

電子回路論第3回

Electric Circuits for Physicists #3

東京大学理学部・理学系研究科

物性研究所

勝本信吾

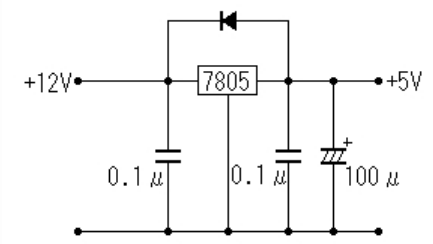
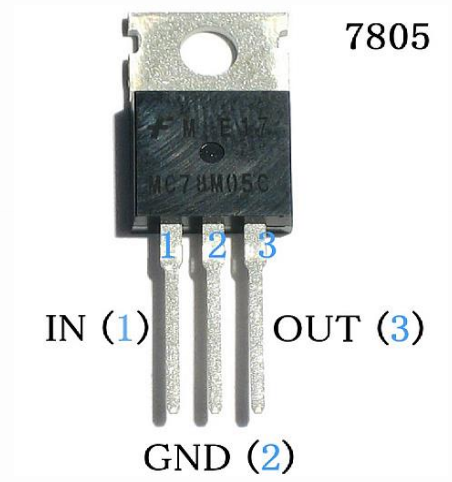
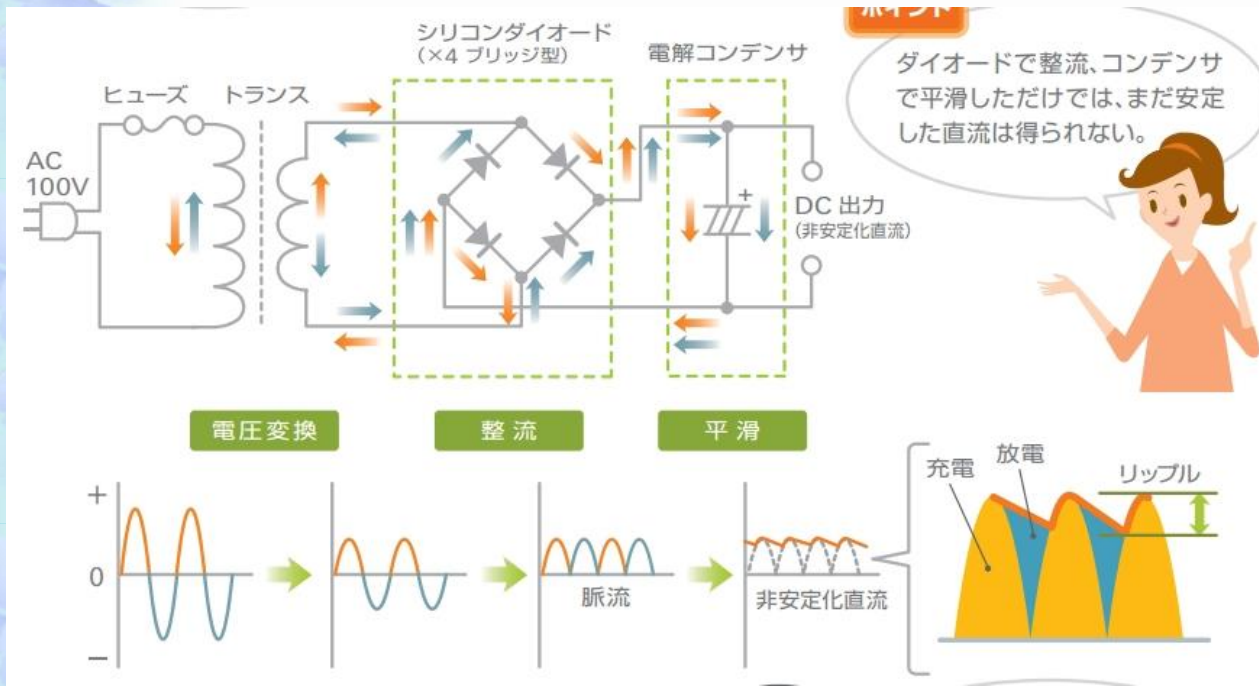
Shingo Katsumoto

電源の雑知識（続き）

Miscellaneous knowledge
on power supplies (continued)

