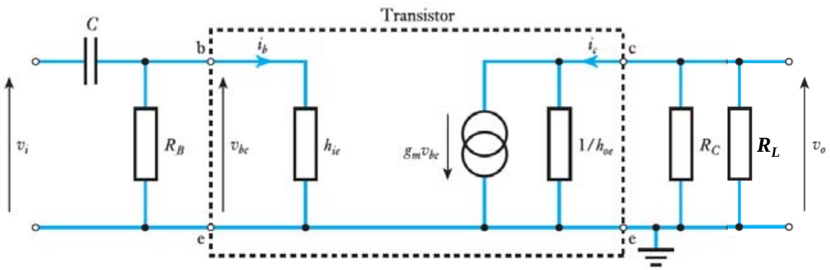


AC gains depend on:

Properties of transistor

And since $g_m \approx 40 \cdot I_C$,
$v_o/v_i \approx -40 \cdot V_{RC}$
the signal gain changes with DC operating point

R_L interacts with R_C to change gain



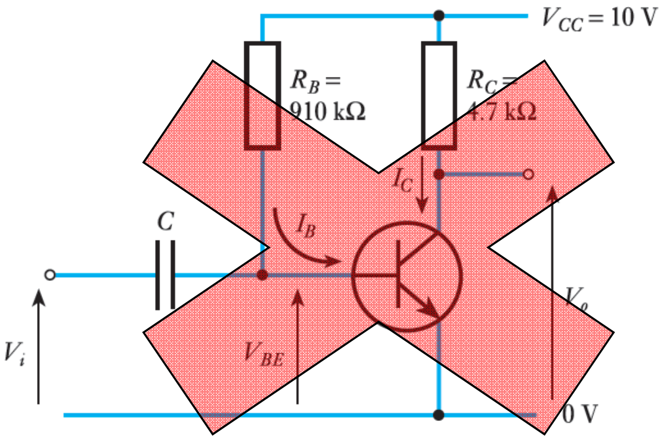
AC-small signal

$$\frac{v_o}{v_i} = -g_m \cdot \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \frac{v_o}{v_i} \approx -g_m \cdot R_C$$

$$r_i = \frac{h_{ie}}{\frac{h_{ie}}{R_B} + 1} \qquad R_B >> h_{ie} \Rightarrow r_i \approx h_{ie}$$

$$r_o = \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow r_o = R_C$$

Problems with this circuit



AC gains depend on:

Properties of transistor

And since $g_m \approx 40 \cdot I_C$,
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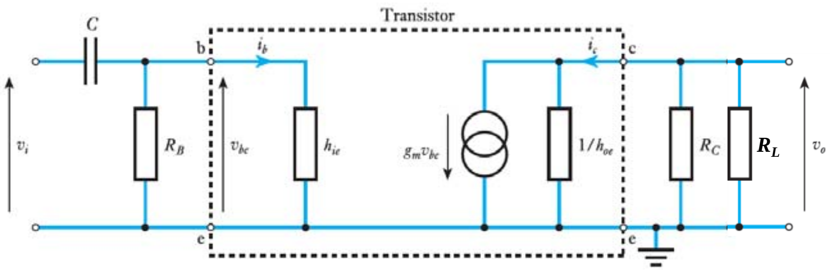


AC-small signal

$$\frac{v_o}{v_i} = -g_m \cdot \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow \frac{v_o}{v_i} \approx -g_m \cdot R_C$$

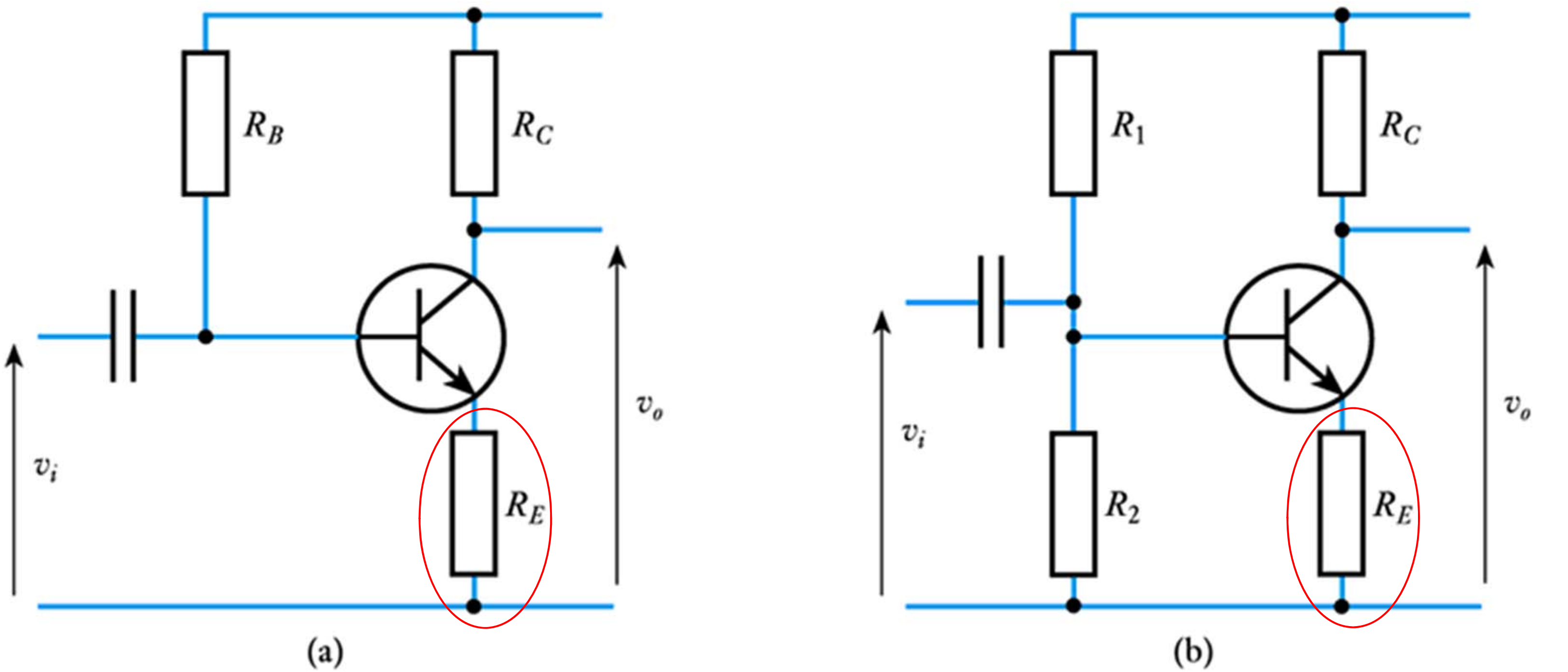
$$r_i = \frac{h_{ie}}{\frac{h_{ie}}{R_B} + 1} \qquad R_B >> h_{ie} \Rightarrow r_i \approx h_{ie}$$

$$r_o = \frac{R_C}{h_{oe} \cdot R_C + 1} \qquad R_C << \frac{1}{h_{oe}} \Rightarrow r_o = R_C$$

The use of feedback

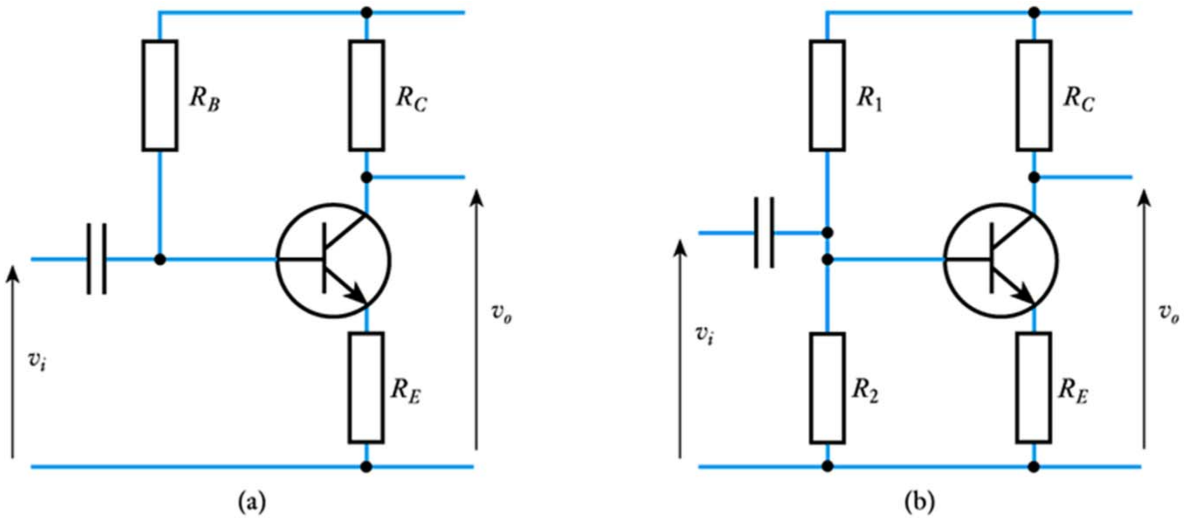
Video 19C

- Feedback can be used to overcome the effects of device variability. Consider the following circuits



How does this work?

- As $v_i \approx v_b$ rises, v_{be} forward bias increases and more i_b flows
- This causes more current, i_c, to flow
- This increases the voltage at the top of R_E *(catches up to v_i)*
- And this reduces the v_{be} forward bias
- Voltage at the top of R_E tracks $v_b \approx v_i$, and reduces gain

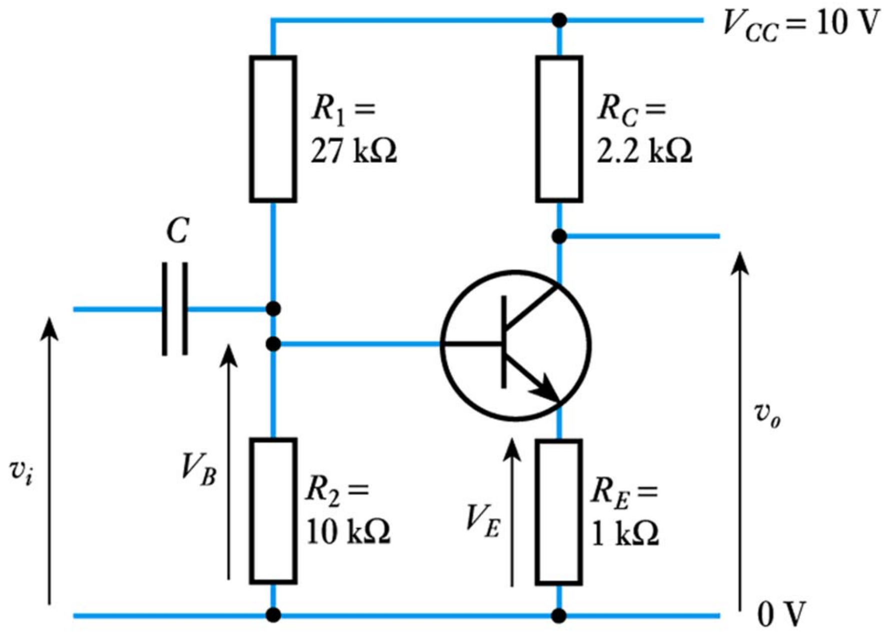


Analysis of amplifier with feedback

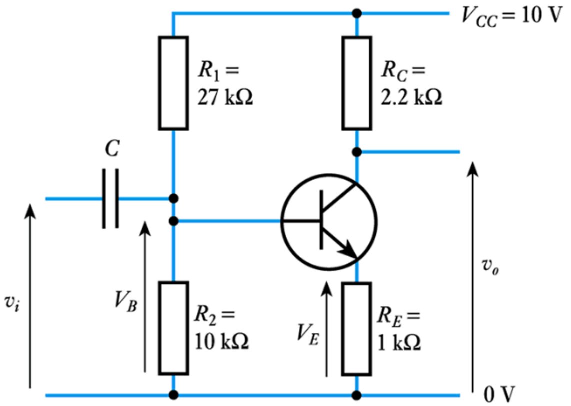
- See **Example 19.3** from course text

  Determine the quiescent voltages and currents in the following circuit
- See **Example 19.4** from course text

