E2.2 Analogue Electronics

- Instructor : Christos Papavassiliou
- Office, email : EE 915, c.papavas@imperial.ac.uk
- Lectures : Monday 2pm, room 408 (weeks 2-11)
  Thursday 3pm, room 509 (weeks 4-11)
- Problem, Quizzes: Thursday 4pm, room 408 (weeks 3-4, 7-11)

- Office hours: Tuesday 11am
  Thursday 10 am
- Office hours start week 3 (week of 1910/09)
- Course website: on blackboard
  (or on my home page)

What analogue electronics is

- Engineering, i.e. the analysis (study and reverse engineering) and synthesis (“design”) of circuits:
  - *Amplifiers, Filters, Oscillators*
  - *Radio*
  - *Multipliers (Modulators – Demodulators)*
  - *Analogue signal processing (e.g. rectifiers, logarithmic amplifiers)*
  - *Fast Digital gates (!)*
- Applications:

  Communications, Signal Processing, Control, Instrumentation, …
- Areas of human activity:

  Industrial, Consumer, Biomedical, …

analogue electronics **is not** only

- CMOS integrated circuits
- Transistor circuits
- Op-amp circuits
- Audio electronics
- Mobile phone circuits
- Radars
- Printed circuit board design
- Integrated circuit design
- Television set repair

In fact, it is all of the above, and much more. Restricting our point of view to one of these will make understanding the topic more difficult.

Course Aims

Learn to analyse electronic circuits

- Analysis is prerequisite to:
  - *DESIGN (including Integrated Circuit design)*
  - *APPLICATION (including repair)*

- Analysis is performed through modelling:
  - *ABSTRACTION: replace groups of components with one symbol*
  - *SIMPLIFICATION but NOT oversimplification*
  - *MATHEMATICS (is a language, not a torture device!)*

- The inverse of ANALYSIS is SYNTHESIS (i.e. DESIGN!)

- The course is closely connected to two other 2nd year courses:
  - *Control Theory*
  - *Signal processing*

because circuits are used to implement control and signal processing
AND because without their methods circuit analysis is not possible (except in trivial cases)

Week-by-week course content

Week 2:	Revision; Thevenin and Norton circuits, ladders.
Week 3 - PS1:	Frequency response of BJT amplifier and Parallel form of Miller Theorem
Week 4 - PS2:	Feedback amplifiers – Gain, port impedances.
Week 5 - PS3:	Series form of Miller Theorem. Emitter Degeneration
Week 6 - PS4:	Frequency response of Common base and Common Collector amplifiers.
Week 7 - PS5:	FET amplifiers; 2 port networks. Composition rules; 2 stage amplifiers
Week 8 - PS6:	The transmission matrix and multistage amplifiers
Week 9 - PS7:	Active filters
Week 10 - PS8:	Active filters; Op-amp internals - oscillators
Week 11:	Nonlinear circuits and introduction to noise

WK		Day	Date	Time	RM		
2	L1	Mon	12/10/09	2pm	408		Introduction - Revision
3	L2	Mon	19/10/09	2pm	408		Miller Theorem: Freq. response of BJT CE amplifier
	C1	Thu	26/10/09	4pm	408		
4	L3	Mon	26/10/09	2pm	408		Feedback amplifiers: Gain
	L4	Thu	29/10/09	3pm	509		Feedback amplifiers: Input - Output Impedance
	C2	Thu	29/10/09	4pm	408	Quiz 1	
5	L5	Mon	02/11/09	2pm	408		Second form of Miller Theorem: Emitter Degeneration
	C3	Thu	05/11/09	3pm	509		
6	L6	Mon	09/11/09	2pm	408		Common Base Amplifier
	L7	Thu	12/11/09	3pm	509		Common Collector Amplifier
7	L8	Mon	16/11/09	2pm	408		Two stage transistor amplifiers
	L9	Thu	19/11/09	3pm	509		Two-port parameters
	C4	Thu	19/11/09	4pm	408		
8	L10	Mon	23/11/09	2pm	408		Interconnection of two-port networks
	L11	Thu	26/11/09	3pm	509		FET amplifiers
	C5	Thu	26/11/09	4pm	408	Quiz 2	
9	L12	Mon	30/11/09	2pm	408		Transmission Matrix - Multistage amps
	L13	Thu	03/12/09	3pm	509		Active filters I
	C6	Thu	03/12/09	4pm	408		
10	L14	Mon	07/12/09	2pm	408		Active filters II
	L15	Thu	10/12/09	3pm	509		Oscillators
	C7	Thu	10/12/09	4pm	408	Quiz 3	
11	L16	Mon	14/12/09	2pm	408		Op-amp internals
	L17	Thu	17/12/09	3pm	509		Beyond Lumped Circuits
	C8	Thu	17/12/09	4pm	408		