DC Stabilized Power Supply 直流安定化電源

Series (Dropper) regulation



From TDK web page

Series regulator power supply



Uni-polar



Dual tracking

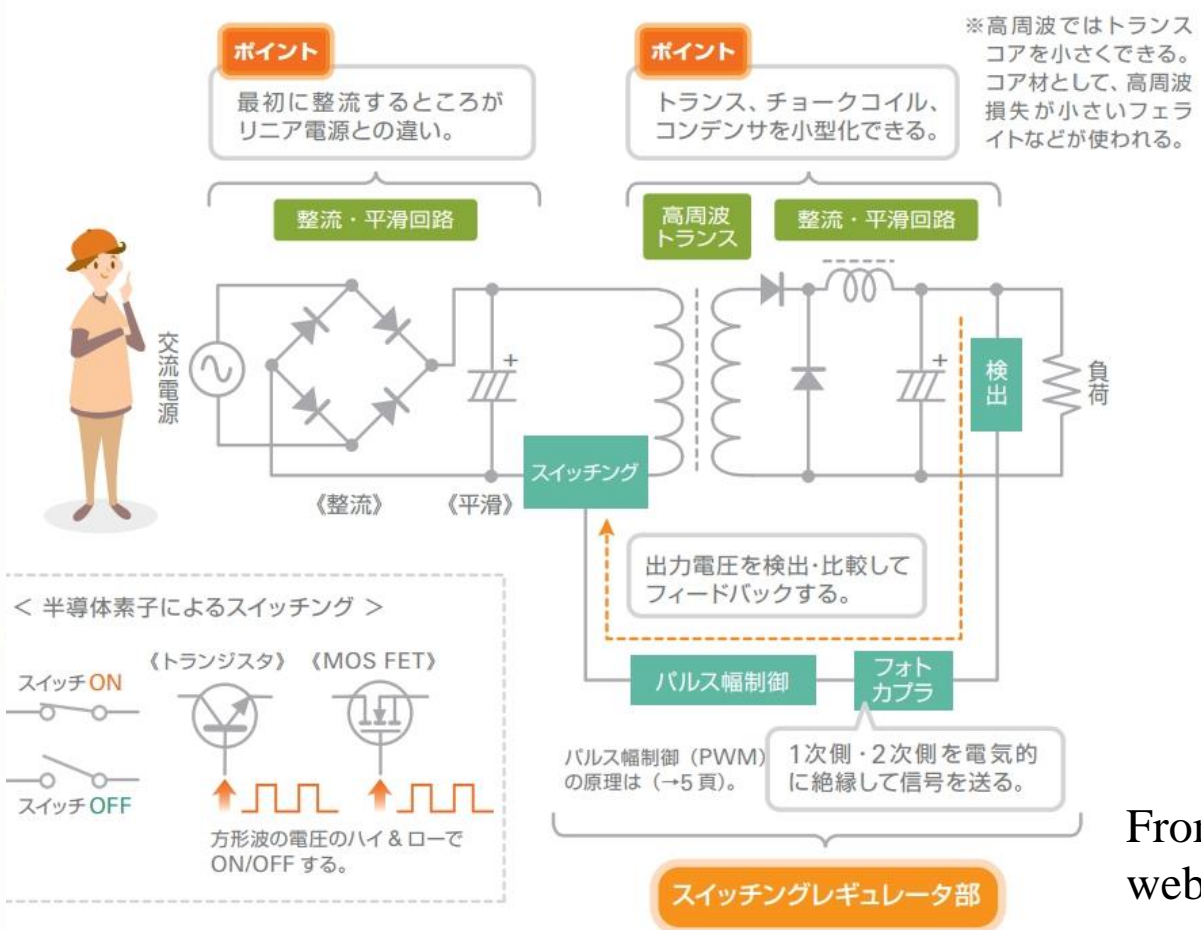


High precision



Bi-polar current source

Switching regulation



From TDK
web page

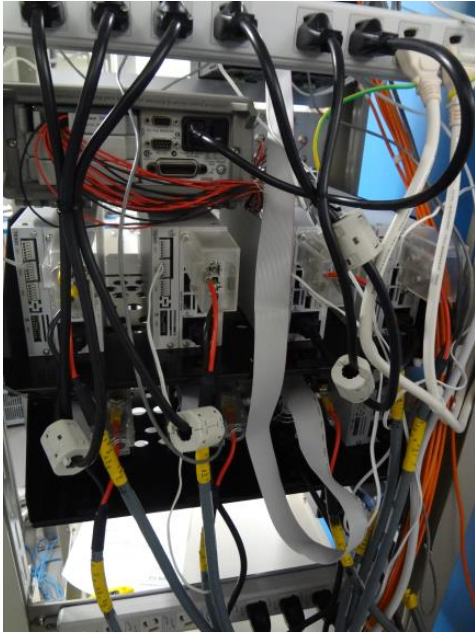
Switching regulator power supply



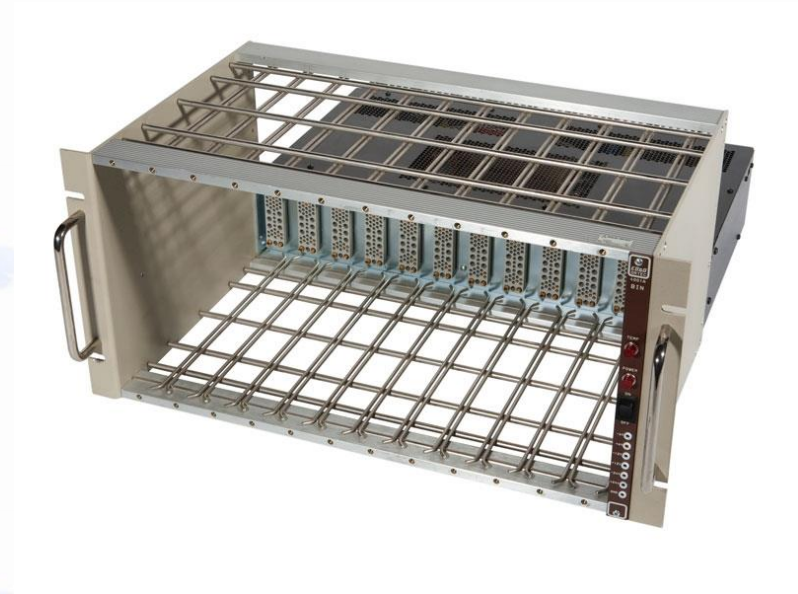
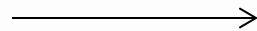
Molecular beam epitaxy
Control panel