  Determine the small-signal behaviour of the following circuit



Results: Bipolar transistor-with feedback



DC-large signal

$$V_B \approx V_{CC}\frac{R_2}{R_1 + R_2}$$

$$V_E = V_B - V_{BE}$$

$$V_{BE} \approx \text{constant} \approx 0.7\text{V}$$

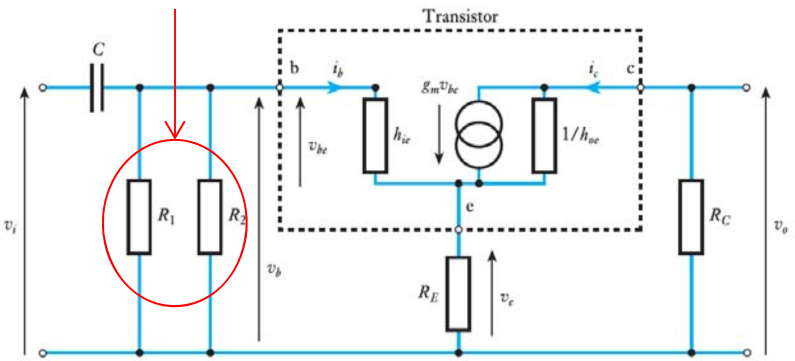
$$I_B << I_C \approx I_E$$

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

$$V_o = V_{CC} - I_C R_C$$

Gain, r_i and r_o only depend on passive components

Note $R_1//R_2$ in series with C



AC-small signal

$$\frac{v_o}{v_i} = -\frac{R_C}{R_E + \dfrac{1}{g_m}} \qquad R_E >> \frac{1}{g_m} \Rightarrow \frac{v_o}{v_i} \approx -\frac{R_C}{R_E}$$

$$r_b = h_{ie} + \left(h_{fe} + 1\right) R_E \qquad h_{fe} \cdot R_E >> h_{ie} >> 1 \Rightarrow r_b \approx h_{fe} \cdot R_E$$

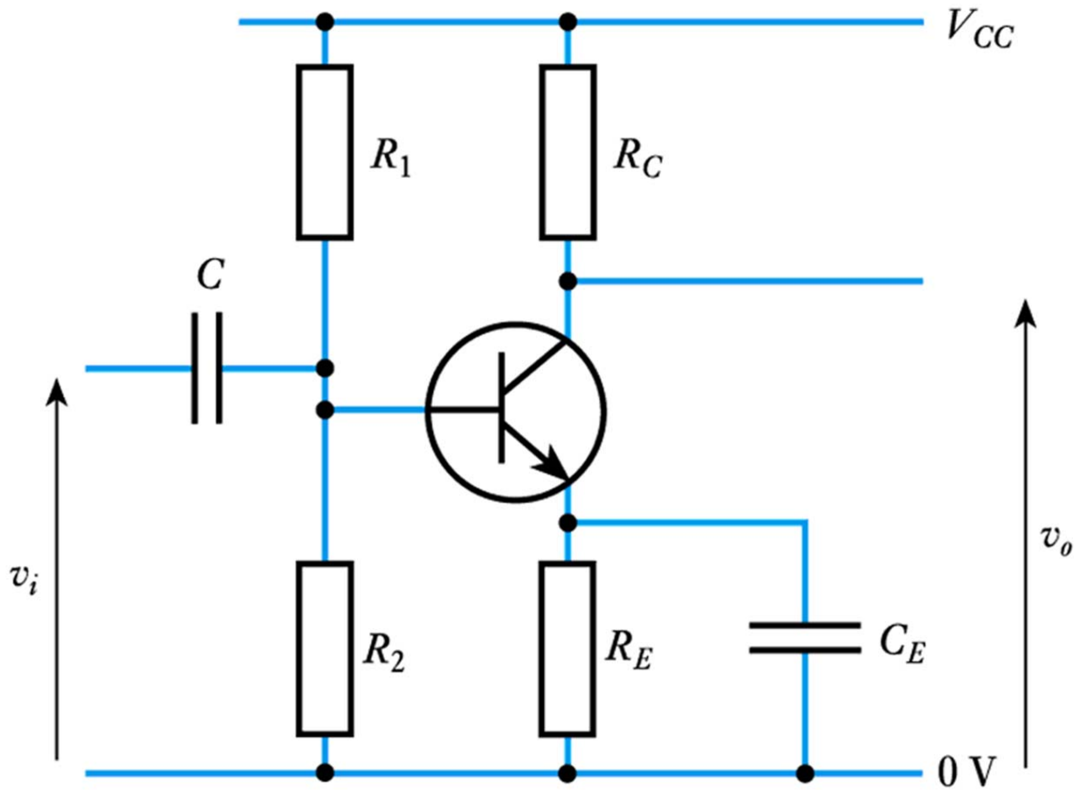
$$r_i = R_1 \parallel R_2 \parallel r_b \qquad r_b >> R_1 \approx R_2 \Rightarrow r_i \approx \frac{R_1 \cdot R_2}{R_1 + R_2}$$

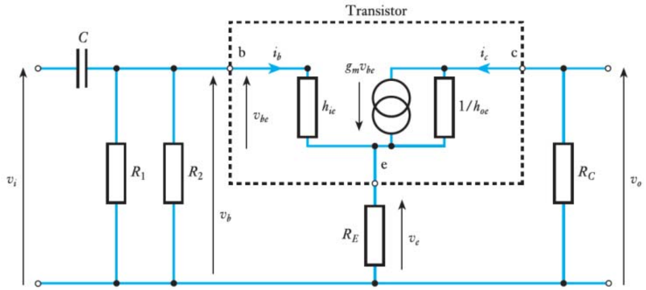
$$r_o = R_C \parallel \left(\frac{1}{h_{oe}} + R_E\right) \qquad R_C << \frac{1}{h_{oe}} + R_E \Rightarrow r_o \approx R_C$$

Reduces the amount of AC negative feedback while maintaining DC feedback.
This *increases the small-signal gain of the circuit* but *does not affect the DC feedback*,
This provides stability to the bias conditions of the circuit

Use of a decoupling capacitor

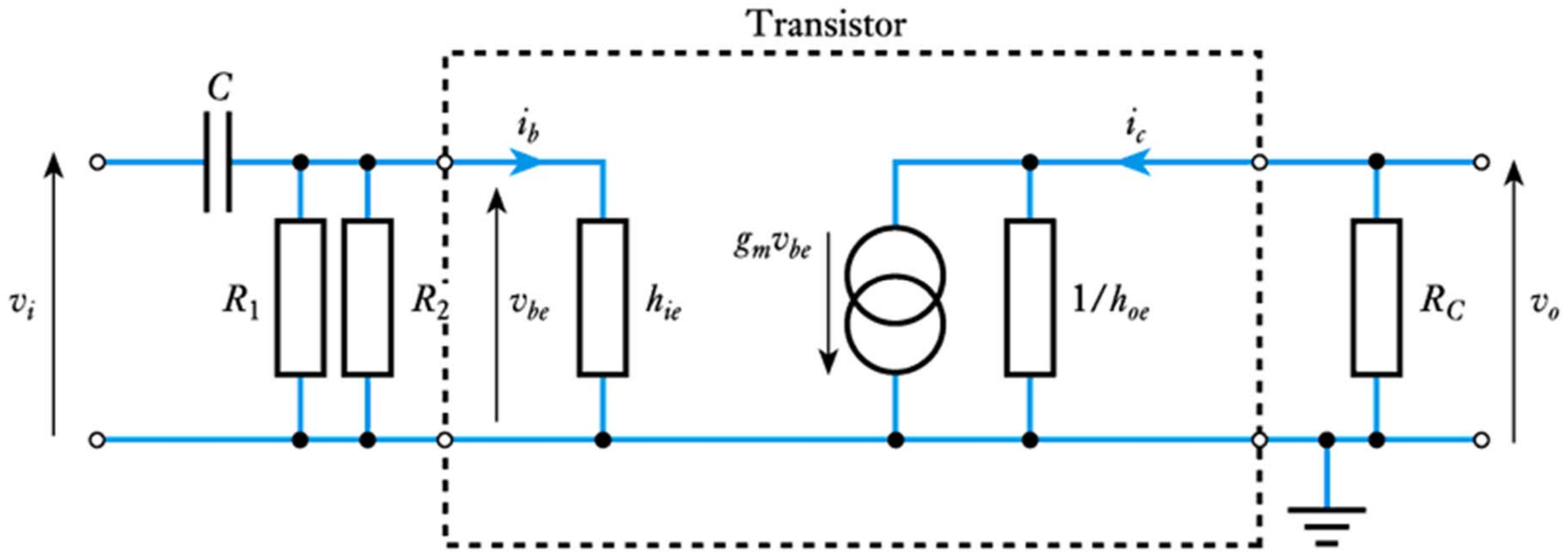
- A decoupling capacitor removes small-signal feedback





