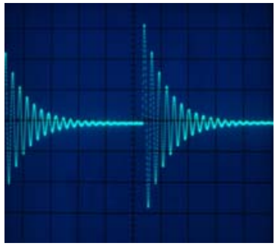
First: Reference Group

- Have two volunteers
  - Please email me so that I am sure to have your correct emails
- Require 1 to 2 more, preferably from other study lines
- Sign up at the break and contact me by email:
  patrick.espy@ntnu.no

Chapter 9

Last time: Transient Behaviour

- Introduction
- Charging Capacitors and Energising Inductors
- Discharging Capacitors and De-energising Inductors
- Response of First-Order Systems
- Second-Order Systems
- Higher-Order Systems

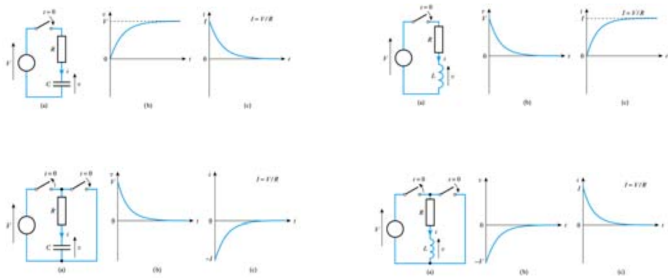


Key Points

- The charging or discharging of a capacitor, and the energising and de-energising of an inductor, are each associated with exponential voltage and current waveforms
- Circuits that contain resistance, and either capacitance or inductance, are termed first-order systems
- The increasing or decreasing exponential waveforms of first-order systems can be described by the initial and final value formulae
- Circuits that contain both capacitance and inductance are usually second-order systems. These are characterised by their undamped natural frequency and their damping factor

Transient Behaviour in RC & RL (1st order) systems

- A comparison of the four circuits



Response of First-Order Systems

9.4

- **Initial and final value formulae**
  - increasing or decreasing exponential waveforms (for either voltage or current) are given by:

$$v = V_f + (V_i - V_f)e^{-t/T}$$

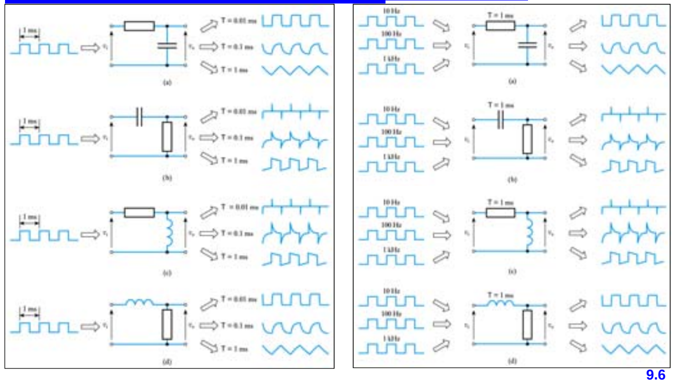
$$i = I_f + (I_i - I_f)e^{-t/T}$$

  - where V_i and I_i are the *initial* values of the voltage and current
  - where V_f and I_f are the *final* values of the voltage and current
  - the first term in each case is the **steady-state response**
  - the second term represents the **transient response**
  - the combination gives the **total response** of the arrangement

9.5

Response to square wave:

change of time constant **change of input frequency**

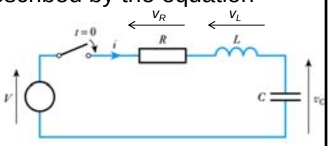


9.6

Second-Order Systems

9.5

- Circuits containing both capacitance and inductance are termed **second-order systems**
  - for example, this circuit is described by the equation



$$v_R + v_L + v_C = V \quad (KVL)$$

$$\text{but} \quad i = C\frac{dv_C}{dt} \quad \text{so:}$$

$$v_R = iR = RC\frac{dv_C}{dt} \qquad v_L = L\frac{di}{dt} = LC\frac{d^2v_C}{dt^2}$$

$$\text{so} \quad v_L + v_R + v_C = V \quad \text{becomes}$$

$$LC\frac{d^2v_C}{dt^2} + RC\frac{dv_C}{dt} + v_C = V \quad \text{of form} \quad \frac{1}{\omega_n^2}\frac{d^2y}{dt^2} + \frac{2\zeta}{\omega_n}\frac{dy}{dt} + y = x$$