Bin 電源ビン



Complicated power lines



Bin

Outline

2.5 Theorems for paired terminal circuits

Superposition, Ho-Thevenin, Reciprocity

2.6 Duality

2.7 Passive devices (elements) and active devices

Ch.3 Transfer function and transient response

3.1 Transfer function of single-pair terminal circuits

Resonance circuit

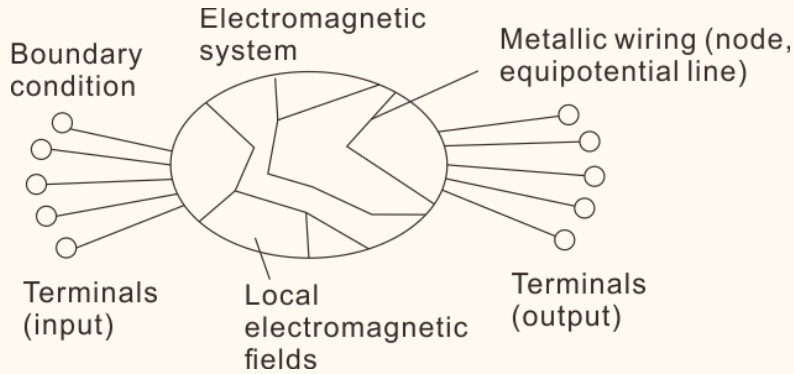
Bode plot

General properties

Appendix B Bridges and balance circuits

Appendix C General properties of resonance circuits

Concept of terminal pair

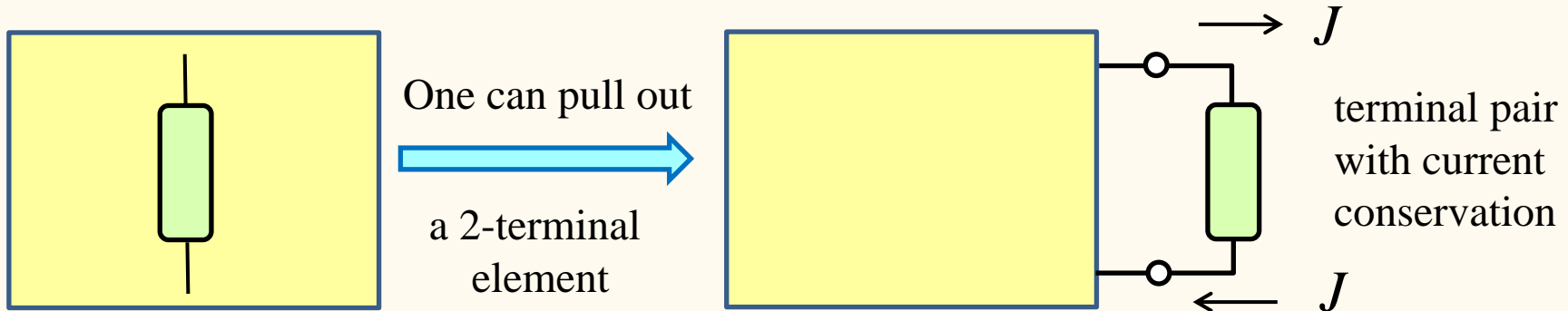


Electric circuit: a viewpoint

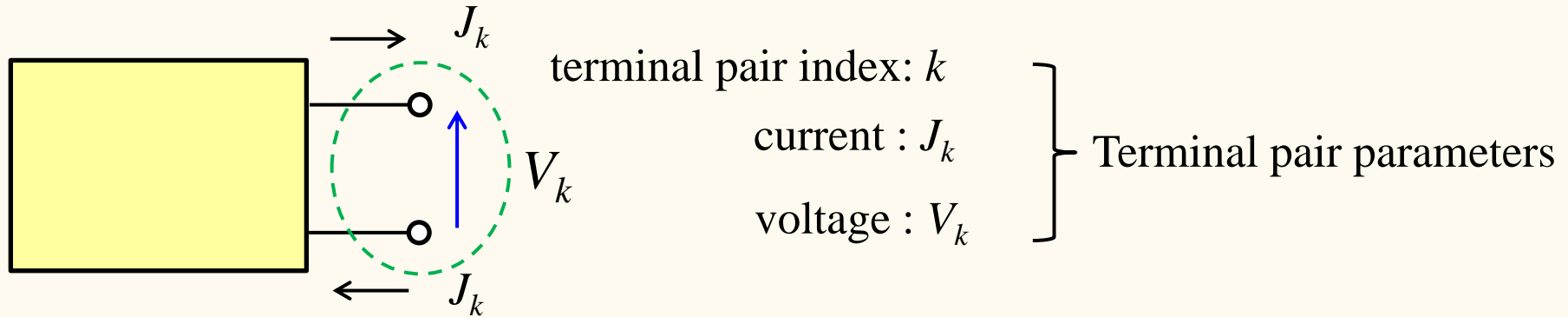
- Local electromagnetic field
- Lumped constant circuit

Two-terminal elements : linear response: Impedance

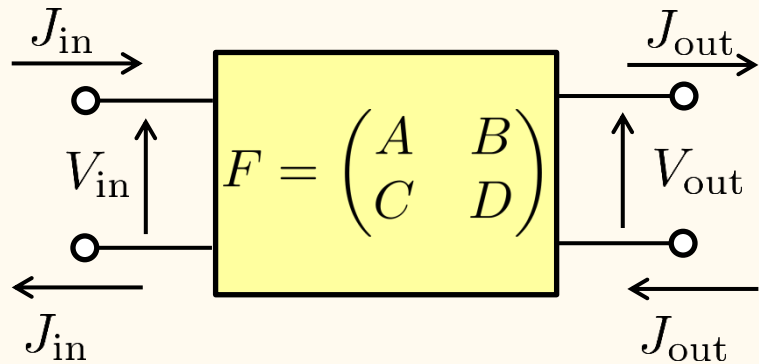
: power (energy) source (electromotive force)