Small signal equivalent circuit without coupling capacitor

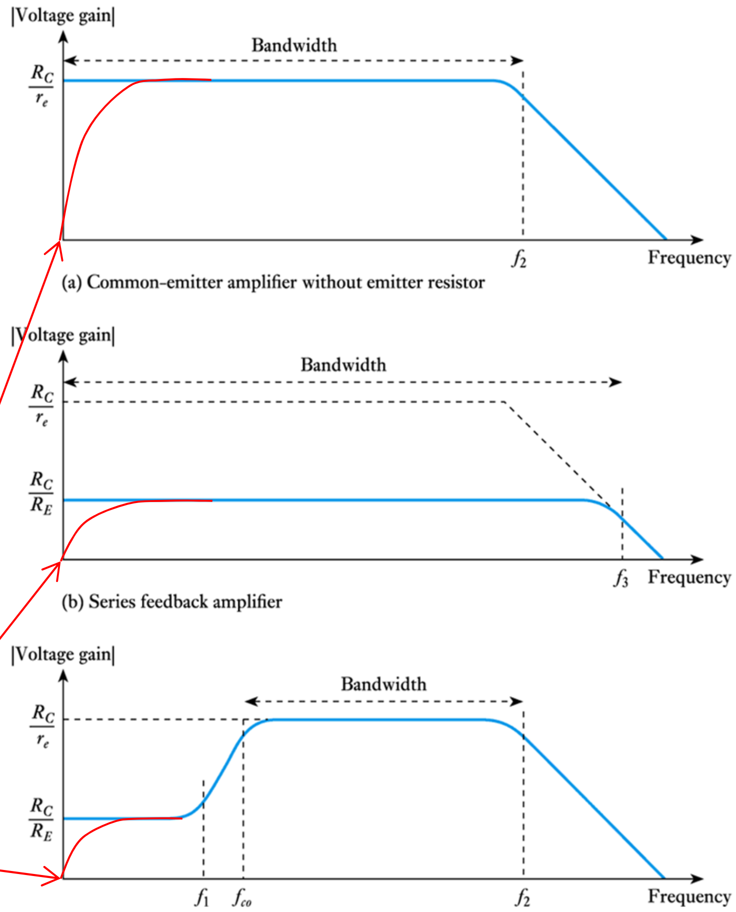
- Small-signal equivalent circuit of an amplifier using a decoupling capacitor (Shorts out R_E in signal band)



Remember $r_e = 1/g_m$ and gain was $g_m \cdot R_c$

- A comparison of the frequency responses of various amplifiers
  - for simplicity, the figure shows the responses of amplifiers that are *not* fitted with coupling capacitors

With an ac coupling capacitor



(a) Common-emitter amplifier without emitter resistor

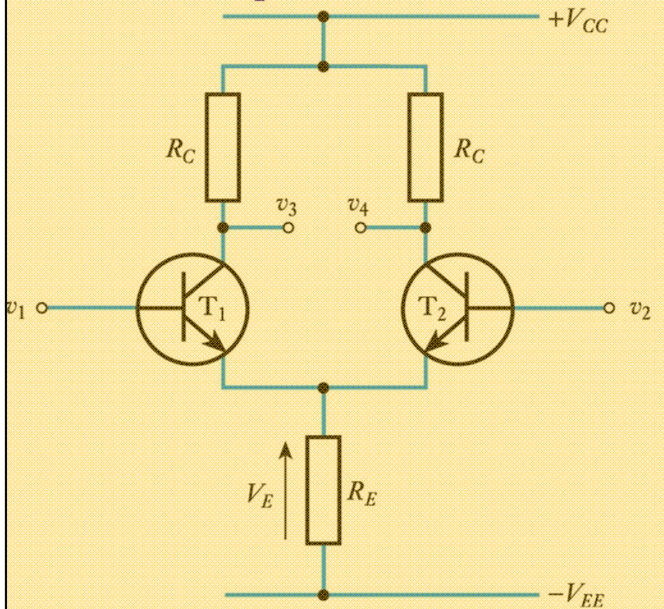
(b) Series feedback amplifier

(c) Common-emitter amplifier with emitter resistor and decoupling capacitor

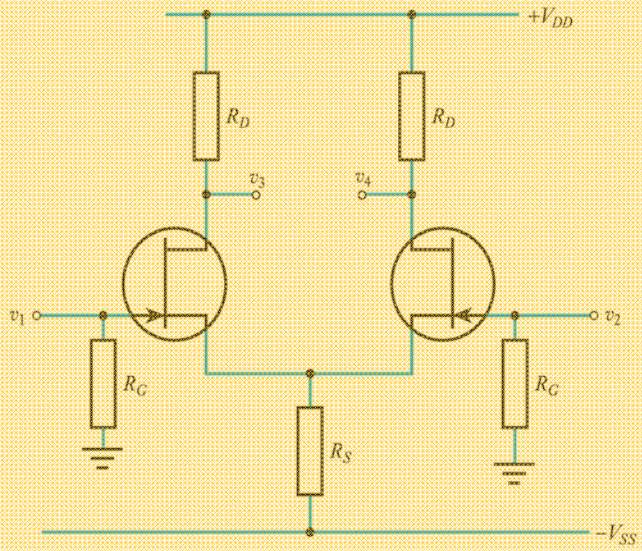
Summary

- DC and small-signal (AC) gains no feedback
    - Gain depends on characteristics of specific transistor
- DC and small-signal gains with negative feedback
    - Small-gain but depends on stable passive resistors
- Decoupling capacitor
    - Claw back some of the lost gain within the signal band

Bipolar transistors as differential amplifiers



Compare



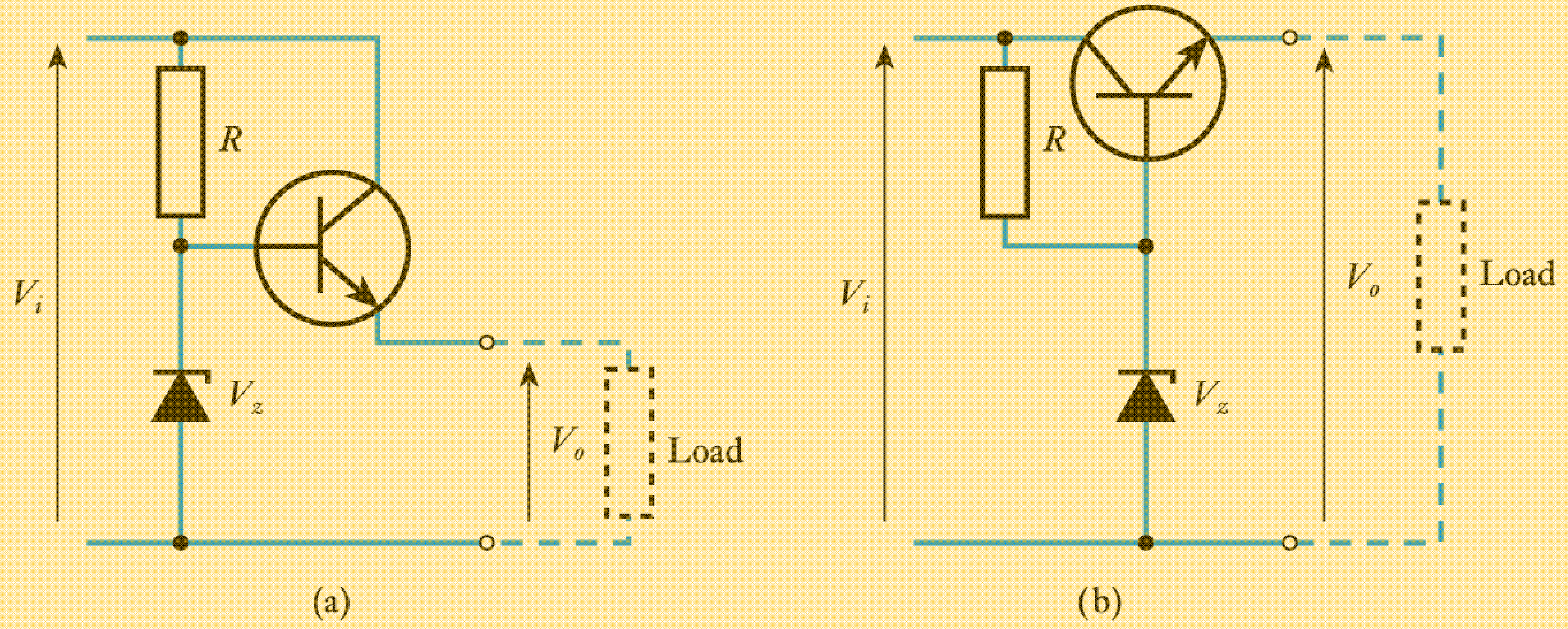
$$\text{voltage gain } = \frac{v_o}{v_i} = \frac{v_3 - v_4}{v_1 - v_2} \approx -g_m R_C$$

$$\text{CMRR } \approx g_m R_E$$

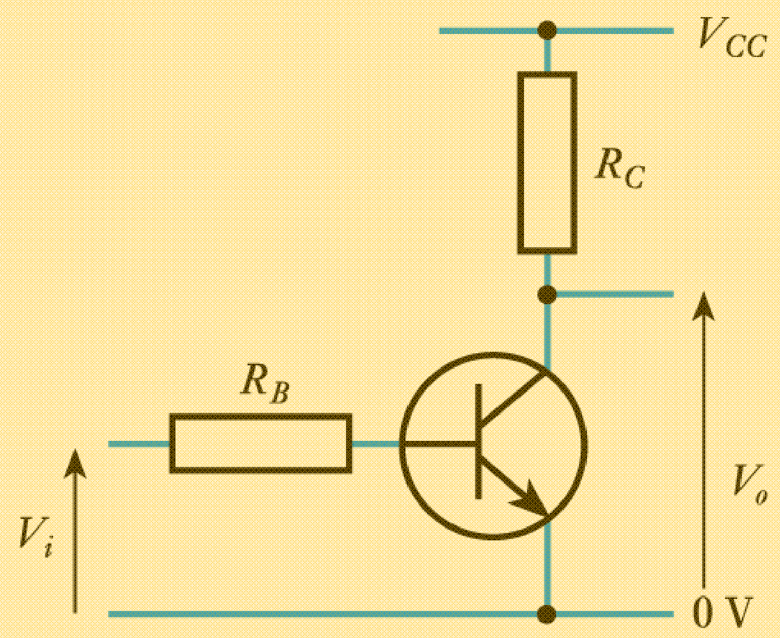
$$\text{voltage gain } = \frac{v_o}{v_i} = \frac{v_3 - v_4}{v_1 - v_2} \approx -g_m R_D$$

$$\text{CMRR } \approx g_m R_S$$

- **A voltage regulator** (keeps constant voltage V_o, since V_B is constant, by adjusting the current through the load)

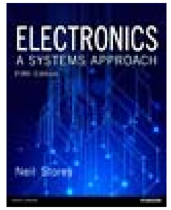


- **A logical switch**
- V_i low, transistor off
  - V_o is at V_{CC}
  - can source current to load
- V_i high, transistor on
  - V_o is drawn to ground
  - Can sink current from load
- Basis of TTL logic (transistor-transistor logic)



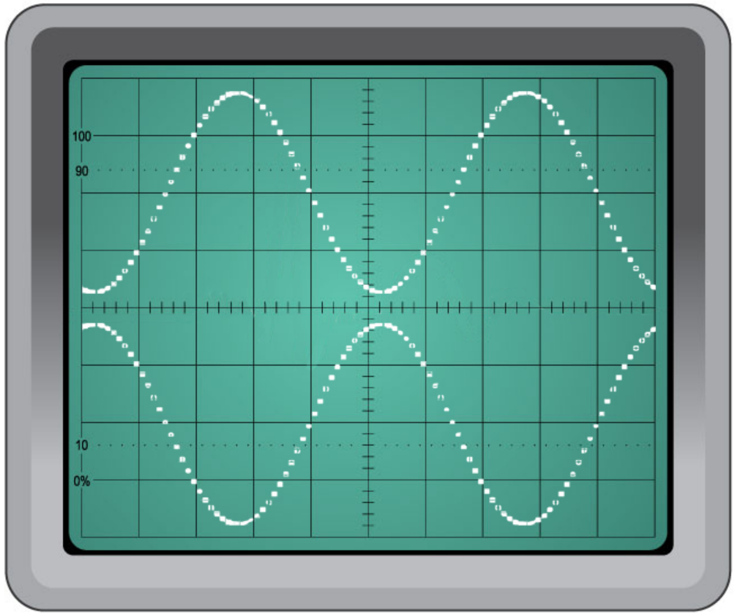
Further Study

Video 19E



Further Study

- The Further Study section at the end of Chapter 19 looks at the design of a phase splitter.
- We considered a simple circuit earlier, but this suffers from the fact that its two outputs have very different output resistances.



