Before and after Shannon

a historical look at the context of information in some 'information engineering' disciplines

Chris Bissell

c.c.bissell@open.ac.uk

http://www.cands.org/Home/people/chris-bissell-1

A talk in two, only loosely related, parts

1. Precursors of Shannon, in an attempt to clear up some confusion
2. A more exploratory look at the background of ‘information’ ideas in information engineering: in particular, a consideration of models, and how information engineers switch between them while preserving some or all of the information

Early concerns (1920s onwards)

- Bandwidth utilisation – how fast can we signal over a given channel?
- At what rate must we sample a given signal to preserve all the information?
- The quantification of information as a logarithmic measure
- The problem of noise

Sampling theorem (at a rate at least twice the signal bandwidth)

- “This is a fact which is common knowledge in the communication art. [...] but in spite of its evident importance [it] seems not to have appeared explicitly in the literature of communication theory.” (Shannon, 1949).
- Mathematicians had studied the problem from a function-theoretic point of view from the mid 19th century or even earlier.
- Other engineers had indeed been publishing on the topic … let’s look at some of them

Towards the sampling theorem

- “As the selectivity of a circuit is increased either by narrowing the transmission band or increasing the number of sections, the time required for sinusoidal currents to build up is proportionately increased. This fact [...] sets a theoretical limit to the amount of selectivity that can be applied in communication circuits.”
    - Carson and Zobel, 1923

Karl Küpfmüller, 1924

- “The time taken by an ac telegraphy signal to build up at the end of a given wave filter is equal to a universal constant divided by the width of the passband of the filter.” (Can be re-phrased into a statement of maximum signalling rate.)
- Used idealised system model
- “If, today, we recognise information along with matter and energy as a third fundamental building block of the world, then Karl Küpfmüller has been a major contributor to the recognition of this fact.” (Vlcek, KK’s obituary, 1977)

Nyquist, 1924, 1928

- 1924: *W* = K log *m*

  where W is the speed of

  transmission of intelligence,

  m is the number of current values,

  K is a constant

- 1928: pulse shaping to eliminate inter-symbol interference (ISI); formal proof of maximum signalling rate; need for 2B Fourier coefficients to specify a bandlimited signal; did ***not*** consider time-domain sampling

Hartley, 1928

- Logarithmic quantification of information in multi-level signalling (cf Nyquist, 1924)
- Elementary ideas about ISI, transient response, and so on
- Explicit time-bandwidth product statement: “the total amount of information which may be transmitted […] is proportional to the product of the frequency-range […] and the time […] available for transmission” – considered changing Morse rate
- Also considered fax, cinema sound and tv!

Kotelnikov: a Soviet survivor

With permission of Kotelnikov family

Kotelnikov's 1933 paper: sampling

- "Any function F(t) consisting of frequencies between 0 and f_1 can be transmitted continuously, with arbitrary accuracy, by means of numbers sent at intervals of $1/2f_1$ seconds."
- Proof using sin x / x function
- Quaternary signalling analysed – implicit noise / signal power trade-off

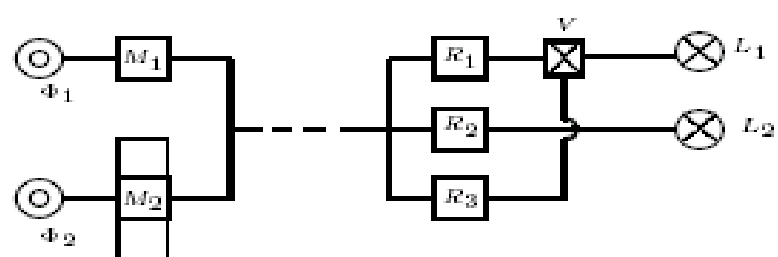


Fig.4

‘K’ on time-bandwidth product

[…] by means of transmission with interruptions any sounds – music say – can occupy less bandwidth than that of the original audible spectrum. To do this, it is sufficient first to record the music to be transmitted on gramophone records, and then to transmit from them but playing back at half the speed, say, of the recording. Then every frequency will take on half its normal value, and the transmission will require half the bandwidth. The original can similarly be recovered by gramophone. It is clear that such transmission cannot increase channel capacity, since the ether or the cable will be occupied the whole time, while communication will proceed with interruptions.

Kotelnikov’s further conclusions

- attempts to increase capacity beyond the theoretical limit represented by single-sideband transmission should be abandoned as theoretically impossible
- the possibilities for what we now call digital techniques should be investigated further
- existing single-sideband technologies should be developed further, since they are the theoretical ‘best option’
- other areas of research should include: the use of directional antennas; the extension of the radio spectrum to ultra short wavelengths; and the improvement of the frequency stability of radio transmitters

- If you’re interested in either of the Ks, have a look at

http://ict.open.ac.uk/classics

End of Part I

- Growing realisation of fundamental limit to rate of information transmission over a bandlimited channel from mid 1920s onwards
- Dissemination of results interesting
  - few of these classic papers have a ‘modern’ ethos of referencing, or fully acknowledged prior work
  - German and Russian work not well known elsewhere
  - Kotelnikov’s work in particular not disseminated
- A number of general misconceptions
  - the term ‘Nyquist sampling theorem’
  - long history of work on sampling / signalling limits

Part II: Now for something completely different …

- Models – preserving information
- Models – approximating information
- Graphical (re)presenting information
- Computers – displaying information

- **Thesis: 20th C information engineers did something rather remarkable in presenting and manipulating information**