9.7

Second-Order Systems

$$\frac{1}{\omega_n^2}\frac{d^2y}{dt^2} + \frac{2\zeta}{\omega_n}\frac{dy}{dt} + y = x$$

with $\omega_n = \dfrac{1}{\sqrt{L \cdot C}}$ *which is* ω_o, the RLC-series resonant frequency

and $\zeta = \dfrac{1}{2}R\sqrt{\dfrac{C}{L}}$ *which is* $\dfrac{1}{2Q}$ where Q is the RLC-series quality factor

So ω_n is the **undamped natural frequency** (ω_o) in rad/s

The frequency at which L and C oscillate energy back and forth

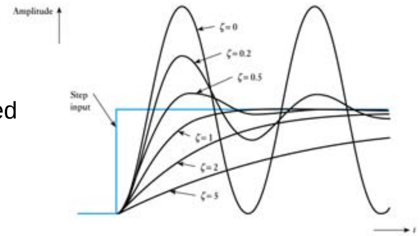
and ζ (Greek Zeta) is the **damping factor** (depends on R)

The rate at which R dissipates the energy stored in L and C

9.8

Transient Response of second-order systems

- ζ =0 undamped
- ζ <1 under damped
- ζ =1 critically damped
- ζ >1 over damped



When the RLC series circuit is used as a band pass filter-
Select ω_o and Q for filter characteristics as well as transient response

Last time: Amplification

Chapter 14

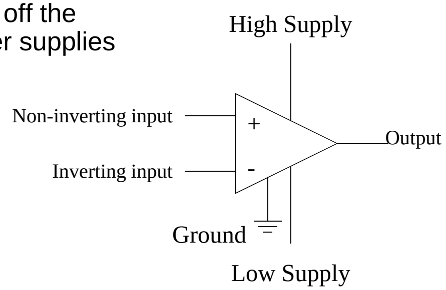
- Introduction
- Electronic amplifiers
- Sources and loads
- Equivalent circuit of an amplifier
- Output power
- Power gain
- Frequency response and bandwidth
- Differential amplifiers
- Simple amplifiers

- **Passive and active amplifiers**
  - **passive amplifiers** – Have no external energy source
    - The power delivered at the output must be less than (or equal to) that absorbed at the input
    - Example: Transformers (step up or step down voltage)
  - **active amplifiers** – Have an external source of power
    - The output can deliver more power than is absorbed at the input
    - But not more than is delivered by the external source
    - We will focus on these

Electronic amplifiers

Can't get more out than Power Supplies put in

- Circuit Symbol
- Usually leave off the external power supplies



Voltage Gain $(A_v) = \frac{V_o}{V_i}$

Current Gain $(A_i) = \frac{I_o}{I_i}$

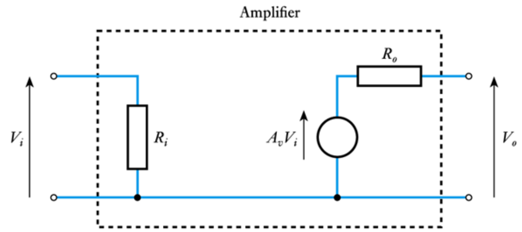
Power Gain $(A_p) = \frac{P_o}{P_i}$

Equivalent circuit of an amplifier

Video 14A

14.4

- input voltage, V_i, sensed across input resistance, R_i
- Amplified to A_vV_i at the output
- Fed to the outside world through output resistance R_o



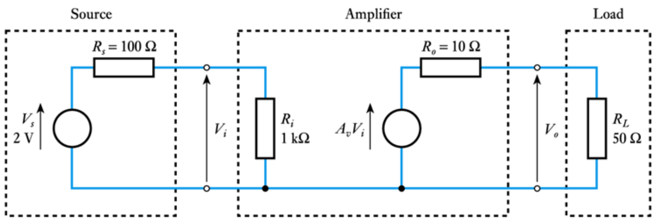
Today

- How the amplifier interacts with the rest of the circuit
- Output power
- Power gain
- Frequency response and bandwidth
- Differential amplifiers
- Simple amplifiers
- Feedback

- **The use of an equivalent circuit**
  (see **Example 14.1** in the course text):

  Example: An amplifier has a voltage gain of 10, an input resistance of 1 kΩ and an output resistance of 10 Ω. The amplifier is connected to a sensor that produces a voltage of 2 V and has an output resistance of 100 Ω, and to a load of 50 Ω. What will be the output voltage of the amplifier (that is, the voltage across the load resistance)?