Two terminal-pair circuit



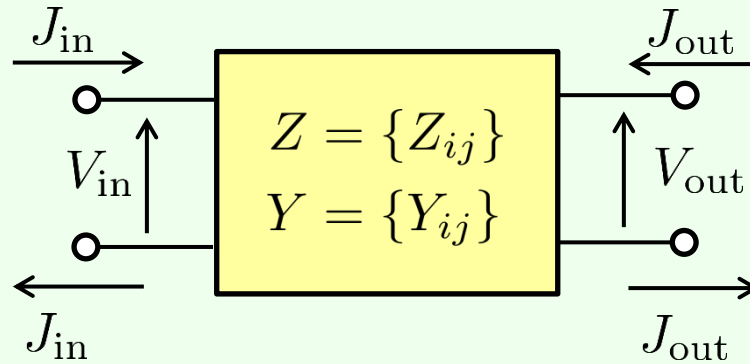
Linear relations between terminal-pair parameters: terminal-pair matrices



F-matrix (cascade matrix)

$$\begin{pmatrix} V_{\text{in}} \\ J_{\text{in}} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_{\text{out}} \\ J_{\text{out}} \end{pmatrix} \equiv F \begin{pmatrix} V_{\text{out}} \\ J_{\text{out}} \end{pmatrix}$$

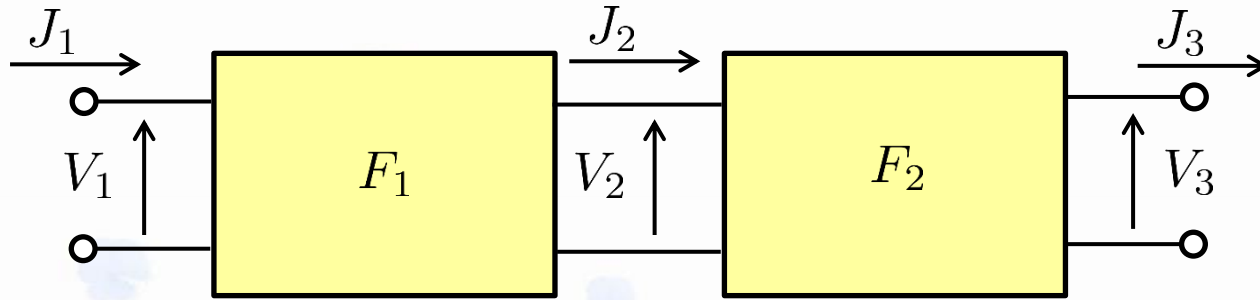
Impedance matrix, Admittance matrix



Impedance matrix
$$\begin{pmatrix} V_{in} \\ V_{out} \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} J_{in} \\ J_{out} \end{pmatrix} \equiv Z \begin{pmatrix} J_{in} \\ J_{out} \end{pmatrix}$$

Admittance matrix
$$\begin{pmatrix} J_{in} \\ J_{out} \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} V_{in} \\ V_{out} \end{pmatrix} \equiv Y \begin{pmatrix} V_{in} \\ V_{out} \end{pmatrix}$$

Cascade connection of 4-terminal circuits



$$\begin{pmatrix} V_1 \\ J_1 \end{pmatrix} = F_1 \begin{pmatrix} V_2 \\ J_2 \end{pmatrix} = F_1 F_2 \begin{pmatrix} V_3 \\ J_3 \end{pmatrix}$$

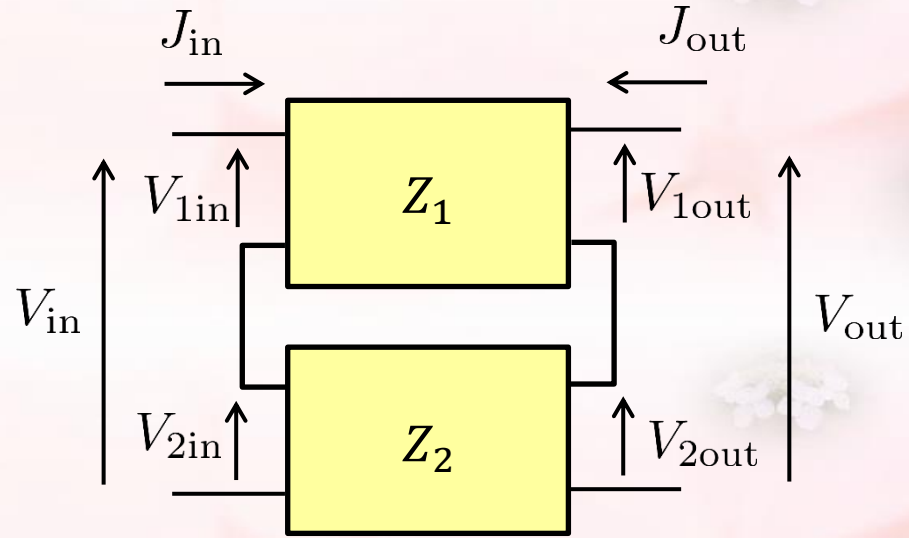
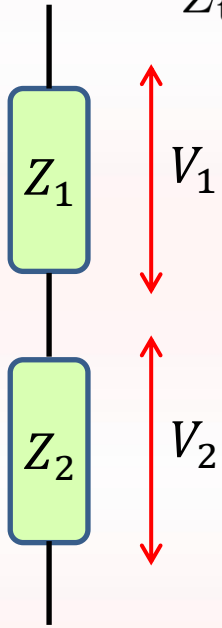
$$F_{\text{cascade}} = \prod_{i=1}^N F_i$$