Duality

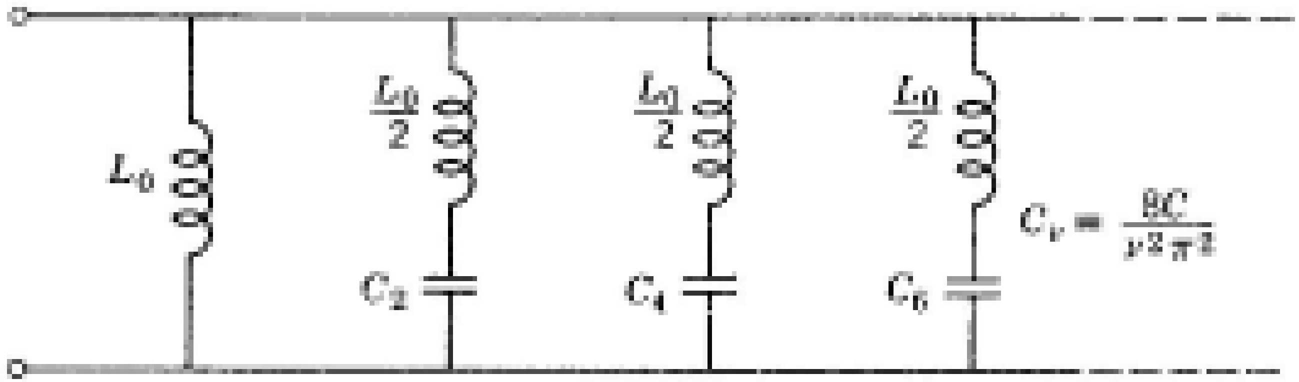
$$I = C\frac{dV}{dt}$$ capacitor

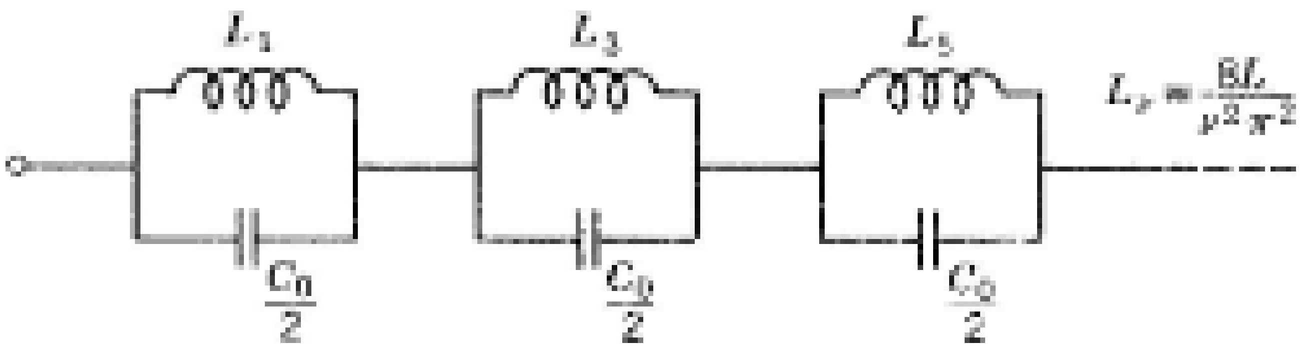
inductor $$V = L\frac{dI}{dt}$$

Duality

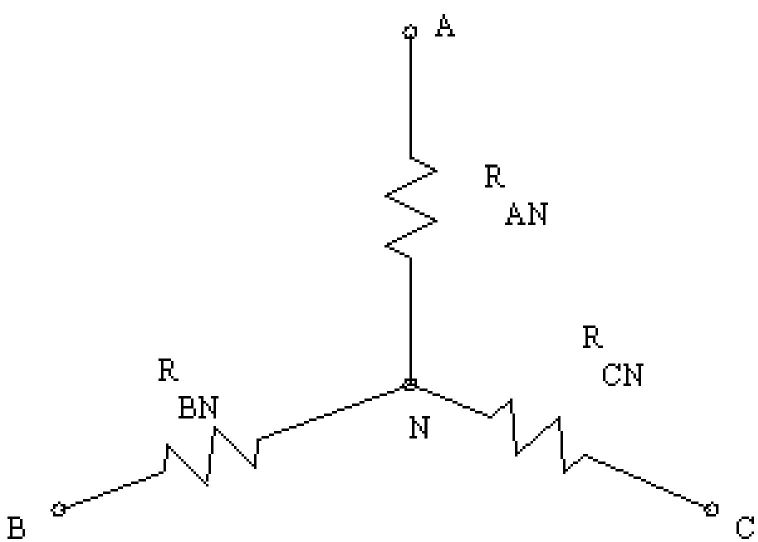
voltage	current
resistance	conductance
inductance	capacitance
short-circuit	open-circuit
series	parallel
node	mesh

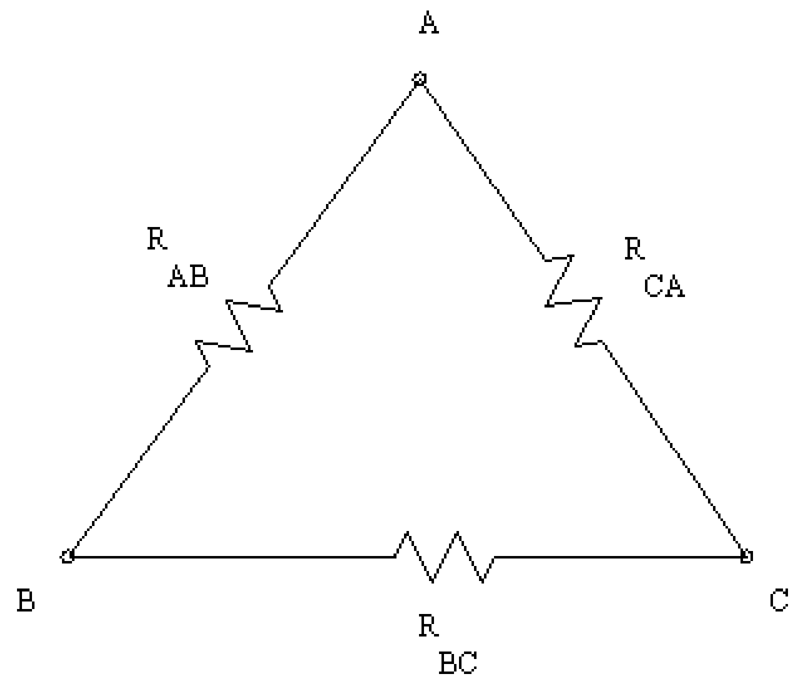
Equivalent models of a transmission line





Star-delta transformation



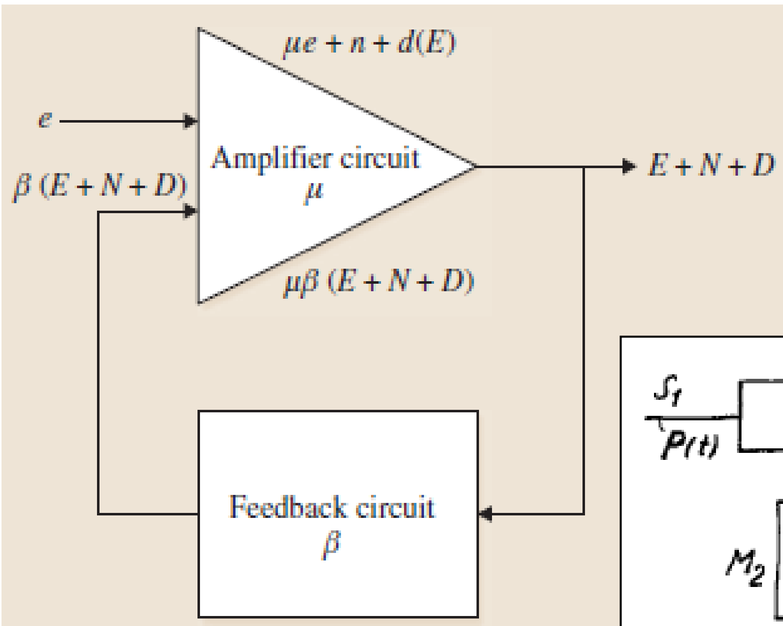


- Information engineers from early 20th century are becoming highly competent in manipulating graphical representations
- And they avoid doing the maths!
- The representations are increasingly ‘reified’, can be manipulated almost like physical objects