Prerequisites

- Analysis of circuits:
  - *Kirchhoff's laws,Nodal Analysis,Thevenin and Norton Theorems, Phasors, Frequency and step Response of RC circuits, DC op-amp circuits: Inverting and Non-Inverting Amplifiers.*
- Analogue electronics:
  - *Static I-V characteristics of BJT and FET transistors*
  - *Small signal models of BJT and FET transistors*
  - *Single Stage Transistor amplifiers with BJT, FET*
- Maths:
  - *Differentiation, Integration*
  - *Second order Ordinary differential Equations*
  - *Complex numbers*
  - *Fourier transforms*

References

- These slides
- Main Course text:
  - *Sergio Franco: Design with Operational Amplifiers and Analog Integrated Circuits, McGraw Hill*
- Any book in analogue electronics you like. There are many! e.g.
  - *Sedra and Smith, Microelectronic Circuits, Oxford U. Press*
- The best general reference in electronics (but not the best to learn from):
  - *Horowitz and Hill, The Art of Electronics, Cambridge U. Press.*

Workload

Direct workload:

- 17 lectures
- 8 problem sessions starting on week 3
- 1 problem sheet/week

Assessment:

- final exam : 2 hours long (100% of the marks)

Indirectly related lab work

The "tools of the trade"

- Kirchhoff's Current Law (KCL) → "nodal analysis"
- Kirchhoff's Voltage Law (KVL) → "mesh analysis" (difficult!)
- Ohm's Law → Idealised Resistors and conductors
- Phasor analysis (i.e. Fourier transform): Capacitors, Inductors
- Modeling:
  - *large signal analysis*
  - *small signal analysis*
- Approximations:
  - *Thevenin and Norton "Theorems"*
- Bode Plots
- All of the above, and more, is implemented in simulators: eg. SPICE
- Mathematics!

Circuit Components

- Independent Sources
  - *Voltage, Current*
- Dependent Sources
  - *Voltage Controlled (Voltage, Current) Source: VCVS and VCCS*
  - *Current Controlled (Voltage, Current) Source: CCVS and CCCS*
- Resistors
- Capacitors, Inductors, transformers
- Diodes,
- Transistors
  - *Bipolar Junction (BJT): NPN, PNP*
  - *Field Effect (FET): n-channel, p-channel, JFET, MOSFET…*
- Operational amplifiers

Computer simulation: SPICE

- Written at the University of California – Berkeley
- User inputs **netlist**, ie a list of components connecting nodes
  - ***The netlist is a way of writing the admittance matrix !***
  - ***Schematic capture is a GUI producing netlists***
- User specifies one or more types of analysis to be performed:
  - *DC bias*
  - *AC small signal*
  - *Transient*
  - *Component sensitivity*
- Commercial versions: very expensive, confusingly complicated!
- Free packages (with schematic, on the web; grab one!):
  - ***5Spice:*** *http://www.5spice.com (schematic capture, includes WinSpice)*
  - ***SIMetrix:*** *www.catena.uk.com/ (complete package)*
  - ***LT Spice :*** *http://www.linear.com/designtools/software/switchercad.jsp*