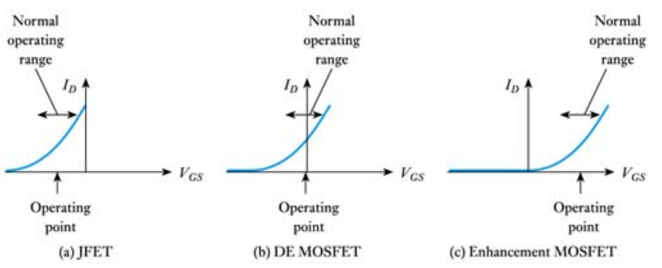
- Design an arrangement to overcome this problem and then compare it with that shown in the video.

Key points

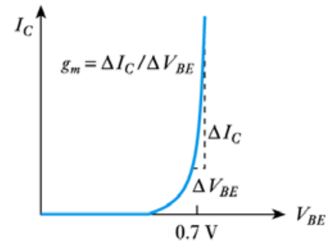
- Bipolar transistors are widely used in both analogue and digital circuits
- They can be considered as either voltage-controlled or current-controlled devices
- Their characteristics may be described by their gain or by their transconductance
- Feedback can be used to overcome problems of variability
- Many amplifier circuits use transistors in a common-emitter configuration where the input is applied to the base and the output is taken from the collector
- Common-collector circuits make good buffer amplifiers
- Bipolar transistors are used in a wide range of applications

FET vs. BJT

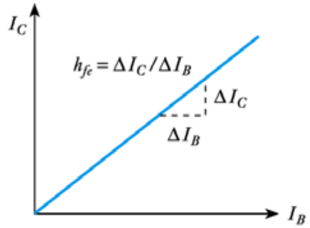
- Device characteristics mean FET-R_i >> BJT-R_i
  - No current flow into FET gate, small I_B in BJT
- Current output $\propto V_{gs}$ or V_{be}
  - FET



BJT



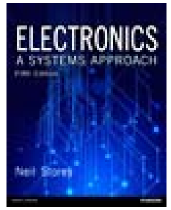
- But Base current in BJT $I_B \approx \text{constant} \cdot e^{40 \cdot V_{BE}}$
  - So BJT looks like a linear current amp
  - makes biasing easy



Comparison of FET and Bipolar

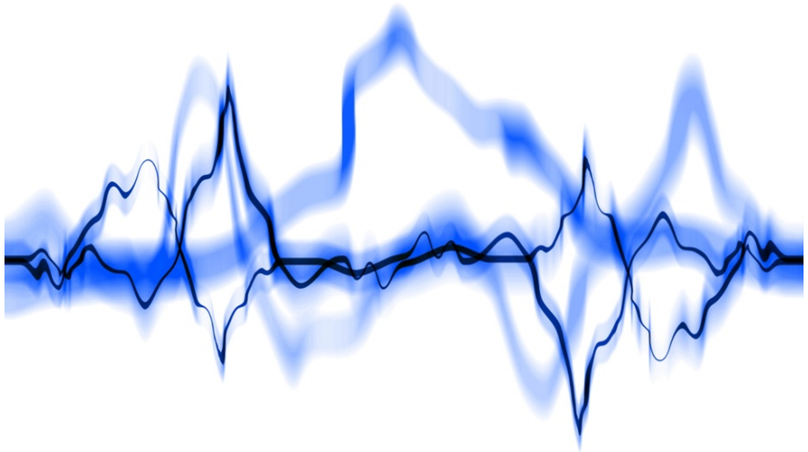
	Field Effect Transistor (FET)	Bipolar Junction Transistor (BJT)
1	Low voltage gain	High voltage gain
2	High current gain	Low current gain
3	Very high input impedance	Low input impedance
4	High output impedance	Low output impedance
5	Low noise generation	Medium noise generation
6	Fast switching time	Medium switching time
7	Easily damaged by static	Robust
8	Some require an input to turn it "OFF"	Requires zero input to turn it "OFF"
9	Voltage controlled device	Current controlled device
10	Exhibits the properties of a Resistor	
11	More expensive than bipolar	Cheap
12	Difficult to bias	Easy to bias

Noise and Electromagnetic Compatibility



Chapter 22

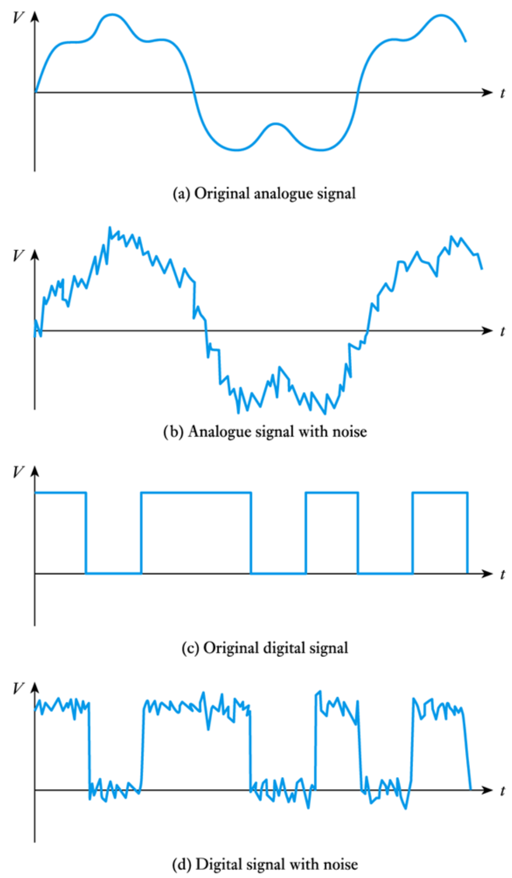
- Introduction
- Noise sources
- Representing noise sources within equivalent circuits
- Noise in bipolar transistors
- Noise in FETs
- Signal-to-noise ratio
- Noise Figure
- Designing for low-noise applications
- Electromagnetic compatibility
- Designing for EMC

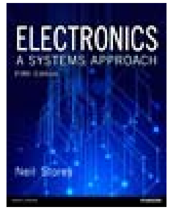


Introduction

22.1

- All systems add noise to the signals that pass through them
- Noise is **random** and not repeatable
- Noise can often be removed from digital signals but this is often impossible with analogue signals





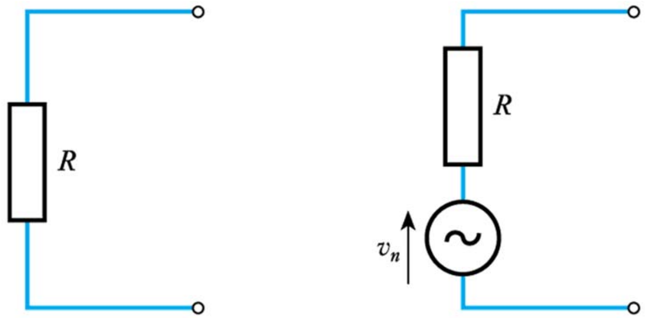
Video 22A   22.2

Noise sources

- ## Thermal noise
  - all components that have resistance, *R*, and temperature, *T*, produce thermal noise in the voltage across the resistor

$$V_{n(\mathrm{rms})} = \left(4k \cdot T \cdot R \cdot B\right)^{1/2}$$

  - thermal noise is both **white** and **Gaussian** over our <u>*measurement*</u> bandwidth, *B.*
  - a 'noisy' resistor can be modelled by an ideal noiseless resistor in series with a voltage generator



(a) A 'noisy' resistor   (b) Equivalent circuit

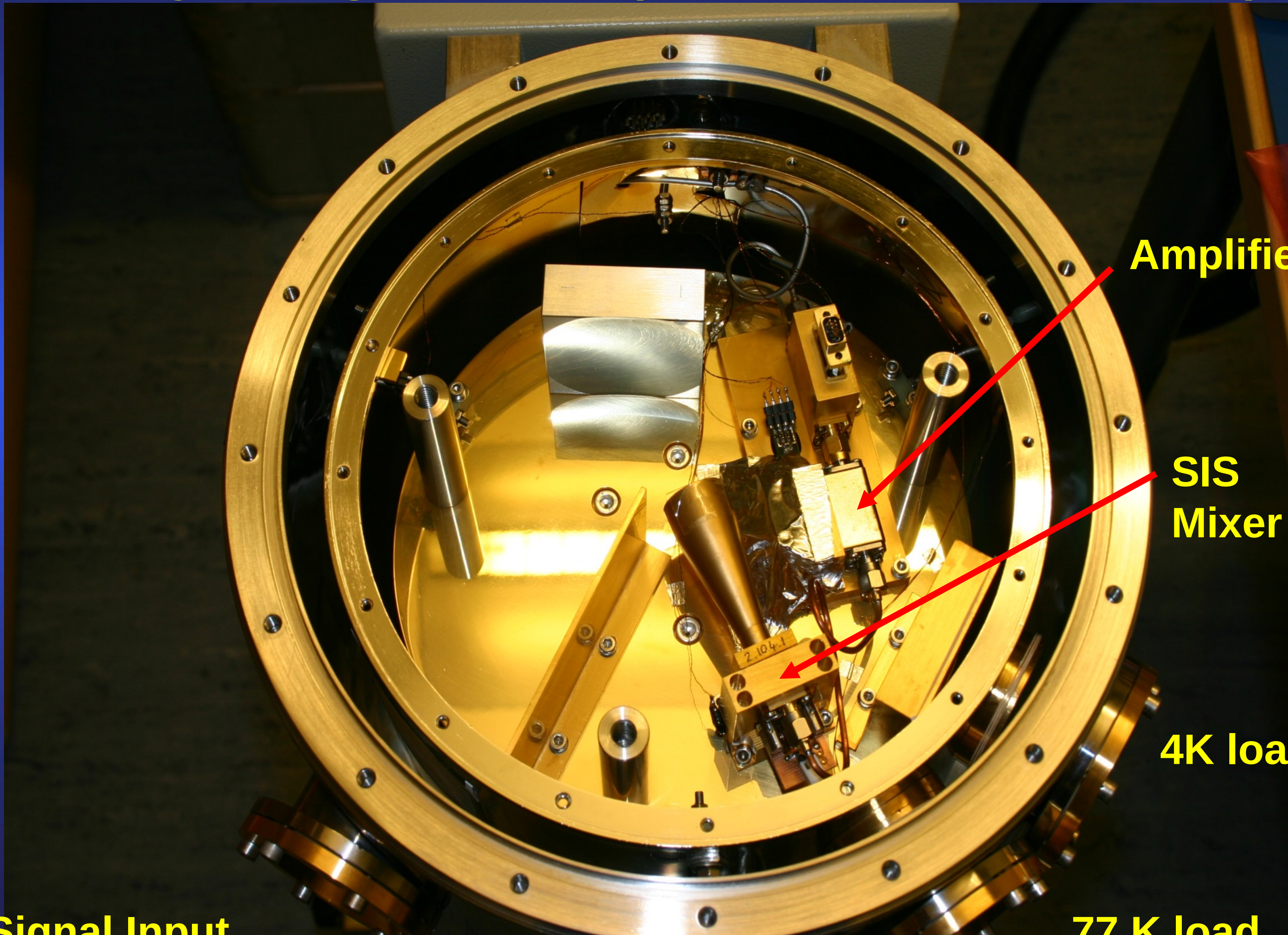
This current noise will appear, for example, in the currents flowing across pn-junctions
If that junction is part of a high-gain transistor amplifier, the noise will also be amplified