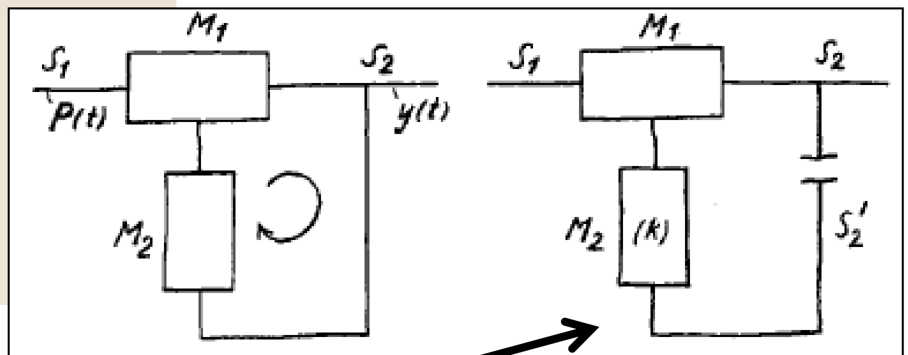
Circuit design

- "... modern circuit theory is concerned but little with the circuit as a physical entity and, instead, has become increasingly involved with ... signals ... Thus the usual circuit diagram may be regarded as a pictorial form of a signal flow graph" Huggins, 1955
- But there is a long history of this, dating from the 1920s

Black's feedback amplifier and Küpfmüller's generic loop (late 1920s)



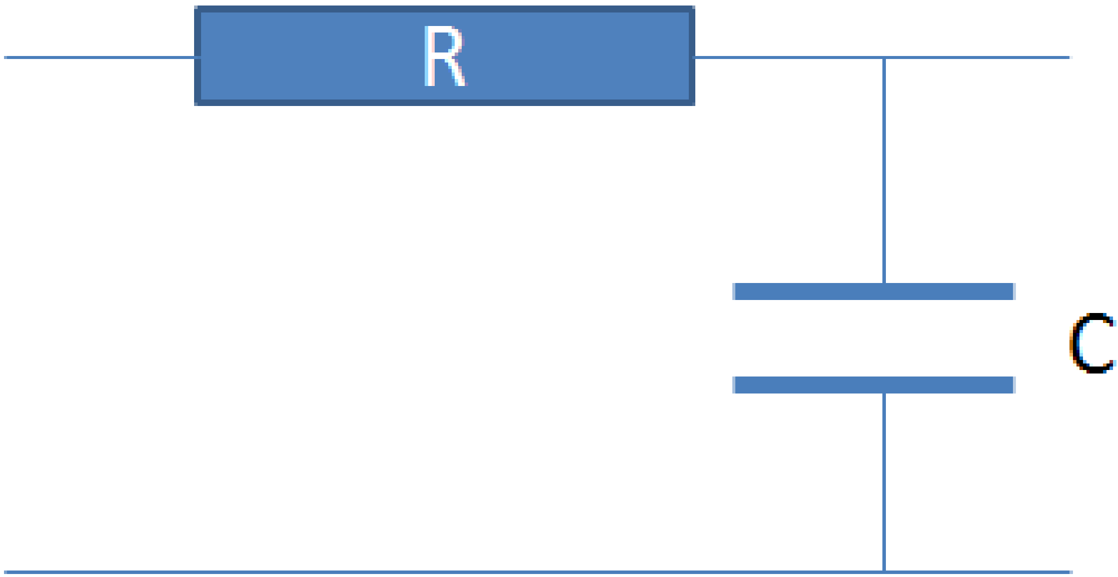
Note the absence of electronic circuit or device symbols; the models are contructed of idealised sub-systems and related signal flows

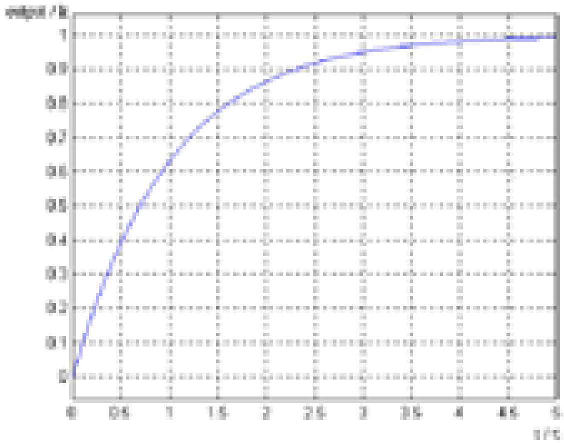


Küpfmüller 'cuts' the loop – as Nyquist did a few years later – to investigate the stability of a feedback system

what if we do not need to preserve all the information?

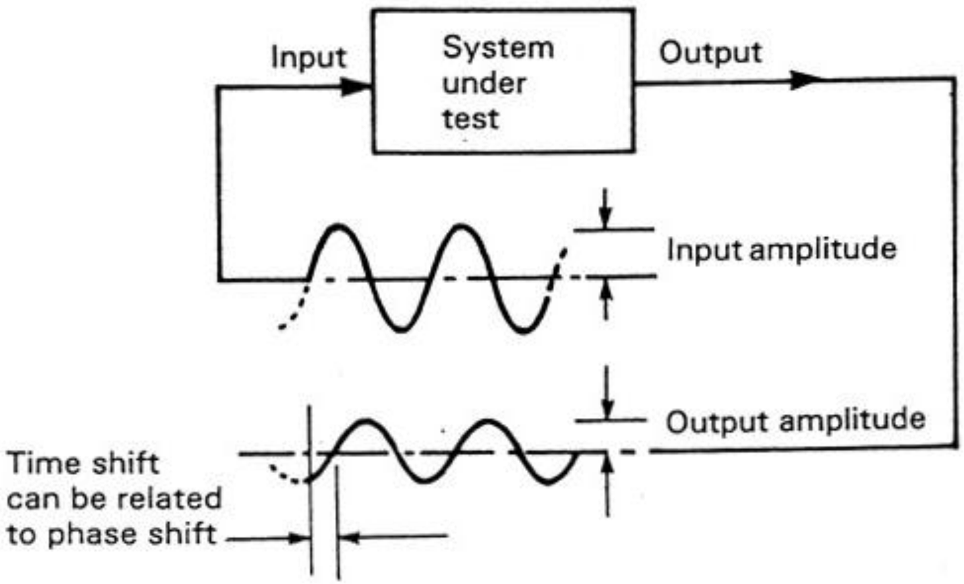
First-order linear system (lowpass filter)