History of SPICE: http://www.ecircuitcenter.com/SpiceTopics/History.htm

Resistors, Conductors, Capacitors, Inductors

- Ohm's law can be written in two ways: $V = IR\ ,\ I = GV$
- Clearly R=1/G
- This is useful in simplifying circuits:
  - *Resistors in series:* $R_{total} = R_1 + R_2$
  - *Resistors in parallel:* $G_{total} = G_1 + G_2$ *NOT:* $R_{total} = \frac{R_1 R_2}{R_1 + R_2}$
- Some standard terminology:
  - *Impedance Z:* $Z = R + jX$ *(R: Resistance, X: Reactance)*
  - *Admittance Y:* $Y = G + jB$ *(G: Conductance, B: Susceptance)*
  - *Immitance: Impedance and Admittace considered together*
- Note that:
  - *Capacitor:* $B_C = \omega C$*; The capacitor is naturally a susceptor*
  - *Inductor:* $X_L = \omega L$*; The inductor is naturally a reactor*
- Nodal analysis is easier if we treat components as admittances
  →Nodal equations and the admittance matrix

The Thevenin Theorem

Any *part of a circuit with 2 external terminals can be replaced by a Thevenin equivalent circuit.*

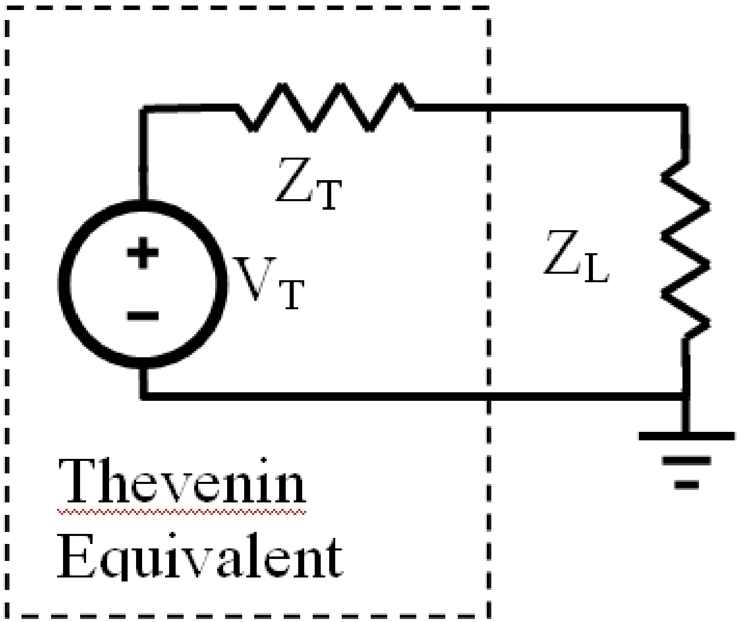
- *Entire networks with 2 terminals can considered to be a single component*

- *The Thevenin voltage source may be a:*

  - *Fixed voltage source*
  - *Voltage controlled voltage source*
  - *Current controlled voltage source*

- *Note that* $V_L = V_T\ Z_L / (Z_T + Z_L)$

- *In real life,* Z_T *is* ***never zero !***



•*The Thevenin theorem is a Taylor expansion of V(I) about the operating point* V_0 , I_0 *(if the expansion exists!)*

The Norton Theorem

Any *part of a circuit with 2 external terminals can be replaced by a Norton equivalent circuit.*

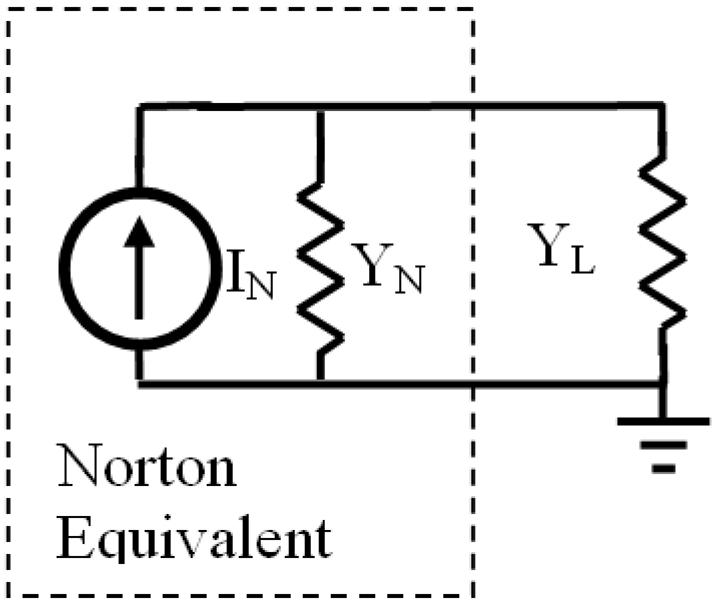
- *Entire networks with 2 terminals can considered to be a single component*