Series connections of 4-terminal circuits

Series connection of 2-terminal elements

Stack along voltage direction

$$Z_{\text{tot}} = Z_1 + Z_2$$



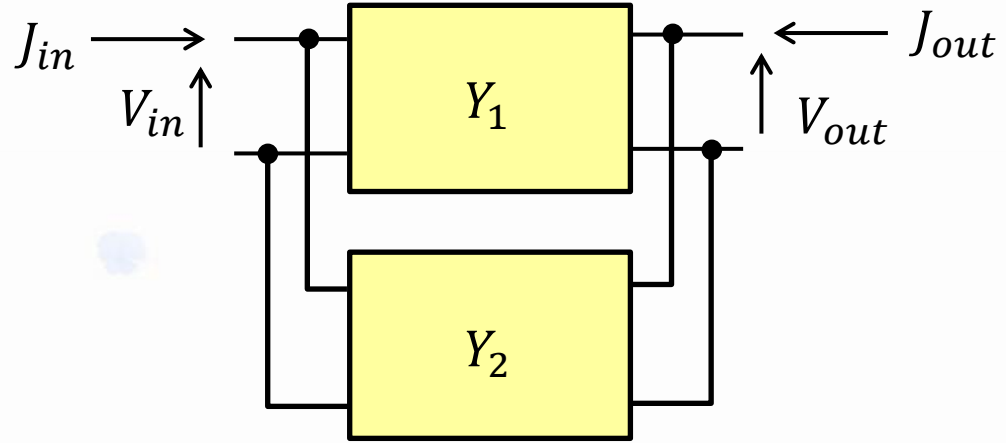
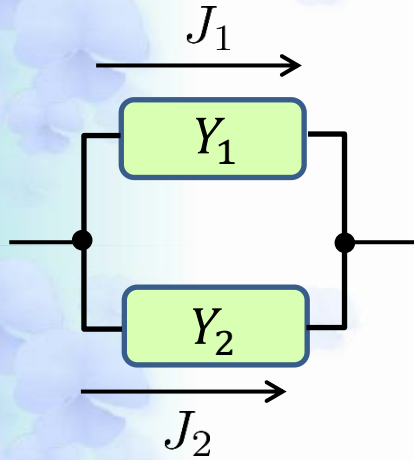
$$\begin{pmatrix} V_{\text{in}} \\ V_{\text{out}} \end{pmatrix} = \begin{pmatrix} V_{1\text{in}} \\ V_{1\text{out}} \end{pmatrix} + \begin{pmatrix} V_{2\text{in}} \\ V_{2\text{out}} \end{pmatrix} = (Z_1 + Z_2) \begin{pmatrix} J_{\text{in}} \\ J_{\text{out}} \end{pmatrix}$$

$$Z_{\text{tot}} = \sum_{i=1}^N Z_i$$

Parallel connections of 4-terminal circuits

Parallel connection of
2-terminal elements

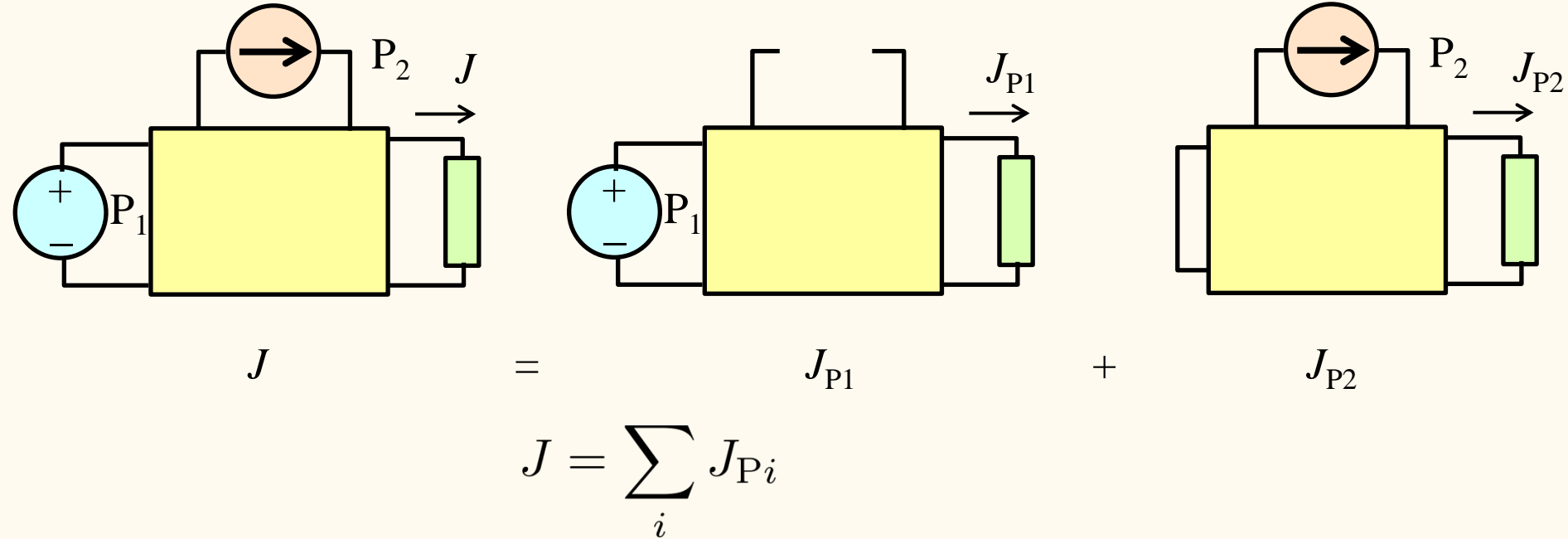
Current participation
with a common voltage