- **Shot noise**
  - the current flowing in a circuit is made up of a large number of individual charge carriers
  - with large currents, the averaging effect gives the impression of a continuous and constant stream
  - for smaller currents the granular nature of the current is more apparent
  - the statistical nature of the flow gives rise to a noise current, the magnitude of which is given by

$$I_{n(\mathrm{rms})} = (2eBI)^{1/2}$$

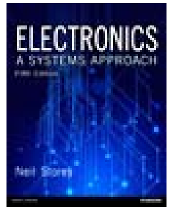
  - shot noise is both white and Gaussian

One way to beat thermal noise: cool everything to 4 K (250 GHz detector)



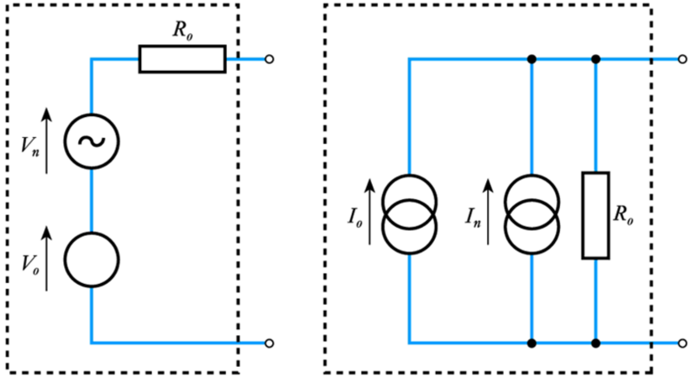
- **1/f noise**
  - produced by a number of noise sources
  - power spectrum is inversely proportional to frequency (falls as 3dB/octave)
  - this form of noise is called ‘pink’ noise (more noise at low frequency)
  - one form of 1/f noise is **flicker noise** which is caused by the random variations in the diffusion of charge carriers within devices
  - other forms include the current-dependent fluctuations of resistance exhibited by all real resistors

- **Interference**
  - – can take many forms
  - – can enter the system at any stage
  - – common noise sources include radio transmitters, AC power cables, lightning, switching transients, mechanical vibrations (particularly in mechanical sensors), ambient light (particularly in optical sensors)
  - – interference will be discussed in more detail when we look at electromagnetic compatibility



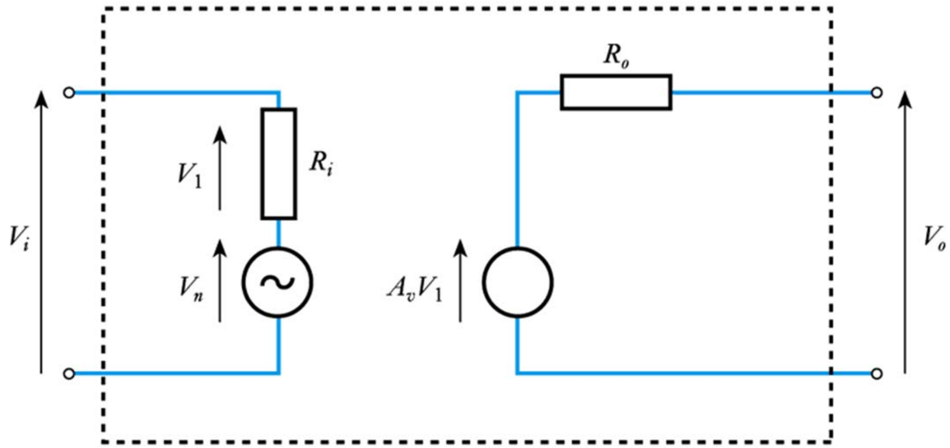
Representing noise in equivalent circuits

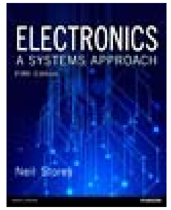
- An output network with noise



Thévenin Norton

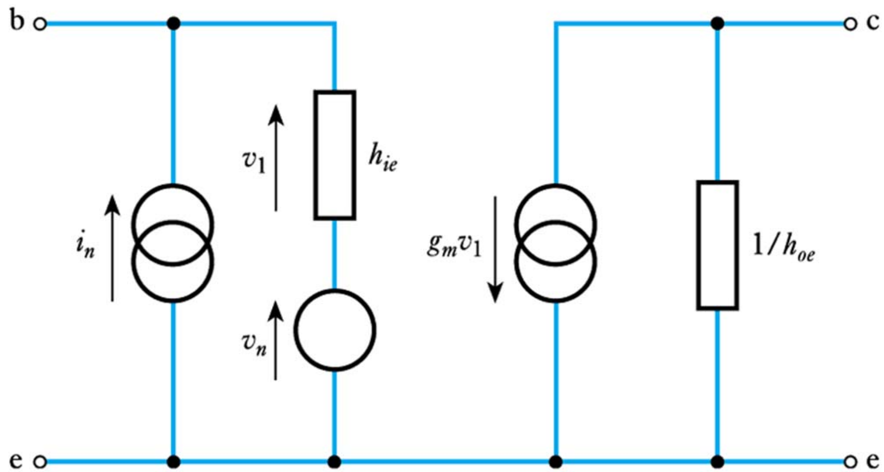
- An Op-amp with noise

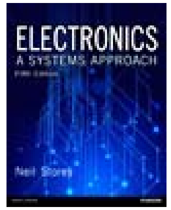




Noise in bipolar transistors

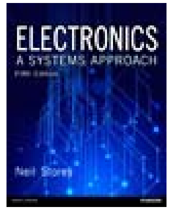
- **Caused by a number of mechanisms**
  - **thermal noise** (produced by resistances in the materials)
  - **shot noise** (produced by the currents across the junctions)
  - **flicker noise** (caused by fluctuations in the diffusion process) This is largest at low frequencies (1/f)





Noise in FETs

- **Caused by a number of mechanisms**
  – noise in FETs is normally dominated by **flicker noise** (particularly at low frequencies) and by **thermal noise** resulting from the resistance of the channel
  – shot noise is normally insignificant, as in MOSFETs there is no junction, and in JFETs the only currents across the gate junction are those caused by leakage



22.6

Signal-to-noise ratio

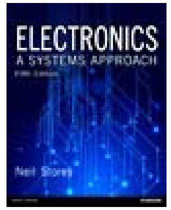
V_s and V_n are rms values
Usually quote max-S/N $\propto$ max(V_s)

- **A measure of signal quality**
  - from earlier we know that

$$\text{S/N ratio} = 20\log_{10}\left(\frac{V_s}{V_n}\right)\text{dB}$$

  - in many cases noise is made up of different components, because of their random nature they cannot simply be added
  - instead we must add squares of the rms voltages (which are related to the noise power) then take the square root to obtain the rms voltage of the combination

$$V_n = \sqrt{\left(V_{n1}^{\;2} + V_{n2}^{\;2}\right)}$$



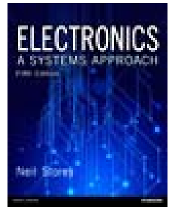
22.7

Noise figure

- **A measure of circuit performance**
  - S/N ratio can be used to indicate the quality of a signal, but not to describe how well an amplifier, or other circuit, performs regarding noise
  - (Noise of source + all amplifier noise sources) / (noise of source)
  - this can be done using the noise figure

$$\mathrm{NF} = 10\log_{10}\frac{\text{noise output power from amplifier}}{\text{noise output power from noiseless amplifier}}$$

$$\mathrm{NF} = 20\log_{10}\frac{\text{rms noise output voltage from amplifier}}{\text{rms noise output voltage from noiseless amplifier}}$$



22.8

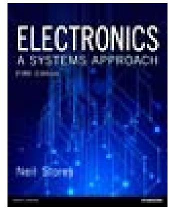
Designing for low-noise applications

- **A number of issues are of importance**
  - – often it is the noise of the first stage that dominates the performance of the entire system
  - – the source resistance is important: optimum $R_s = \sqrt{\dfrac{V_n^2}{I_n^2}}$
  - – bipolar transistors can produce good low-noise circuits with source resistances from a few hundred ohms to few hundred kilohms
  - – FETs can produce good low-noise circuits with source resistances from a few tens of kilohms up to several hundred megohms
  - – Low $R_S \Rightarrow$ bi-polar; High $R_S \Rightarrow$ FET