- We start by constructing an equivalent circuit of the amplifier, the source and the load



- From this we can calculate the output voltage:

$$V_i = \frac{R_i}{R_S + R_i} V_S$$ V_i is from V_s divided between R_i and R_s

$$= \frac{1\text{k}\Omega}{100\,\Omega + 1\text{k}\Omega} 2\text{ V} = 1.82\text{ V}$$

$$V_o = A_v V_i \frac{R_L}{R_o + R_L}$$ V_o is from AV_i divided between R_o and R_L

$$= 10\ V_i \frac{50\ \Omega}{10\ \Omega + 50\ \Omega}$$

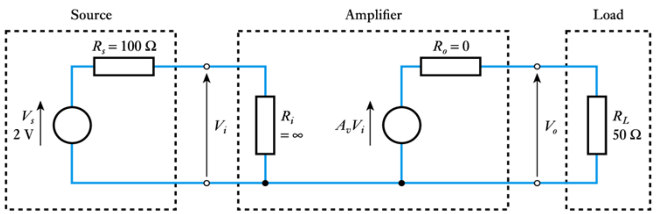
$$= 10 \times 1.82 \frac{50\ \Omega}{10\ \Omega + 50\ \Omega} = 15.2\text{ V}$$

- The **voltage gain** of the circuit in the previous example is given by:

$$\text{Voltage gain } (A_V) = \frac{V_o}{V_i} = \frac{15.2}{1.82} = 8.35$$

  - note that this is considerably less than the stated gain of the amplifier (which is 10)
  - this is due to **loading effects**
  - the gain of the amplifier in isolation is its **unloaded voltage gain**

- An **ideal voltage amplifier** would not suffer from loading
  - it would have $R_i = \infty$ and $R_o = 0$
  - consider the effect on the previous example



- If $R_i = \infty$, then $\frac{R_i}{R_S + R_i} \approx \frac{R_i}{R_i} = 1$
- Therefore

$$V_i = \frac{R_i}{R_S + R_i} V_S \approx V_S = 2\text{ V}$$

$$V_o = A_v V_i \frac{R_L}{R_o + R_L}$$

$$= 10\ V_i \frac{50\ \Omega}{0\ \Omega + 50\ \Omega}$$

$$= 10 \times 2 \frac{50\ \Omega}{50\ \Omega} = 20\text{ V}$$

  - the effects of loading are removed (see **Example 14.3**)

Output power

14.5

- Power Gain is the ratio of the output power P_o is that dissipated in the load resistor to the input power absorbed at the input

$$P_i = \frac{V_i^2}{R_i} \qquad P_o = \frac{V_o^2}{R_L}$$

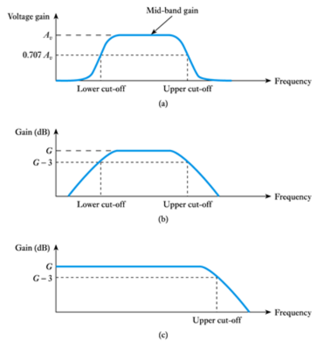
- Power transfer is at a *maximum* when $R_L = R_o$
  - **maximum power theorem** (see Thevenin lecture)
  - choosing a load to maximize power transfer is called **matching**
  - However, voltage gain is often more important than power transfer, particularly in instrumentation

Frequency response and bandwidth

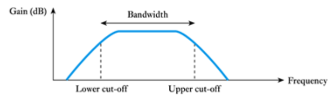
14.7

- All real amplifiers have limits to the range of frequencies over which they can be used
- The gain of a circuit in its normal operating range is termed its **mid-band gain**
- The gain of all amplifiers falls at high frequencies
  - characteristic defined by the **half-power point**
  - gain falls to **1/√2 = 0.707** times the mid-band gain
  - this occurs at the **cut-off frequency**
- In some amplifiers gain also falls at low frequencies
  - these are **AC coupled amplifiers**

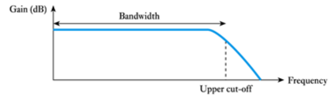
- (a) shows an AC coupled amplifier
- (b) shows the same amplifier – with gain in dBs
- (c) shows a DC coupled amplifier – the gain is constant down to DC



- The **bandwidth** is the difference between the upper and lower cut-off frequencies …