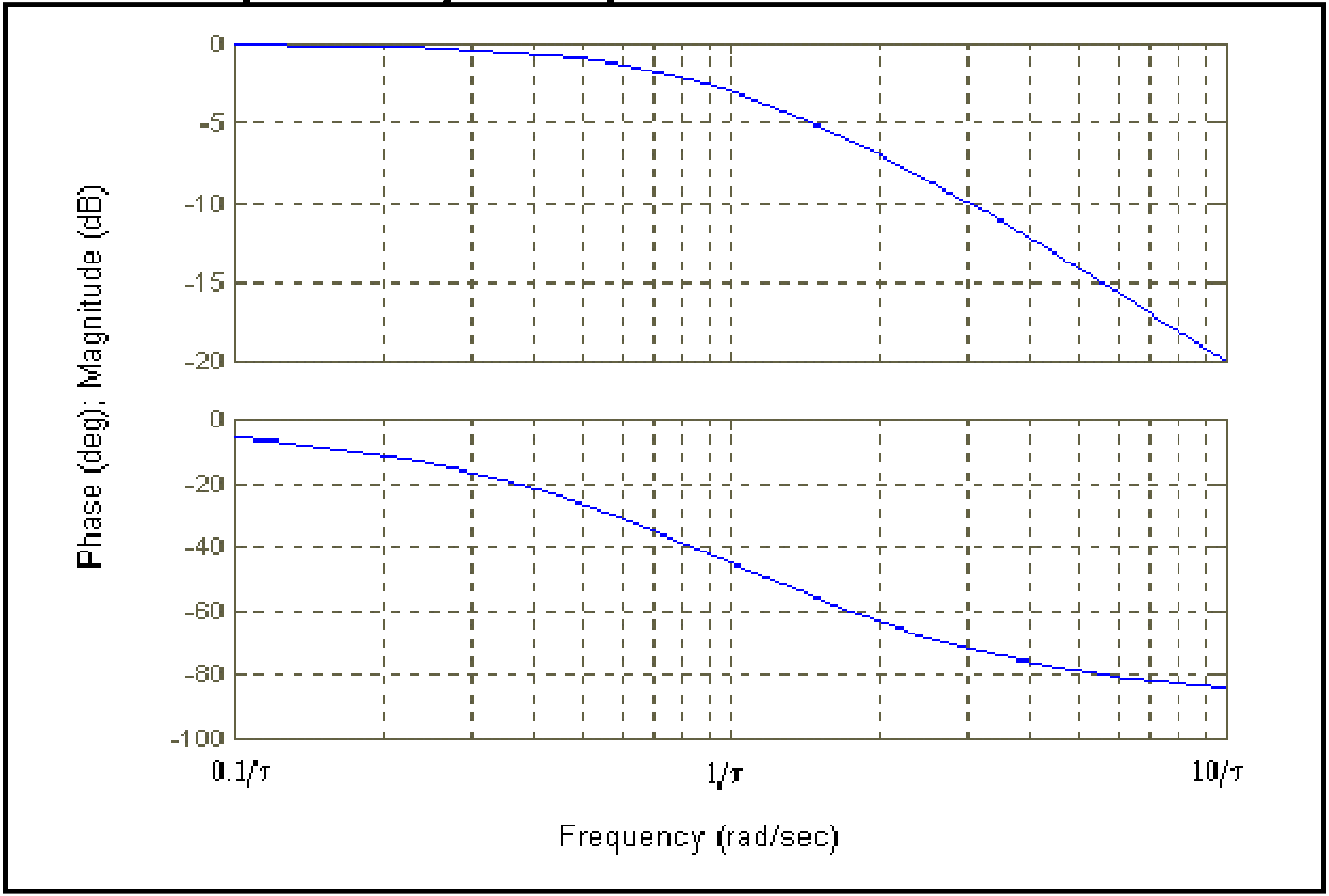
System step response

Frequency response

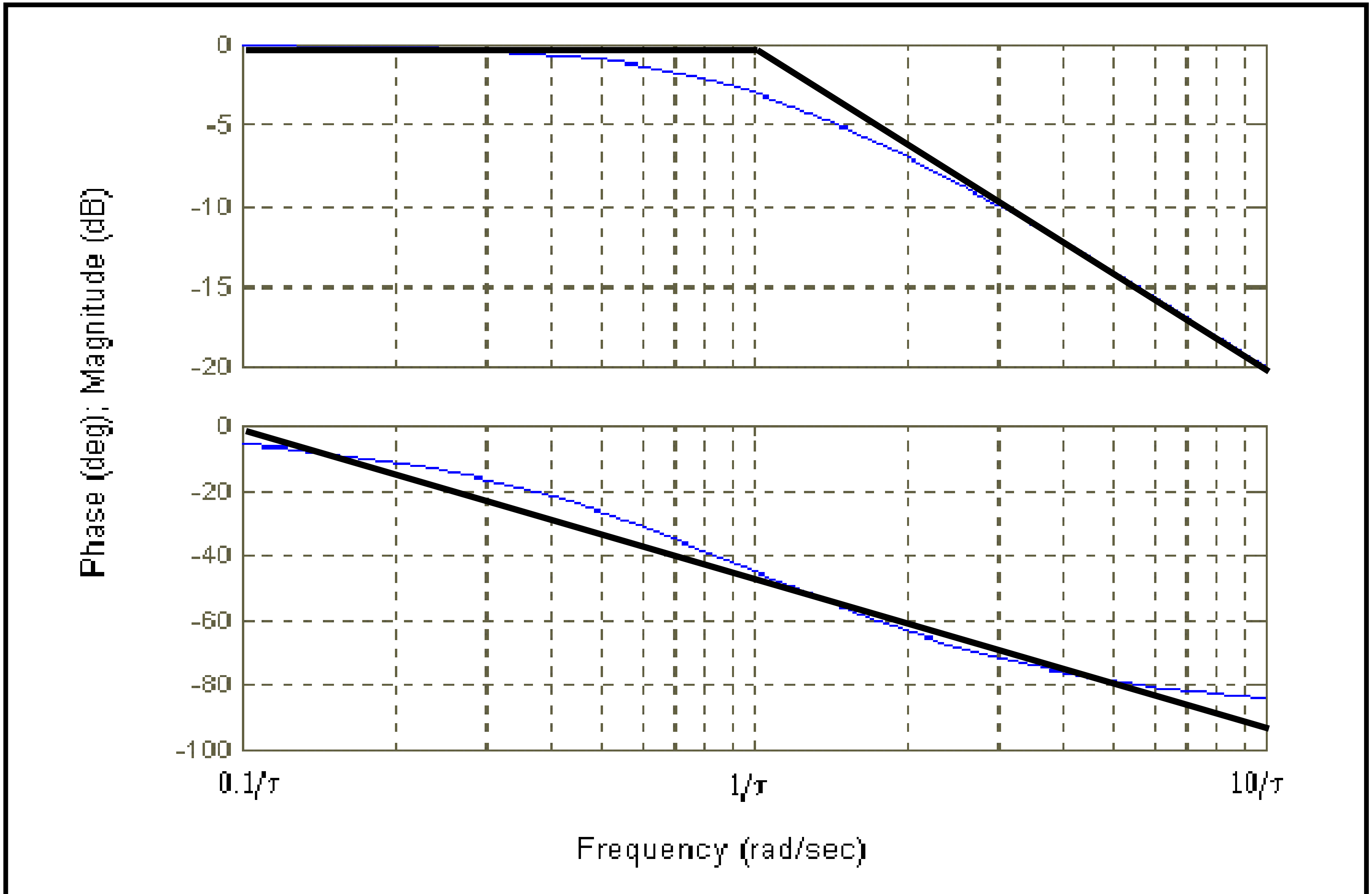


Amplitude ratio and phase shift for any given frequency define a linear system