So far we have looked at self-generated noise. What about pick-up noise

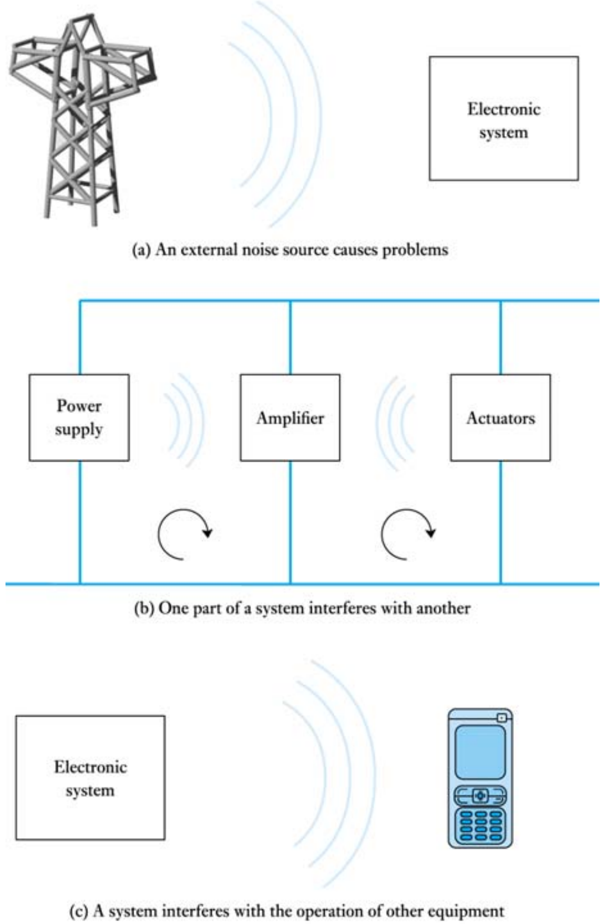
Electromagnetic compatibility

Video 22B



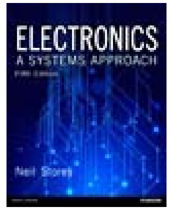
22.9

- Examples of EMC problems



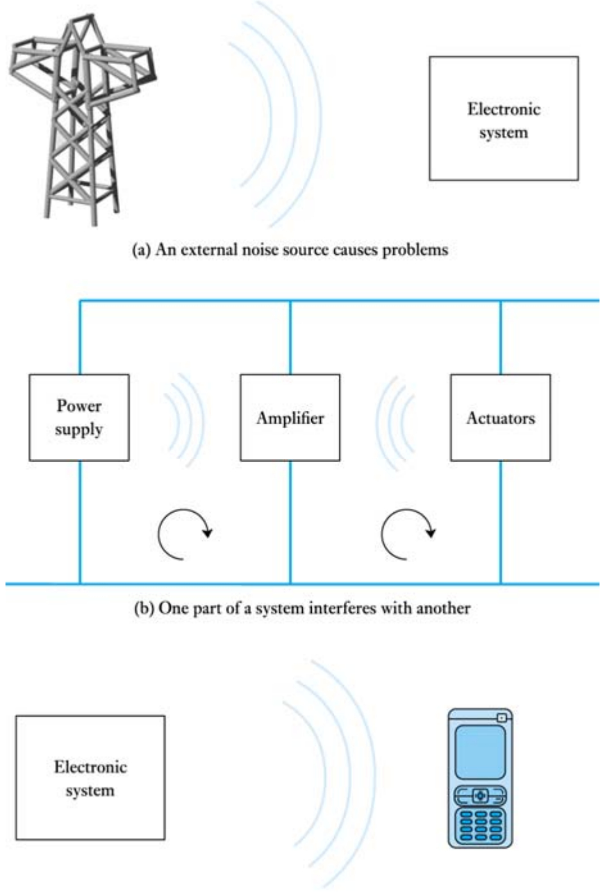
Electromagnetic compatibility

Video 22B



22.9

- Examples of EMC problems
- Generally, noise at f < 30 MHz is conducted ("in wire")
- Noise at f > 30 MHz, or transients can be radiated
- Current loops ⇒ magnetic dipole radiation

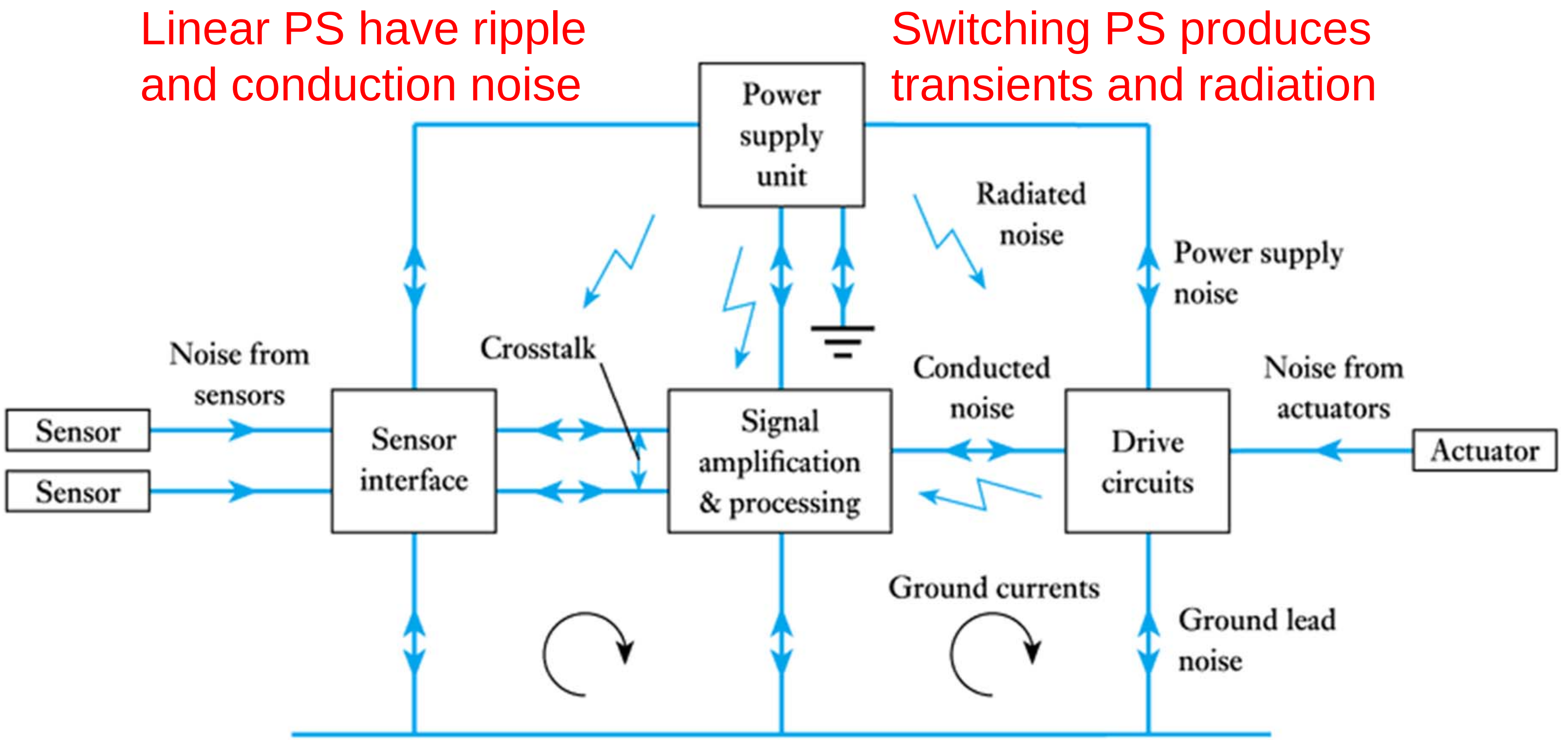


(a) An external noise source causes problems

(b) One part of a system interferes with another

(c) A system interferes with the operation of other equipment

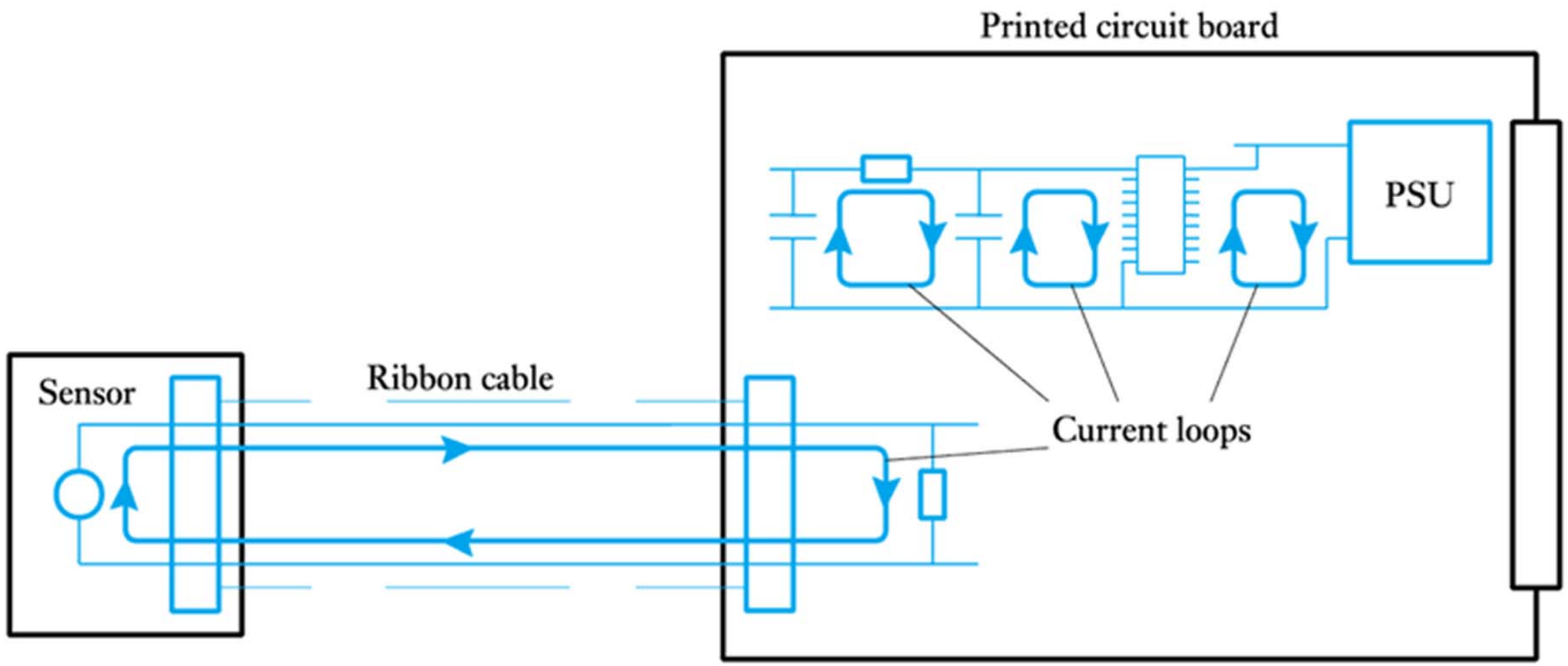
- Electromagnetic coupling between stages