- … or the difference between the upper-cut-off frequency and zero in a DC coupled amplifier

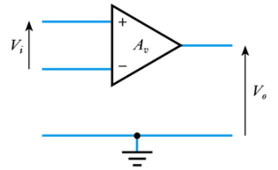


Differential amplifiers

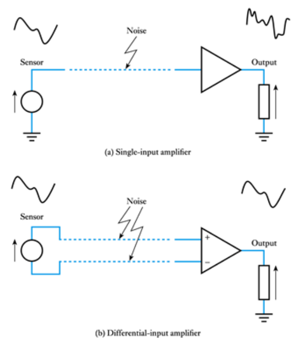
Video 14C

14.8

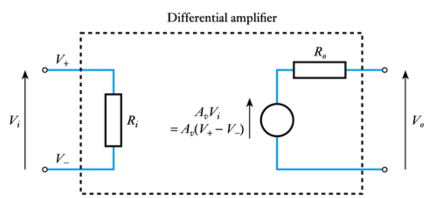
- Differential amplifiers have two inputs and amplify the voltage difference between them
  - Inputs are called the **non-inverting input** (labelled +) and the **inverting input** (labelled –)



- An example of the use of a differential amplifier



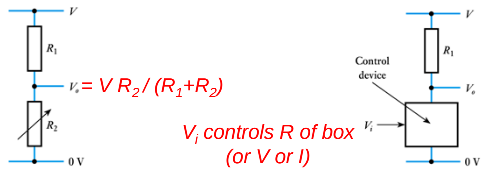
- **Equivalent circuit of a differential amplifier**
  - one of the commonest forms of differential amplifier is the **operational amplifier** – discussed in later lectures



Simple amplifiers

14.9

- Operational amplifiers are relatively complex circuits
- Amplifiers can also be formed using a ‘control device’
  - circuit is similar to a potential divider with one resistor replaced with a ‘control device’ typically a **transistor**



A potential divider

A simple amplifier

Further Study

Video 14D Further Study

- The Further Study section at the end of Chapter 14 considers the initial stages of the design of an audio amplifier.
- Your task here is not to define the actual circuit, but simply to determine its required gain.

- Try to establish the requirements of the circuit and then take a look at the video.

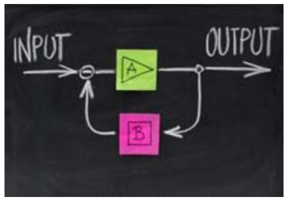
Key points

- Amplification forms part of most electronic systems
- Amplifiers may be *active* or *passive*
- Equivalent circuits are useful when investigating the interaction between circuits
- The gain of all amplifiers falls at high frequencies
- The gain of some amplifiers falls at low frequencies
- Differential amplifiers take as their input the difference between two input signals
- Some amplifiers are very simple in construction

Control and feedback

Chapter 15

- Introduction
- Open-loop and closed-loop systems
- Automatic control systems
- Feedback systems
- Negative feedback
- The effects of negative feedback
- Negative feedback – a summary



Introduction

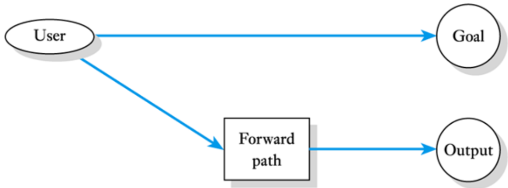
15.1

- **Control** is one of the basic functions performed by many systems
  - this often involves **regulation** or **command**
- The goal is:
  - to determine the value or state of some physical quantity
  - and often to maintain it at that value, despite variations in the system or the environment

Open-loop and closed-loop systems

15.2

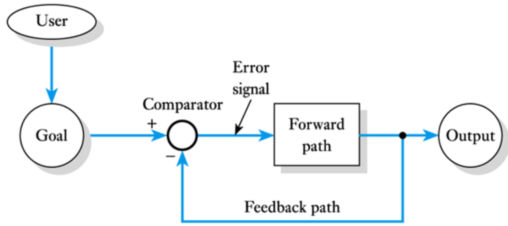
- Simple control is often **open-loop**
  - user has a **goal** and selects an input to a system to try to achieve this



(a) An open-loop system

14.33

- More sophisticated arrangements are **closed-loop**
  - user inputs the goal to the system