$$Y_{\text{tot}} = \sum_{i=1}^N Y_i$$

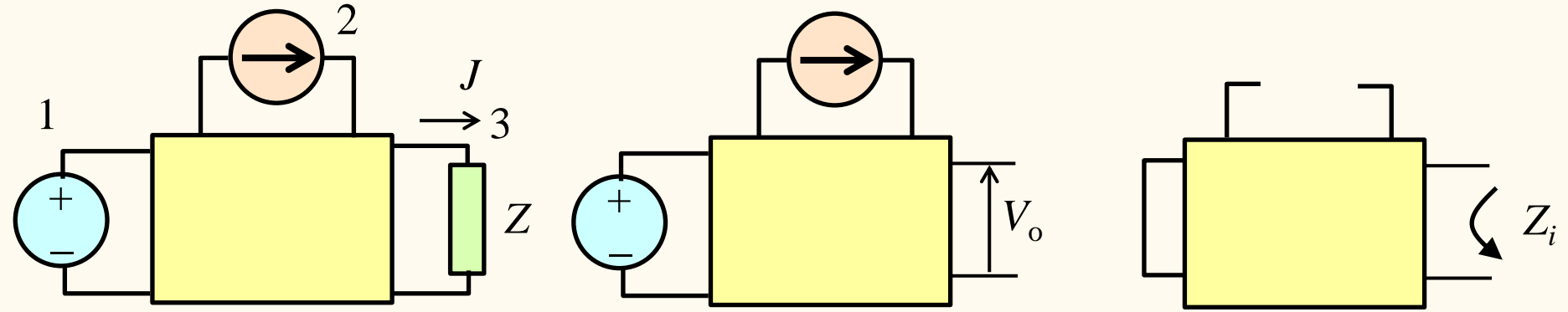
Theorems for terminal-pair circuits

Superposition theorem:



J_{p_i} : The current caused on the output by i -th power source.

Ho-Thevenin's theorem



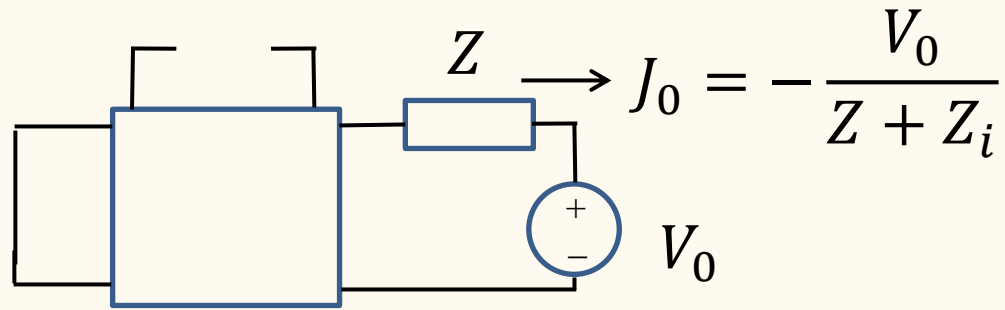
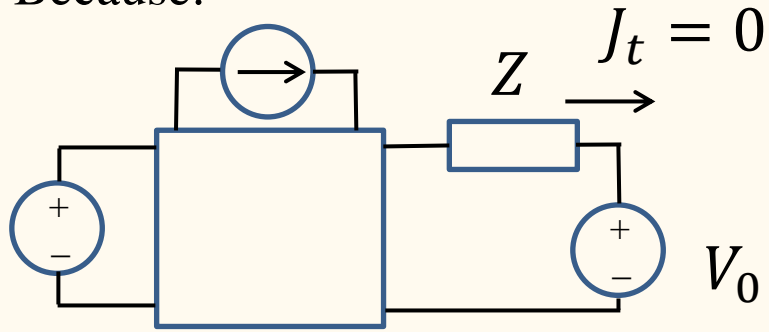
Consider a circuit with an open terminal pair (No.3). Obtain current J when the open pair is connected with impedance Z .

1. Measure the open terminal voltage V_o .
2. Turn off all the power sources (voltage sources: short, current sources: open). Measure the open circuit impedance Z_i .

$$\text{Then } J = \frac{V_o}{Z + Z_i}$$

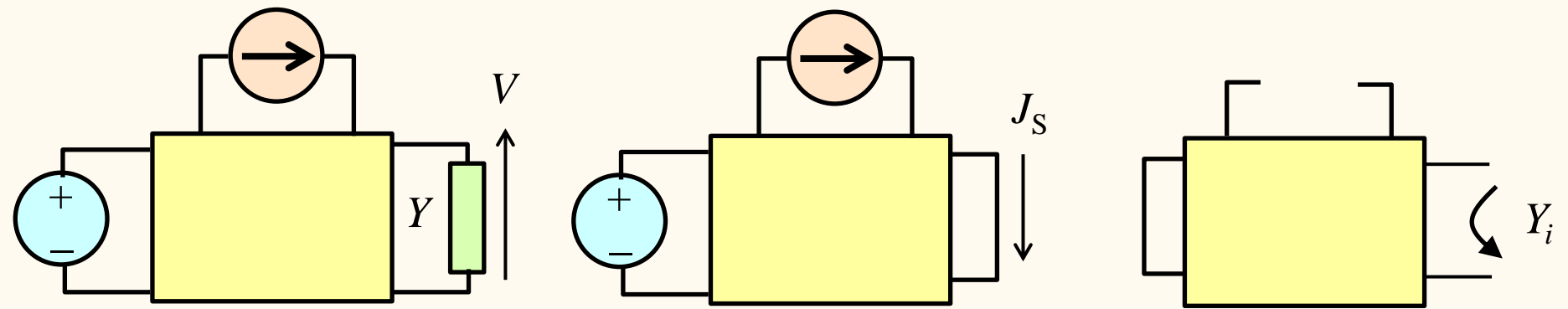
Ho-Thevenin's theorem

Because:



$$J = J_t - J_0 = \frac{V_0}{Z + Z_i}$$

Norton's theorem



$$V = \frac{J_S}{Y + Y_i}$$

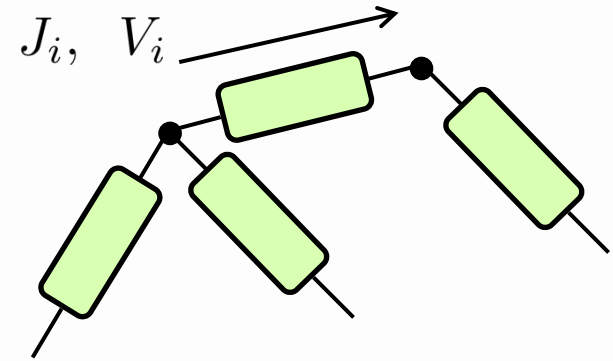
Dual theorem to Ho-Thevenin

Review: Tellegen's theorem

$i = 1, \dots, m$: index of branches

$$\sum_{i=1}^m V_i J_i = 0 \quad \mathbf{V} \perp \mathbf{J}$$

$\underbrace{\hspace{1.5cm}}_{\text{Power of } i\text{-th branch}}$



Comments

1. Power conservation law
2. Holds for any kind of circuit (irrespective of linear, or non-linear)
3. Holds for two independent circuit conditions (as long as D is the same)

D : incidence matrix

Reciprocity theorem

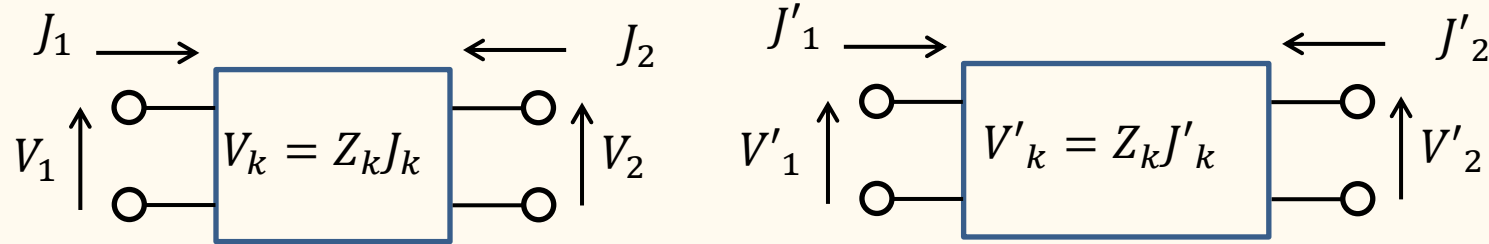
An n -terminal pair linear circuit

At one state $(V_1, J_1), (V_2, J_2), \dots, (V_n, J_n),$

at another state $(V'_1, J'_1), (V'_2, J'_2), \dots, (V'_n, J'_n)$

$$\sum_{i=1}^n V_i J'_i = \sum_{i=1}^n V'_i J_i$$

Proof: Consider a two terminal-pair circuit with m branches.



Tellegen's theorem

$$\left\{ \begin{array}{l} -V_1 J'_1 - V_2 J'_2 + \sum_k V_k J'_k = 0 \\ -V'_1 J_1 - V'_2 J_2 + \sum_k V'_k J_k = 0 \end{array} \right.$$

But $V_k J'_k = V'_k J_k = Z_k J_k J'_k$

$$\therefore V_1 J'_1 + V_2 J'_2 = V'_1 J_1 + V'_2 J_2$$

Duality 双対性

直列接続	並列接続
開放	短絡
電場	磁場
キルヒホッフの第2法則	キルヒホッフの第1法則
電圧	電流
インピーダンス	アドミッタンス
抵抗	コンダクタンス
静電容量	インダクタンス
鳳-テブナンの定理	ノートンの定理

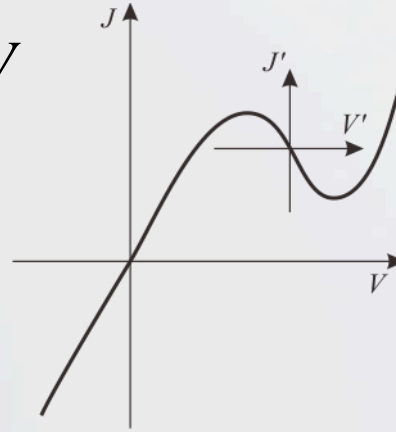
Series	Parallel
Open	Short
Voltage	Current
Impedance	Admittance
Capacitance	Inductance
Electric field	Magnetic field
Resistance	Conductance
Ho-Thevenin	Norton
Kirchhoff's 2 nd law	Kirchhoff's 1 st law