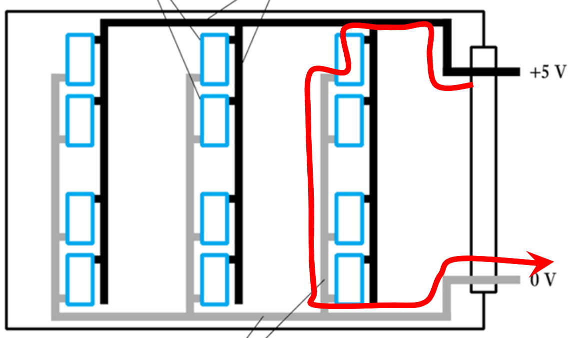
Designing for EMC

22.10

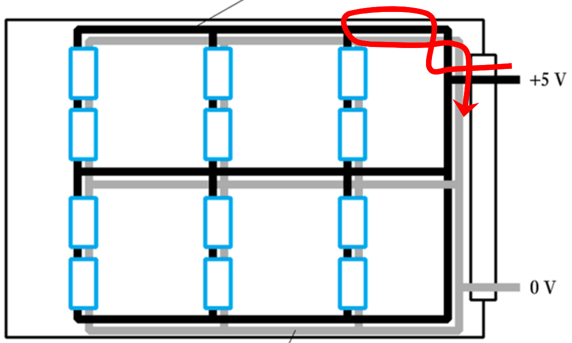
- Examples of current loops within circuits



- Examples of power supply routing methods
- 2-Rail technique can allow large current loops to form
- Better to use grid
- Use rounded corners to reduce field strength
- Extend to power plane and ground plane in multi level boards

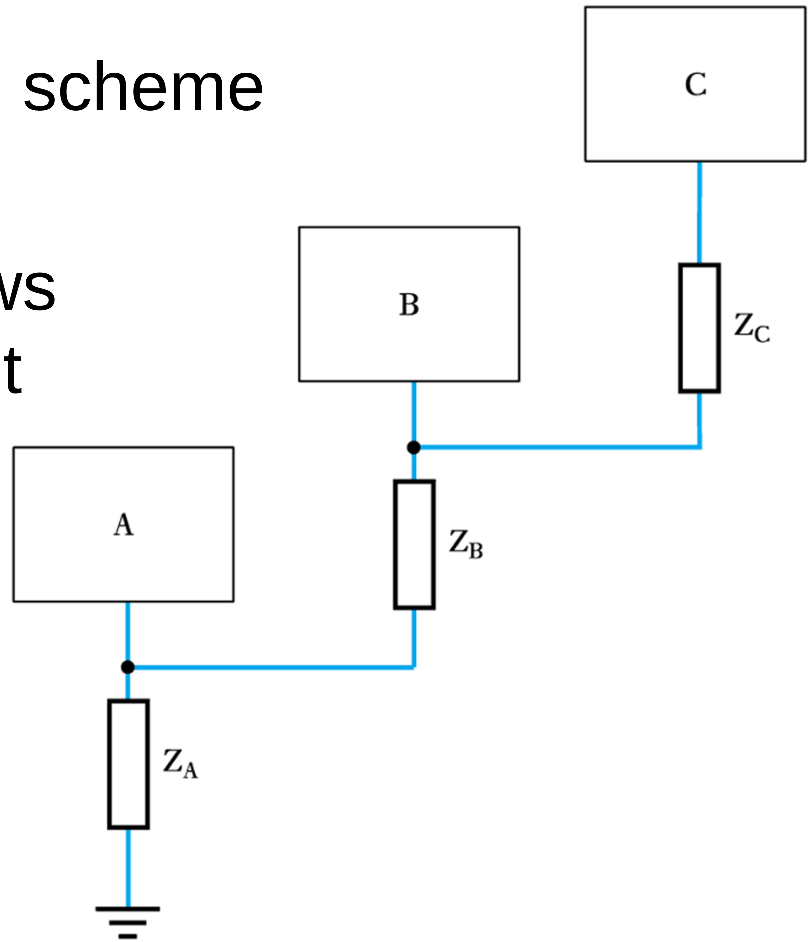


(a) A poor 'comb' layout

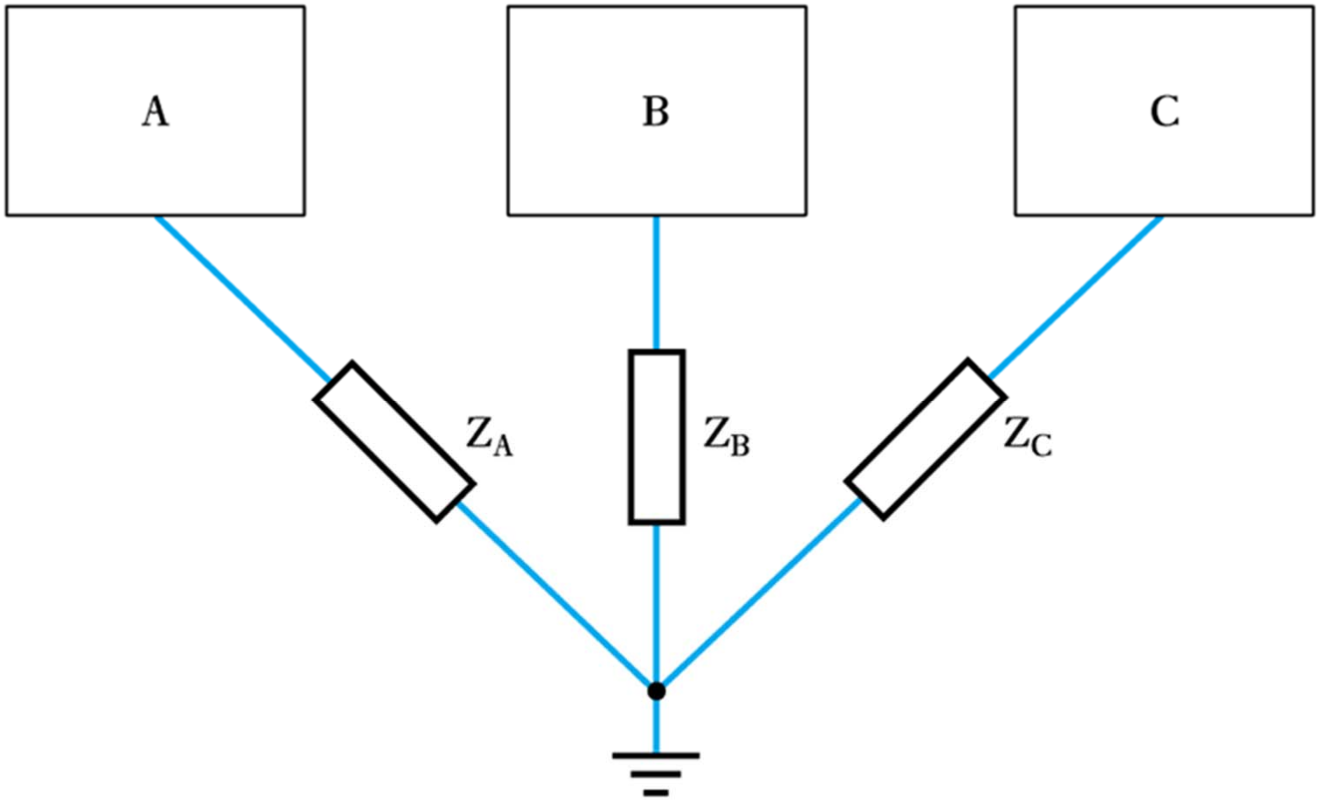


(b) A better 'grid' arrangement

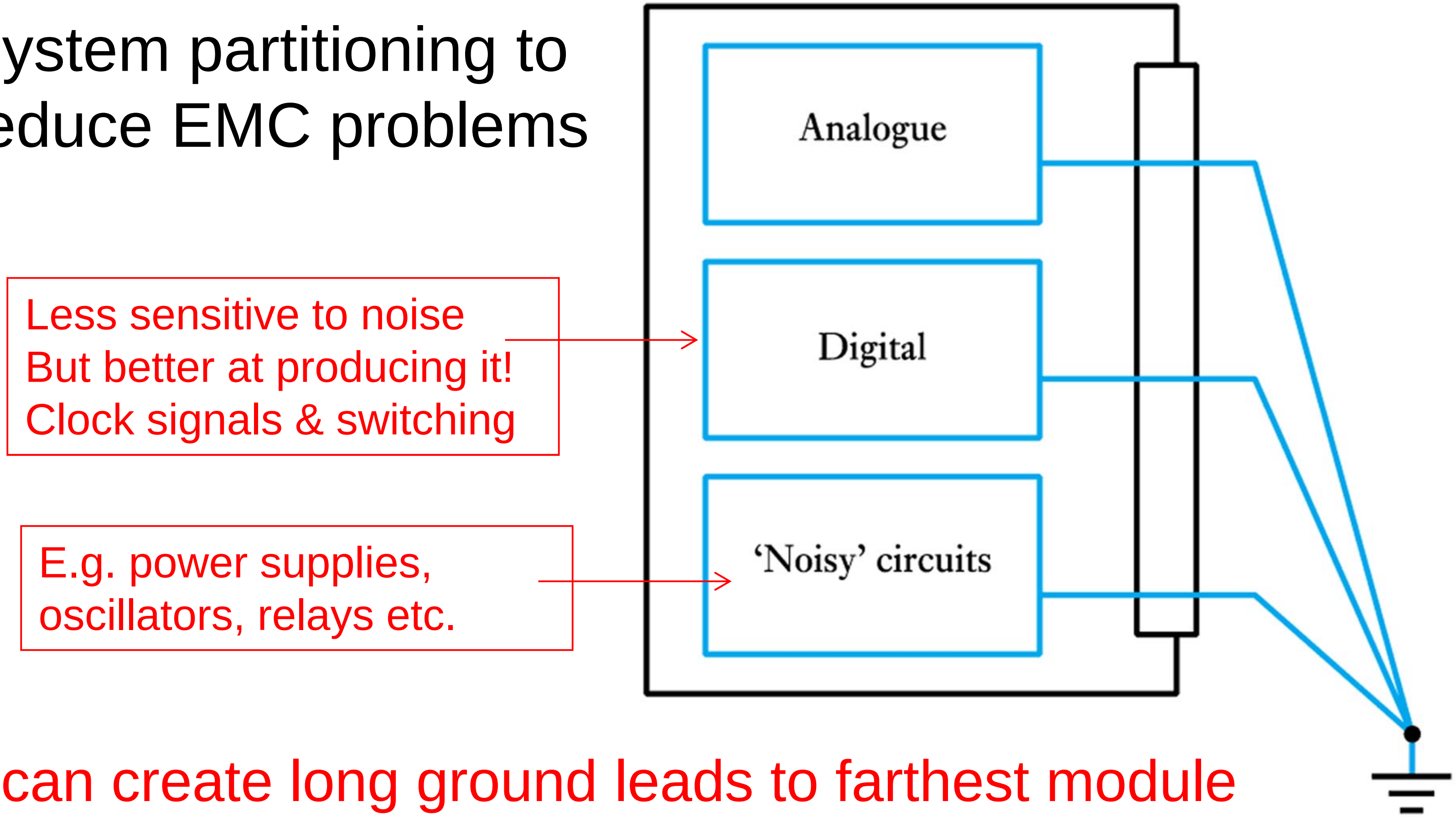
- A simple series grounding scheme
- If module B suddenly draws power, large return current will raise the potential of the ground point in A