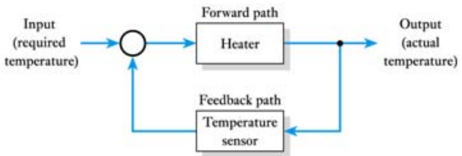
(b) A closed-loop system

14.34

Automatic control systems

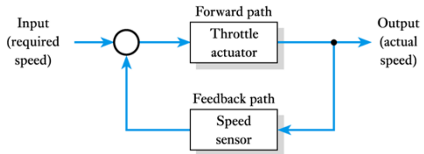
15.3

- Examples of automatic control systems:
  - **temperature control using a room heater**



14.35

- Examples of automatic control systems:
  - **cruise control in a car**

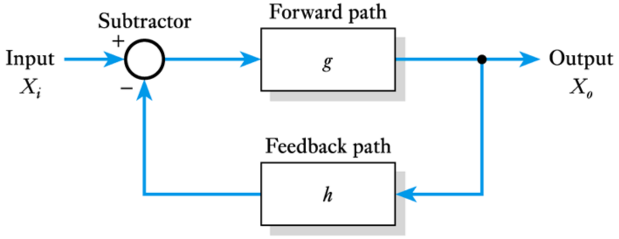


14.36

Generalized feedback systems

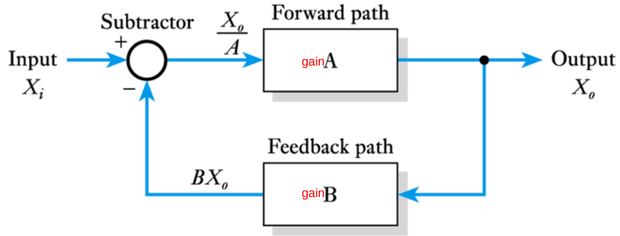
Video 15A 15.4

- A generalised feedback system input transformed by g, output transformed by h



If the transfer function, g and h, are just gains

- By inspection of diagram we can add values



$\frac{X_o}{A} = X_i - BX_o$ or rearranging $\frac{X_o}{X_i} = \frac{A}{1+AB}$

- Thus

$$\text{Overall gain } G = \frac{X_o}{X_i} = \frac{A}{1+AB}$$

- This is the **transfer function** of the arrangement
- Terminology:
  - *A* is also known as the **open-loop gain**
  - *G* is the overall or **closed-loop gain**

- Effects of the product *AB*
  - If *AB* is negative
    - If *AB* is negative and less than 1, (1 + *AB*) < 1
    - In this situation G > A and we have **positive feedback**
  - If *AB* is positive
    - If *AB* is positive then (1 + *AB*) > 1
    - In this situation G < A and we have **negative feedback**
    - If *AB* is positive *and AB* >>1

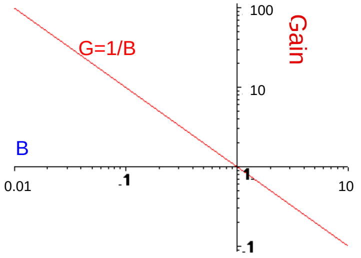
$$G = \frac{A}{1+AB} \approx \frac{A}{AB} = \frac{1}{B}$$

– gain is independent of the gain of the forward path *A*

$$\text{Overall gain } G = \frac{X_o}{X_i} = \frac{A}{1+AB}$$

Negative feedback (A*B > 0)

- Examine Overall Gain = A/(1+A*B)
  - **A=100000**, B = 0.01 to 10 (Negative Feedback)



If B=0→Gain = open loop A

If B<1 → AB>>1 Gain < A and ≈1/B

note Gain >1

If B>1 → AB>>1 Gain < A and ≈1/B

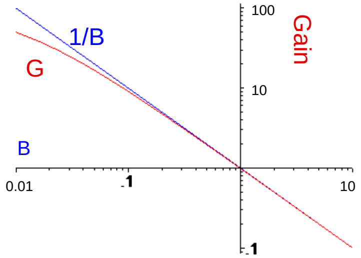
now Gain <1

AB>>1 → Gain independent of A

$$\text{Overall gain } G = \frac{X_o}{X_i} = \frac{A}{1+AB}$$

Negative feedback (A*B > 0)

- Examine Overall Gain = A/(1+A*B)
  - **A=100**, B = 0.01 to 10 (Negative Feedback)



If B=0→Gain = open loop A

If B ≥1 → AB>>1 Gain < A and ≈1/B

note Gain <1

If B<1 → as 1/B→A, Gain ≤ 1/B

A influences the total gain

By using a large A, the system gain is independent of A!