Frequency response: first order

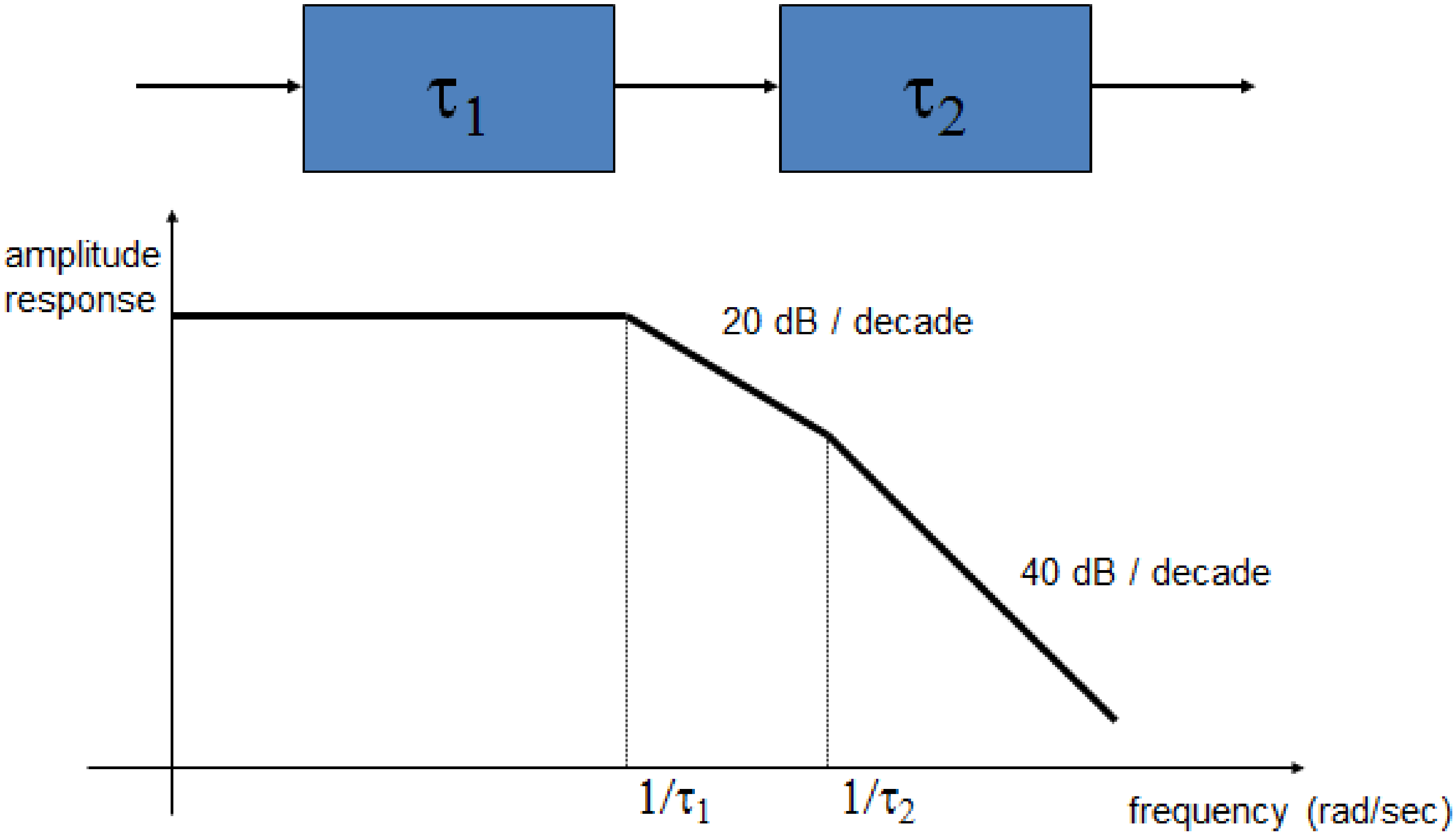


Bode linear approximation (first order)



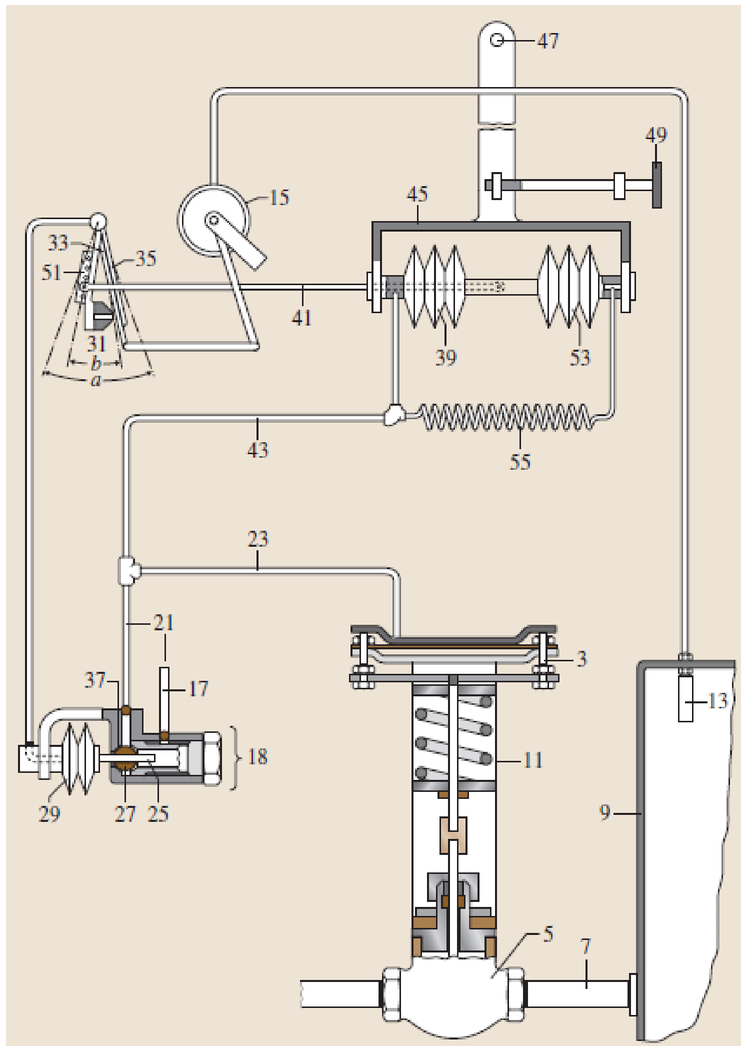
Cascaded first-order systems:

Bode's linear approximations ease design

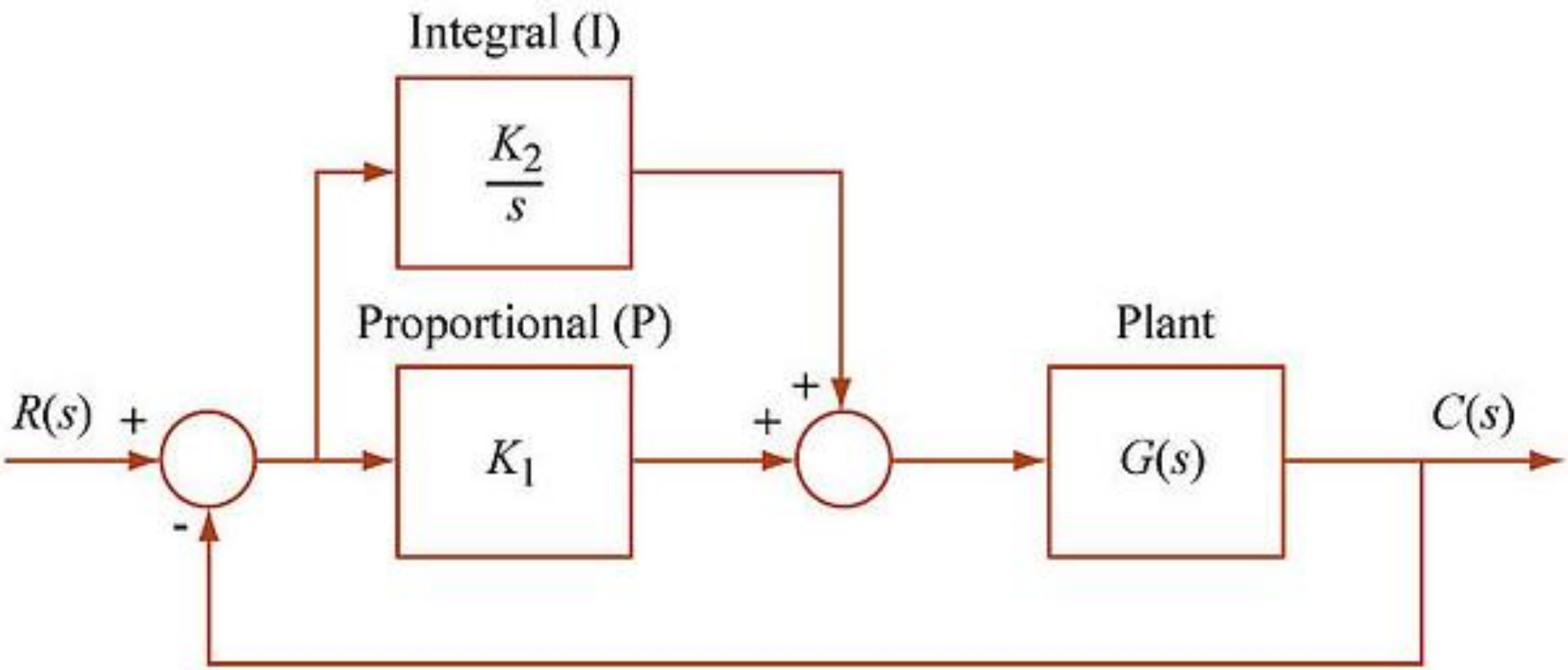


- Representations of systems
- Examples from control engineering

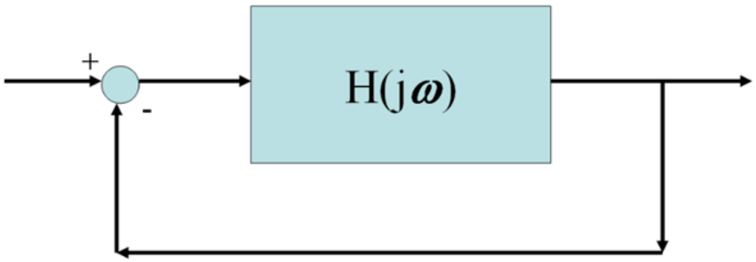
A 'proportional + integral' P+I controller (1930s Stabilog^{TM} patent)



Another view of P+I: signal flow again!



From open to closed loop

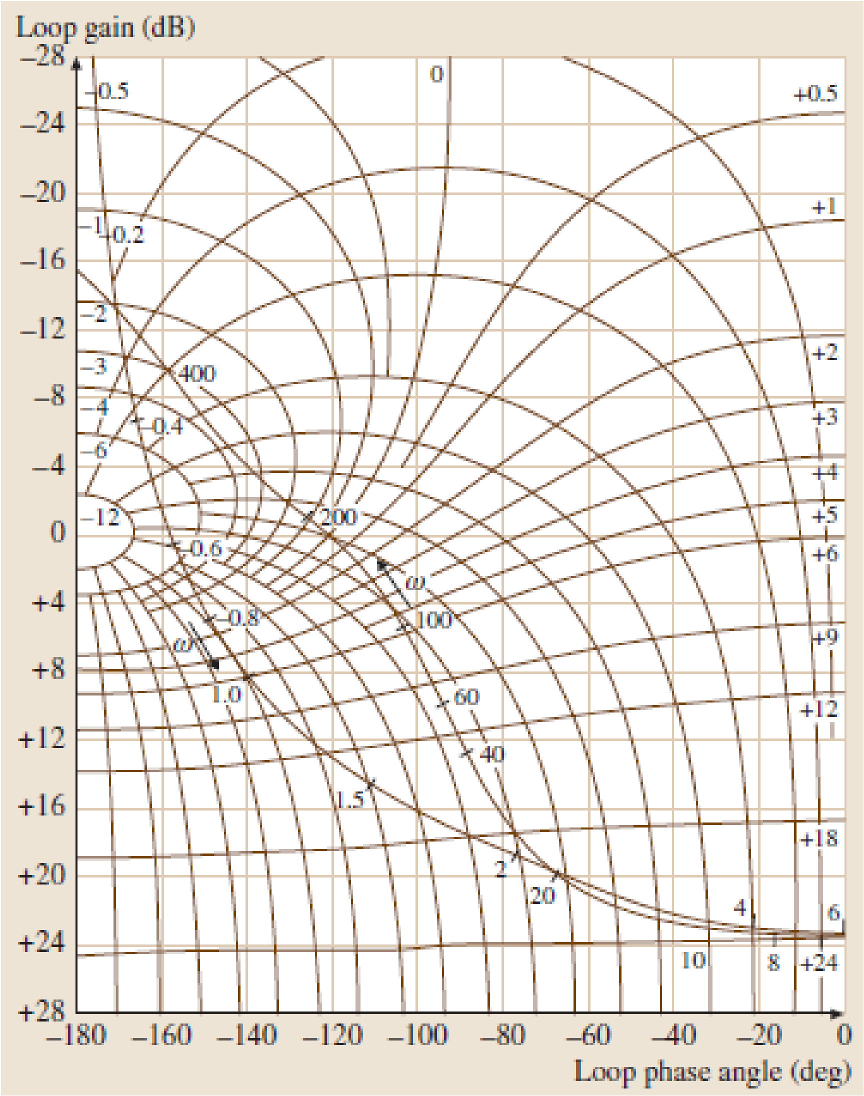


closed-loop transfer function

$$= H(j\omega) / [1 + H(j\omega)]$$

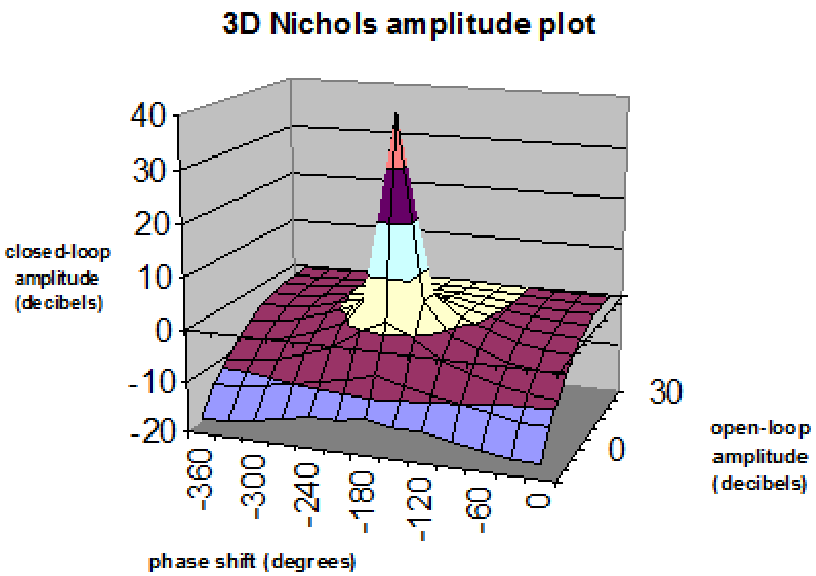
Given a knowledge of H (by modelling or measurement), how do we get to a closed-loop model?