- A single-point grounding scheme uncouples modules

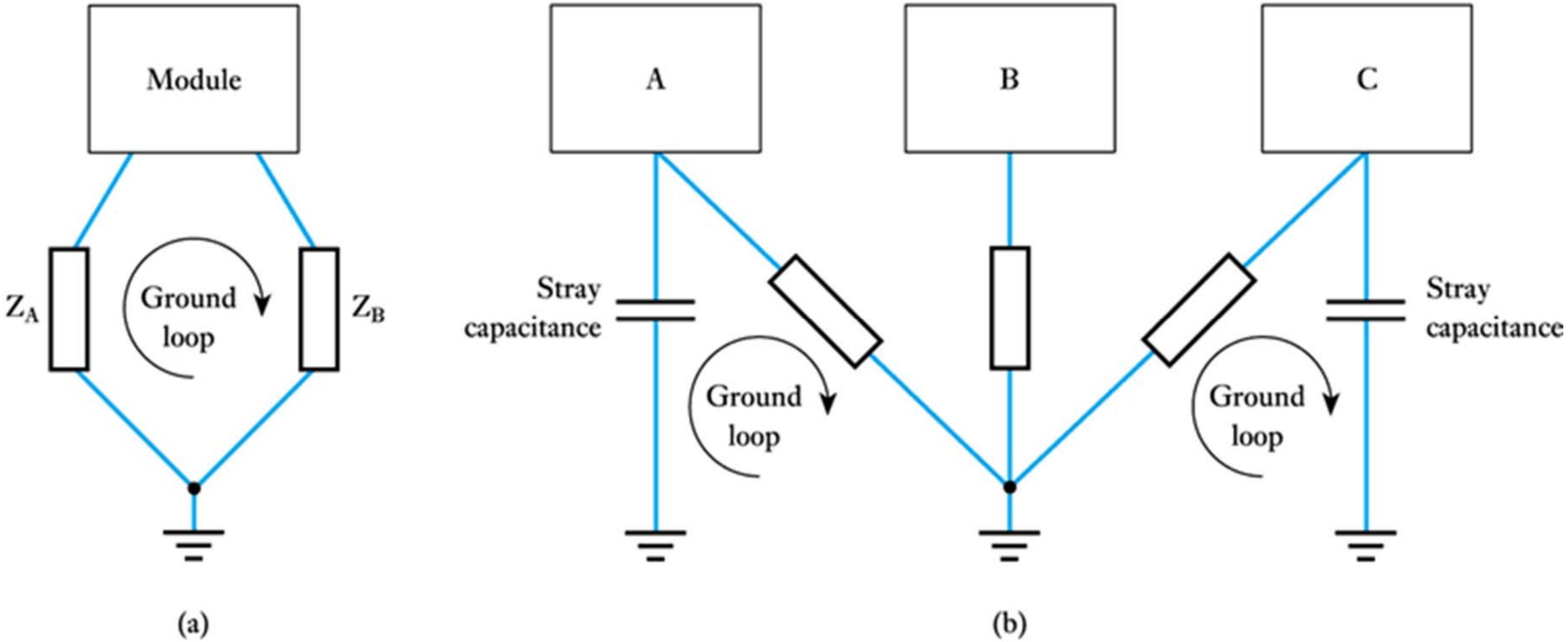


- System partitioning to reduce EMC problems

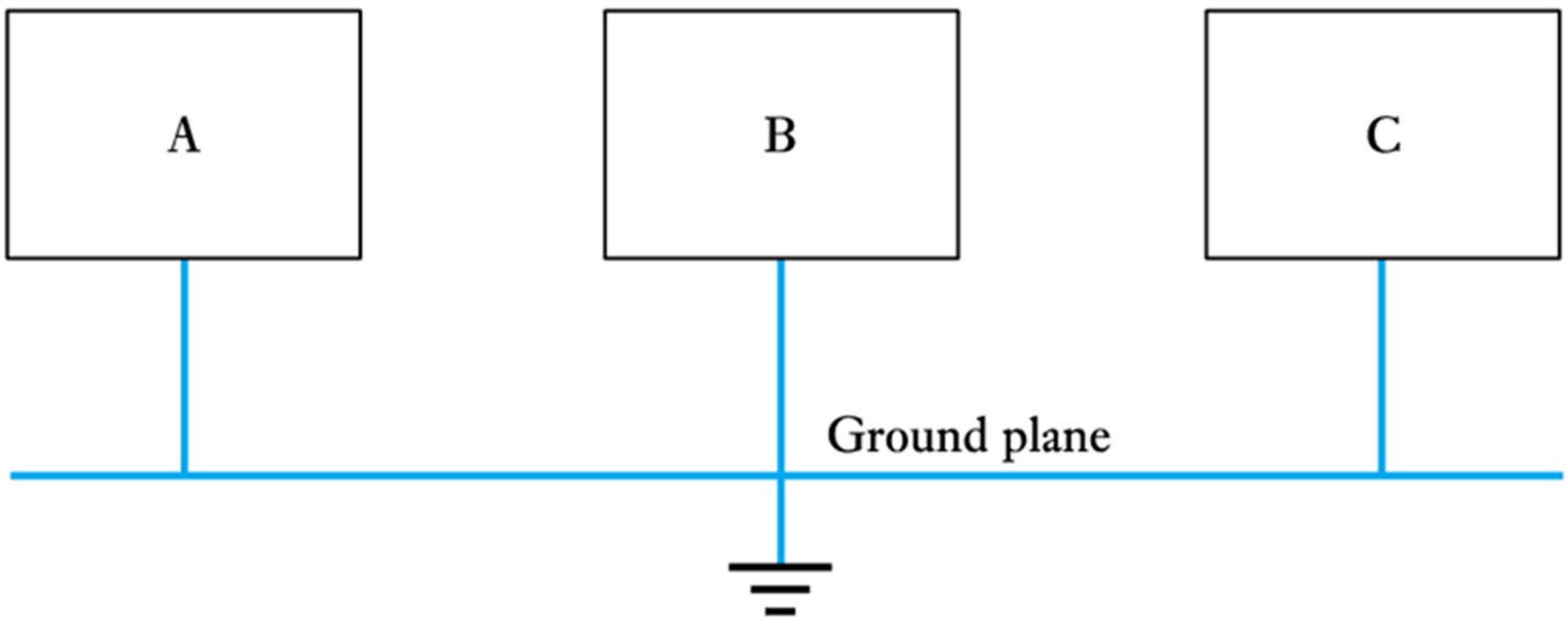


But can create long ground leads to farthest module

- Multiple paths to ground create Ground loops
- Stray capacitance at high frequency (> 1 MHz) can create loops where you least expect them

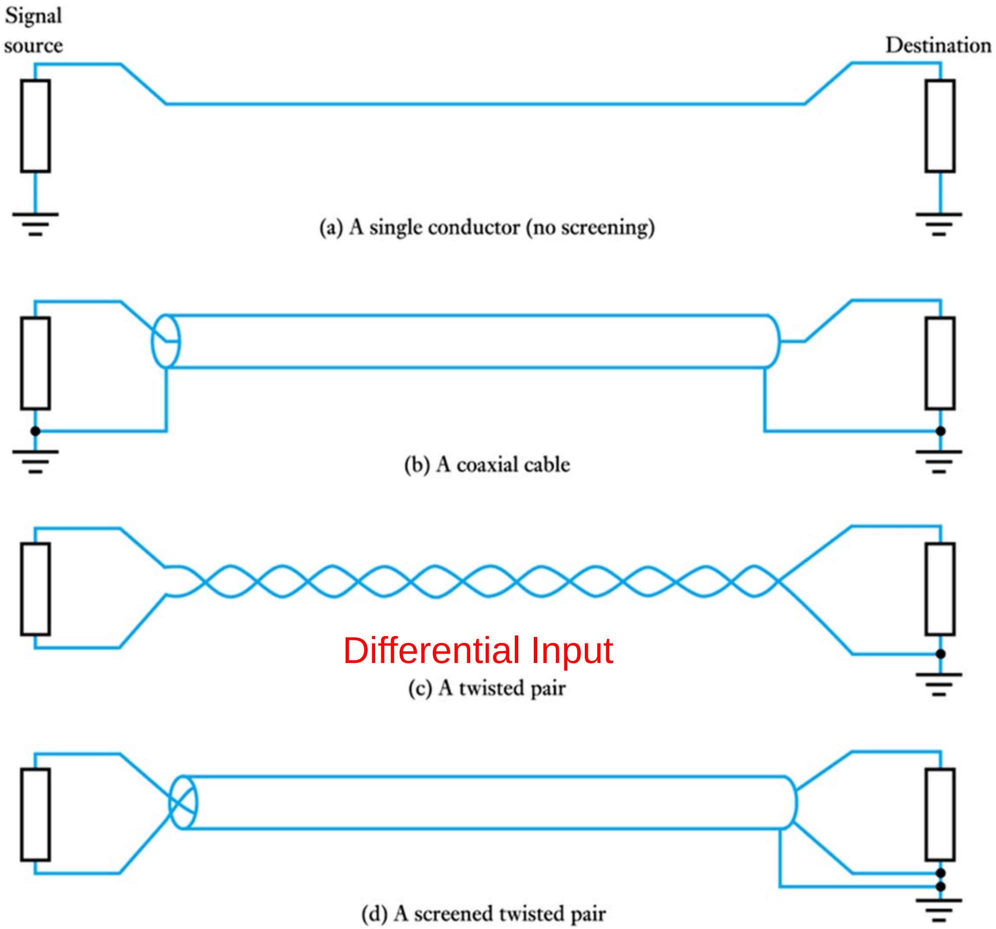


- A multipoint grounding scheme (good at high frequencies or modules where you don't know how they are grounded internally)

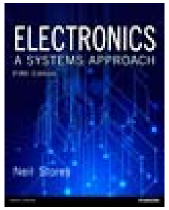


- Cable-screening techniques

- Can have separate Signal and Chassis grounds, tied at a single point.



Further Study



Video 22C Further Study

- The Further Study section at the end of Chapter 22 considers the implications of EMC for safety critical systems, such as those found within cars.

- Identify some of the safety-related systems within a modern car and consider how EMC related factors could affect their operation. Then, watch the video for a discussion of some of the issues involved.

Key points

- Noise in electronic circuits can be of various forms, including thermal noise, shot noise, 1/f noise and interference
- Both bipolar transistors and FETs suffer from noise
- Electromagnetic compatibility (EMC) is concerned with the ability of a system to operate in the presence of interference and to not interfere with other equipment (or itself)
- Circuit layout plays a major role in determining EMC performance