Negative feedback

Video 15B

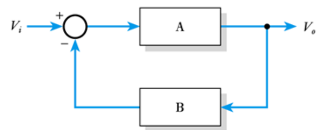
15.5

- Negative feedback can be applied in many ways
  - X_i and X_o could be temperatures, pressures, etc.
  - here we are mainly interested in voltages and currents
- Is particularly important in overcoming **variability**
  - all active devices suffer from variability
    - their gain and other characteristics vary with temperature and between devices
  - we noted above that using negative feedback we can produce an arrangement where the gain is *independent* of the gain of the forward path (A)
    - this gives us a way of overcoming problems of variability in the device with gain A.

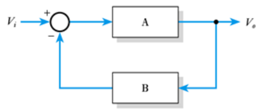
Negative feedback – an example

- Consider the following example (**Example 15.1** in text)
  Example: Design an arrangement with a stable voltage gain of 100 using a high-gain active amplifier. Determine the effect on the overall gain of the circuit if the voltage gain of the active amplifier varies from 100,000 to 200,000.

  We will base our design on our standard feedback arrangement



- We will use our active amplifier for *A* and a stable feedback arrangement for *B*

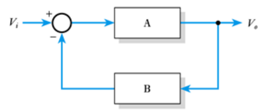


- Since we require an overall gain of 100 and

$$G = \frac{1}{B}$$

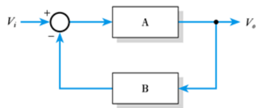
we will use ***B* = 1/100 or 0.01**

- Now consider the gain of the circuit when the gain of the active amplifier ***A* is 100,000**



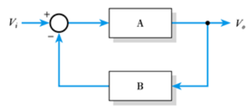
$$G = \frac{A}{1+AB} = \frac{100,000}{1+(100,000 \times 0.01)}$$
$$= \frac{100,000}{1+1000}$$
$$= 99.90$$
$$\approx \frac{1}{B}$$

- Now consider the gain of the circuit when the gain of the active amplifier ***A* is 200,000**



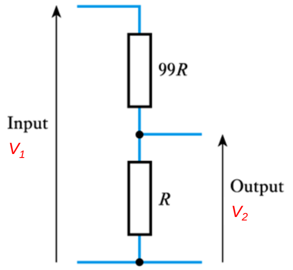
$$G = \frac{A}{1+AB} = \frac{200,000}{1+(200,000 \times 0.01)}$$
$$= \frac{200,000}{1+2000}$$
$$= 99.95$$
$$\approx \frac{1}{B}$$

- Note that a change in the gain of the active amplifier of 100% causes a change in the overall gain of just 0.05 %



- Thus, the use of negative feedback makes the gain largely independent of the gain of the active amplifier
- However, it does require that *B* is stable
  – fortunately, *B* can be based on stable passive components

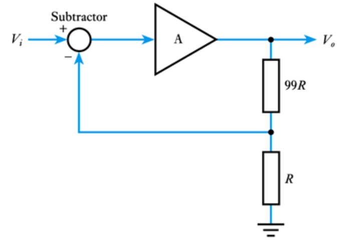
- Implementing the passive feedback path
  - to get an overall gain of greater than 1 requires a feedback gain *B* of less than 1
  - in the previous example the value of *B* is 0.01
  - this can be achieved using a simple potential divider



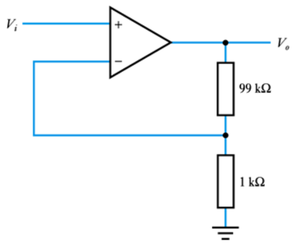
$V_2 = 0.01 * V_1$

- Thus, we can implement our feedback arrangement using an active amplifier and a passive feedback network to produce a stable amplifier
- The arrangement on the right has a gain of 100 …

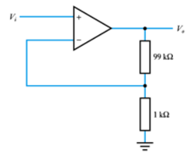
  … but how do we implement the subtractor?