Nichols chart (1947)



Plot H on rectilinear grid, read off closed loop response from curves.

Simple! (Just imagine curves as contours, so the closed loop frequency response corresponds to walking around the 'pole'.)



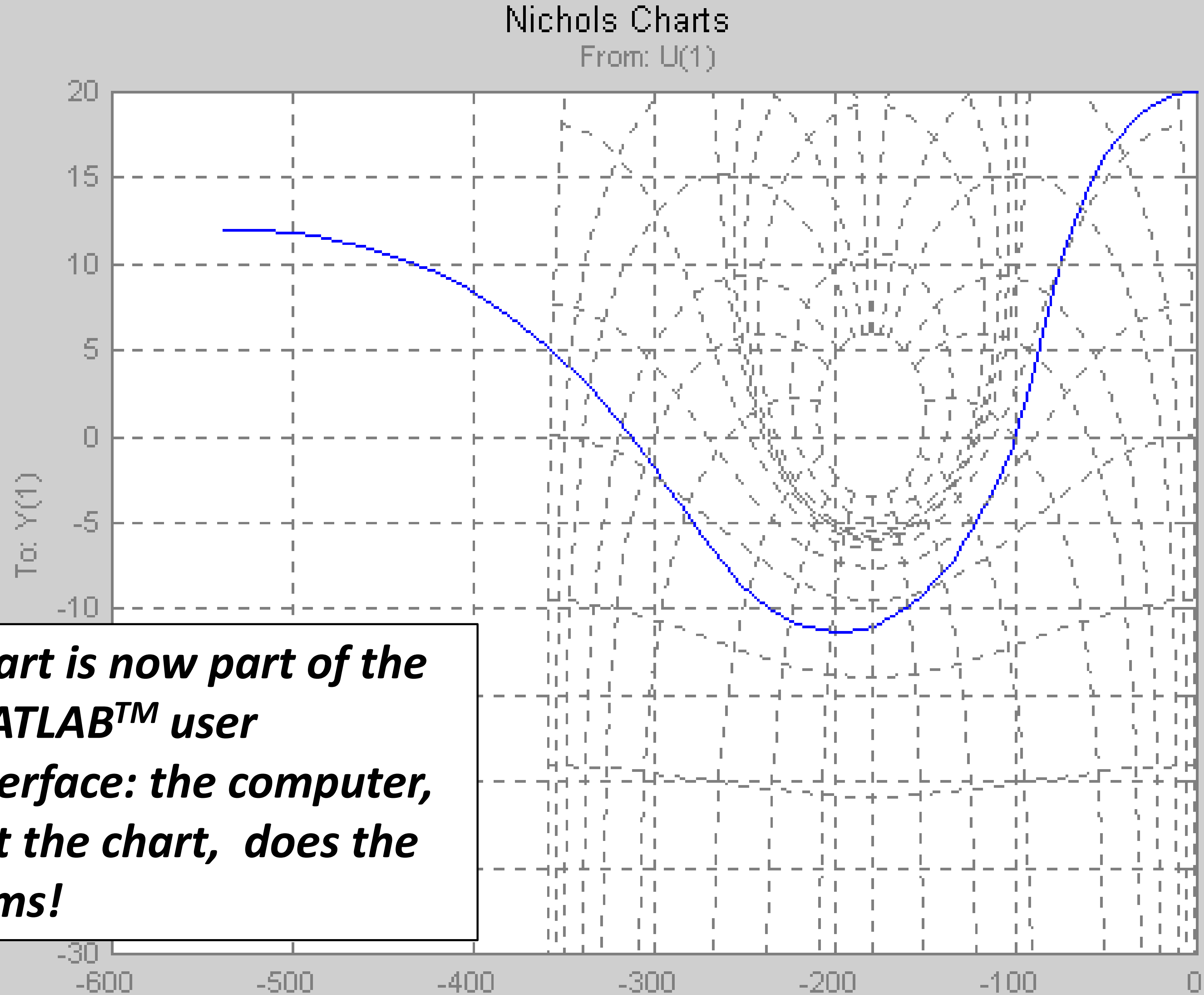
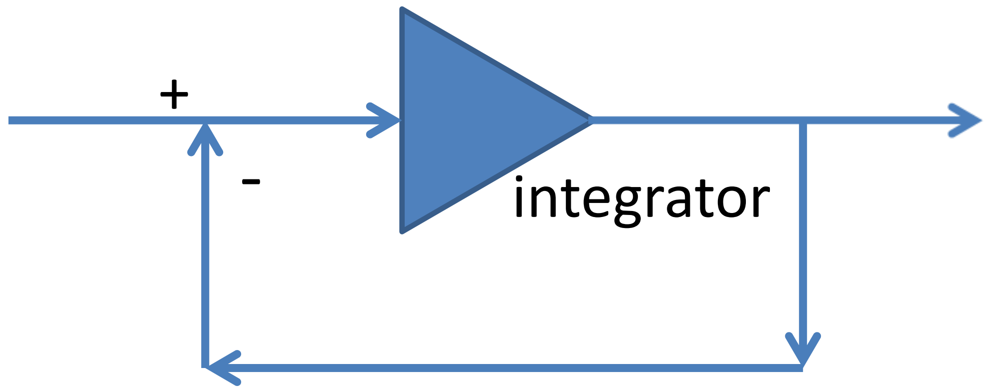


Chart is now part of the MATLAB™ user interface: the computer, not the chart, does the sums!

Non-digital information processing

- Analogue computers
- Interconnected electronic / electrical components to simulate the dynamic behaviour of mechanical, aeronautical, or other systems

Topologies: back to lowpass first-order



Feedback can be a pure construct!