- *The Norton current source may be a:*

    - *Fixed current source*
    - *Voltage controlled current source*
    - *Current controlled current source*

- *Note that* $I_L = I_N \; Y_N / (Y_N + Y_L)$

- *In real life,* Y_N *is **never zero !***



•*The Norton theorem is a Taylor expansion of I(V) about the operating point* V_0 , I_0 *(if the expansion exists!)*

Thevenin and Norton special cases

A Thevenin equivalent circuit with:

- *zero Thevenin impedance is an ideal voltage source*
- *infinite Thevenin impedance is an ideal current source*

➔ *If the magnitude of the Thevenin impedance is larger than the magnitude of the load impedance connected to it we usually prefer to model the component using a Norton equivalent circuit*

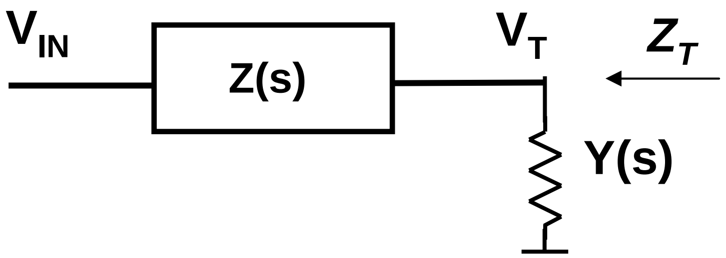
•*A Norton equivalent circuit with:*

- ***zero Norton admittance is an ideal current source***
- *infinite Norton admittance is an ideal voltage source*

➔ *If the magnitude of the Norton admittance is larger than the magnitude of the load admittance connected to it we usually prefer to model the component using a Thevenin equivalent circuit*

The Thevenin equivalent of a voltage divider

- Think of the series element as an impedance Z(s)
- Think of the shunt element as an admittance T(s)
- Both Z and Y are arbitrary functions of frequency s=jw
- Thevenin voltage is the value of the voltage divider:



$$V_T = \frac{V_{IN}}{1+Z(s)Y(s)}$$

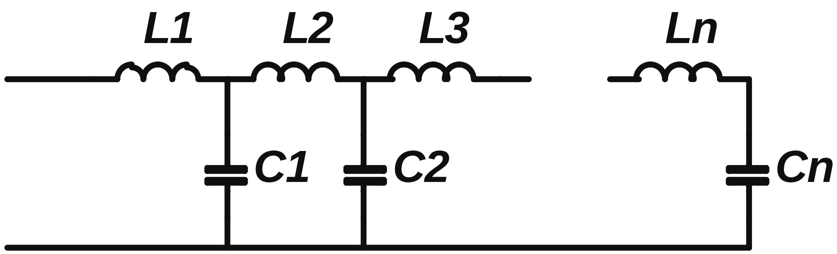
- Thevenin impedance is the parallel combination of Z an Y:

$$Z_T = \frac{V_{oc}}{I_{sc}} = \left(\frac{V}{1+Z(s)Y(s)}\right) \Big/ \frac{V}{Z(s)} = \frac{Z(s)}{1+Z(s)Y(s)}$$

- These forms are easy to remember!

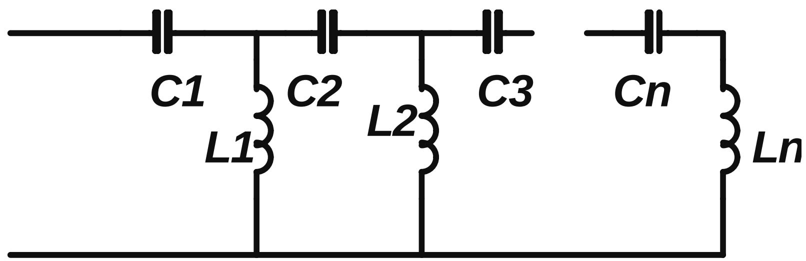
Ladder networks

First Cauer form



(a)