- A differential amplifier is effectively an active amplifier combined with a subtractor. A common form is the **operational amplifier** or **op-amp**
- The arrangement on the right has a gain of 100



- In this circuit the gain is determined by the passive components and we do not need to know the gain of the op-amp
  - however, earlier we assumed that *AB* >> 1
  - that is, *A* >> 1/*B*
  - that is, **open-loop gain >> closed-loop gain**
  - therefore, the gain of the circuit must be much less than the gain of the op-amp
  - see **Example 15.2** in the course text



The effects of negative feedback

15.6

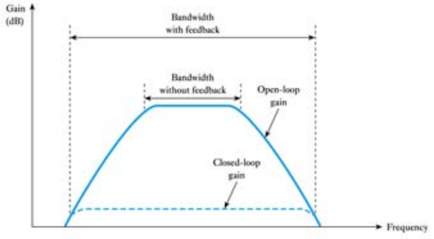
- **Effects on gain**
  - negative feedback produces a gain given by

$$G = \frac{A}{1 + AB}$$

  - there, feedback *reduces* the gain by a factor of 1 + *AB*
  - this is the price we pay for the beneficial effects of negative feedback

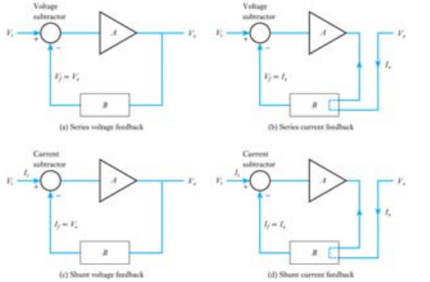
- **Effects on frequency response**
  - from earlier lectures we know that all amplifiers have a limited frequency response and bandwidth
  - with feedback we make the overall gain largely independent of the gain of the active amplifier
  - this has the effect of increasing the bandwidth, since the gain of the feedback amplifier remains constant as the gain of the active amplifier falls
  - however, when the open-loop gain is no longer much greater than the closed-loop gain the overall gain falls

- therefore the bandwidth *increases* as the gain is *reduced* with feedback
- in some cases the **gain x bandwidth = constant**



The effects of negative feedback (contd.)

- **Effects on input and output resistance**
  - negative feedback can be used in a number of ways.



– negative feedback can either *increase* or *decrease* the input or output resistance depending on how it is used.
  - if the output voltage is fed back this tends to make the output voltage more stable by *decreasing* the output resistance
  - if the output current is fed back this tends to make the output current more stable by *increasing* the output resistance
  - if a voltage related to the output is subtracted from the input voltage this *increases* the input resistance
  - if a current related to the output is subtracted from the input current this *decreases* the input resistance
  - the factor by which the resistance changes is (1 + *AB*)
  - we will apply this to op-amps in a later lecture

- **Effects on distortion and noise**
  - many forms of **distortion** are caused by a non-linear amplitude response
    - that is, the gain varies with the amplitude of the signal
  - since feedback tends to stabilise the gain it also tends to reduce distortion – often by a factor of (1 + *AB*)
  - **noise** produced *within* an amplifier is also reduced by negative feedback – again by a factor of (1 + *AB*)
    - note that noise already corrupting the input signal is *not* reduced in this way – this is amplified along with the signal

- **Effects on stability**
  - from earlier we know that

$$G = \frac{A}{1 + AB}$$

  - so far we have assumed that *A* and *B* are positive real numbers
  - real amplifiers produce phase shifts at some frequencies
  - a phase shift of 180° represents an inversion of the gain
  - this will turn *negative* feedback into *positive* feedback
  - therefore, feedback has implication for **stability**
  - we will return to look at stability in later lectures

Negative feedback – a summary

15.7

- All negative feedback systems share some properties
  1. They tend to maintain their output independent of variations in the forward path or in the environment
  2. They require a forward path gain that is greater than that which would be necessary to achieve the required output in the absence of feedback
  3. The overall behaviour of the system is determined by the nature of the feedback path
- Unfortunately, negative feedback does have implications for the **stability** of circuits – this is discussed in later lectures

Further Study

Video 15C

Further Study

- The Further Study section at the end of Chapter 15 sites an air conditioning system as an example of an arrangement that can be either open- or closed-loop in operation.
- Identify a range of other control systems and decide whether these are open- or closed-loop arrangements and then watch the video.

Key points

- Feedback is used in almost all automatic control systems
- Feedback can be either negative or positive
- If the gain of the forward path is A, the gain of the feedback path is B and the feedback is subtracted from the input then

$$G = \frac{A}{1 + AB}$$

- If AB is positive and much greater than 1, then $G \approx 1/B$
- Negative feedback can be used to overcome problems of variability within active amplifiers
- Negative feedback can be used to increase bandwidth, and to improve other circuit characteristics