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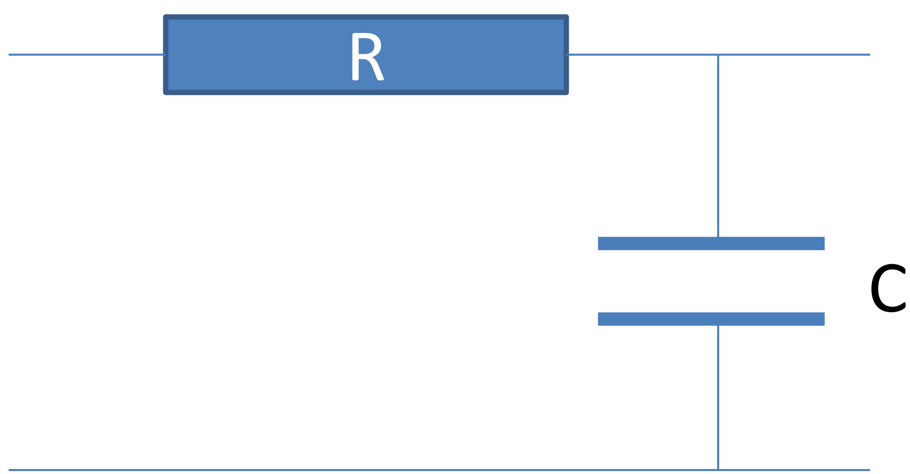
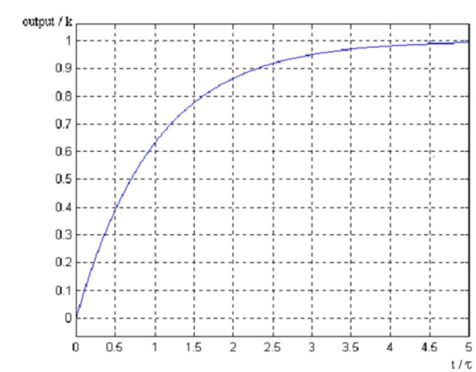
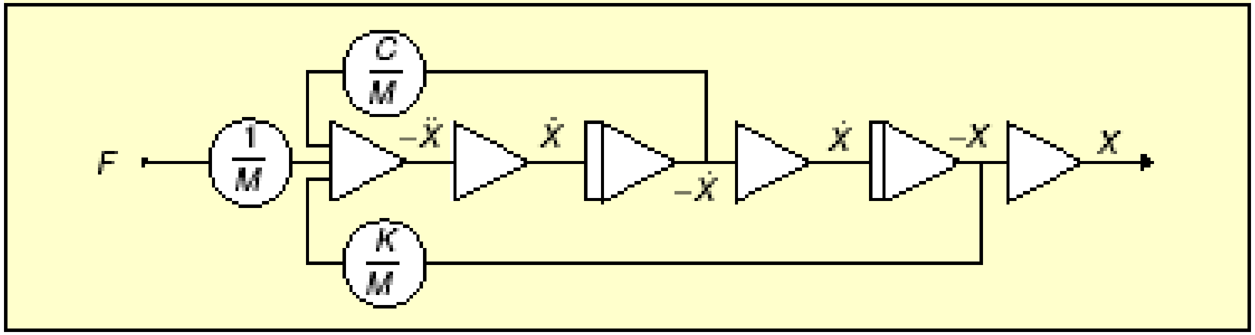




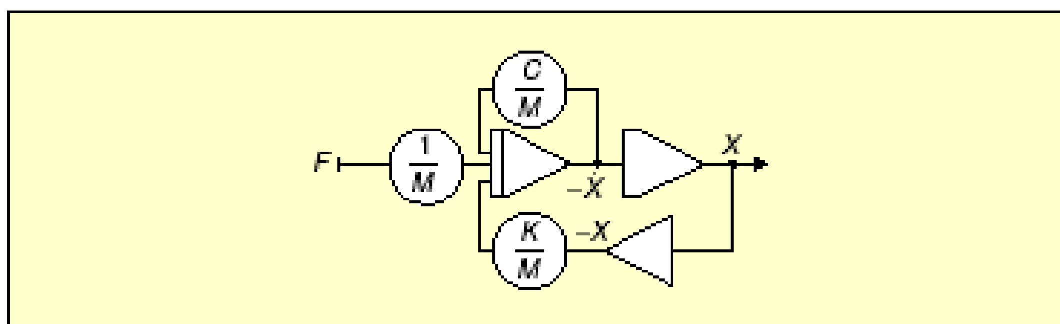
System step response

Manipulating models: solving a 2nd order differential equation by analogue computer

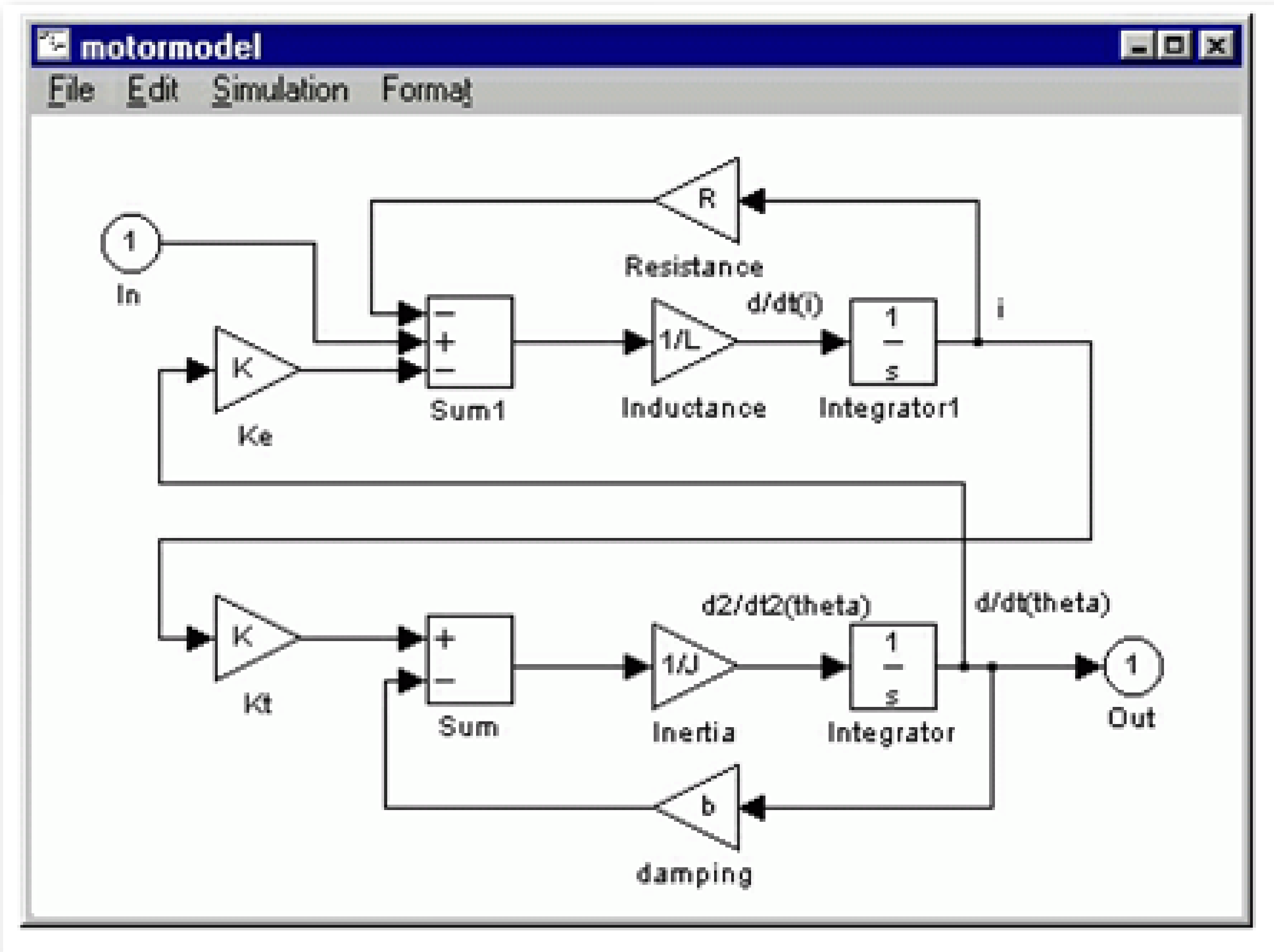


Reconfigure to reduce number of integrators and amplifiers

Source: George Fox Lang (2000)



Matlab interface: the analogue computer legacy



Conclusions to Part II

- Information engineers developed a huge range of graphical models
- Some preserved all the information
- Some preserved enough information for the task in hand
- Although they were not ‘information-theoretic’ in the Shannon sense, they were a novel way of handling tools for design, a reflection of the new notions of information processing
- Their legacy remains in CAD software to this day!