Second Cauer form

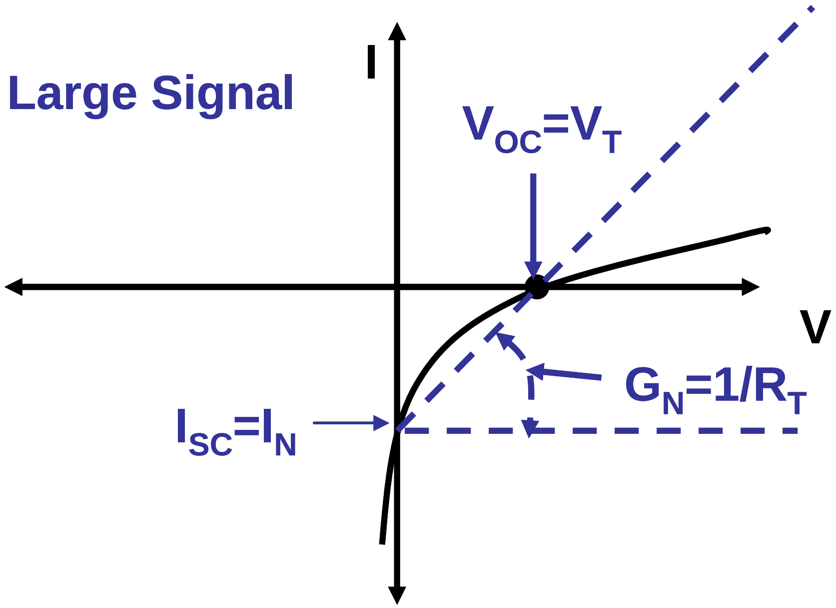


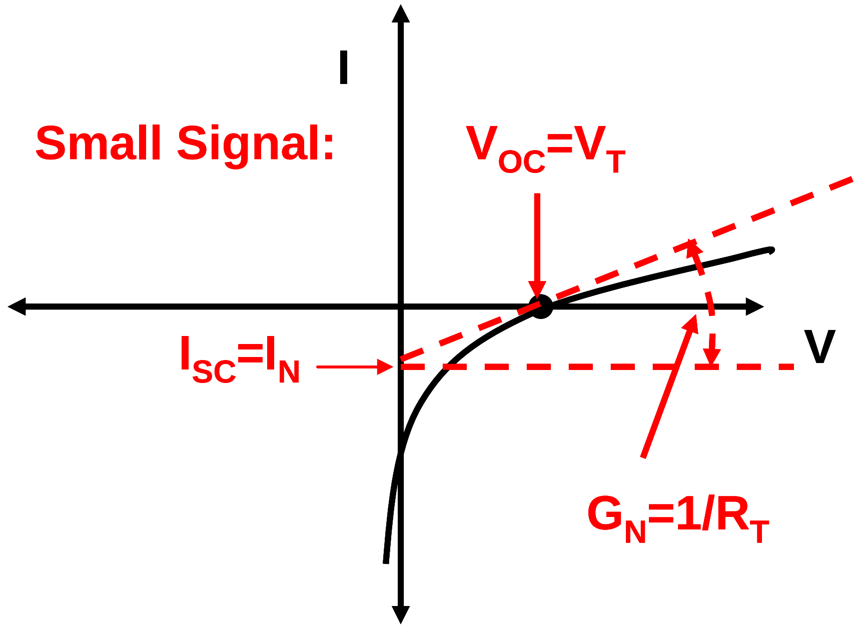
(b)

When they are made of L and C they are called “canonical filters” or “Cauer forms”. They are the most efficient filter implementations.

- **Start from left**
- **do a sequence of Thevenin and Norton transformations**
- **NEVER do nodal analysis**
- **if components are RLC both the Thevenin voltage and Thevenin impedance are ratios of polynomials in frequency**

Small Signal and Large Signal models





*Model is **secant** on the IV curve*

*Model is **tangent** on the IV curve*

The following relations are always valid:

$$R_T = 1/G_N$$

$$V_T = I_N R_T$$

- *Most circuits (except of ideal sources) have both Thevenin and Norton equivalents*
- *Unless we say otherwise, we are only concerned with **small signal** equiv. circuits.*