2.7 Definition: Passive elements and active elements

Two terminal: current J , voltage V

$JV \geq 0$: passive element

$JV < 0$: active element



Locally active
two-terminal element

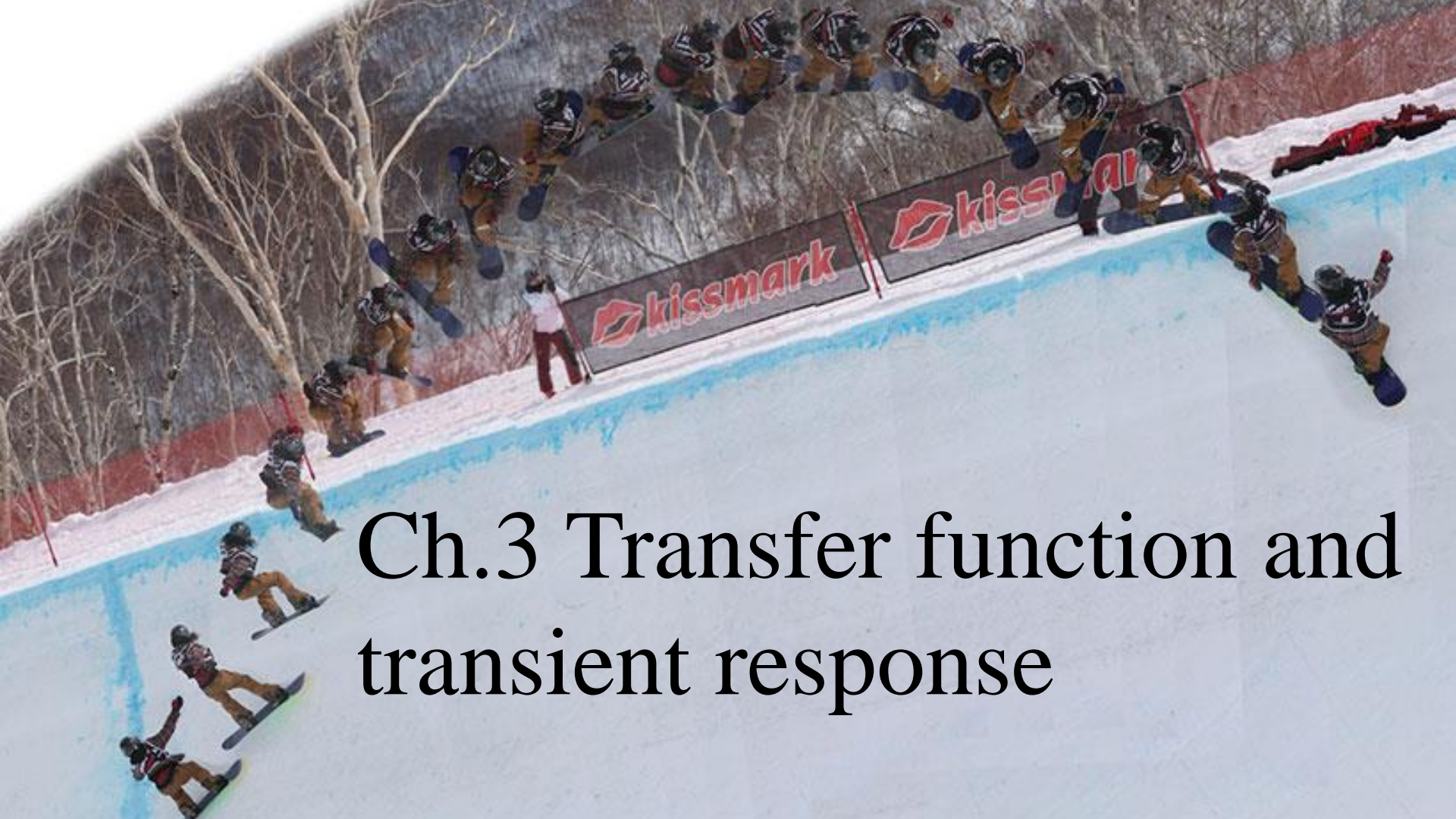
More than three-terminal: treat as a terminal pair circuit



$$P = J_{in} V_{in} + J_{out} V_{out}$$

$P \geq 0$: passive element

$P < 0$: active element



Ch.3 Transfer function and transient response

3.1 General Properties of Resonance and Resonance Circuits

3.1.1 Resonance Phenomena

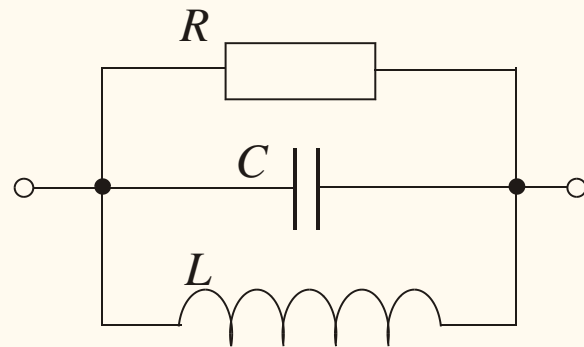
Harmonic oscillator: $\frac{d^2q}{dt^2} = -\omega_0^2q$

Kirchhoff's law $L \frac{dJ_L}{dt} = -L \frac{d^2q_L}{dt^2} = \frac{q}{C} = RJ_R = R \frac{dq_R}{dt}$
 $dq_L + dq_R + dq = 0$

$$\frac{d^2q}{dt^2} + \frac{1}{CR} \frac{dq}{dt} + \frac{1}{LC}q = \frac{d^2q}{dt^2} + \frac{1}{\tau} \frac{dq}{dt} + \omega_0^2q = 0$$

$$q = \exp(\lambda t) \quad \lambda = \frac{1}{2\tau} \left[-1 \pm \sqrt{1 - 4(\omega_0\tau)^2} \right] \approx -\frac{1}{2\tau} \pm i\omega_0 \quad (\omega_0\tau \gg 1)$$

Resonant (angular) frequency $\omega_0 \equiv \frac{1}{\sqrt{LC}}$



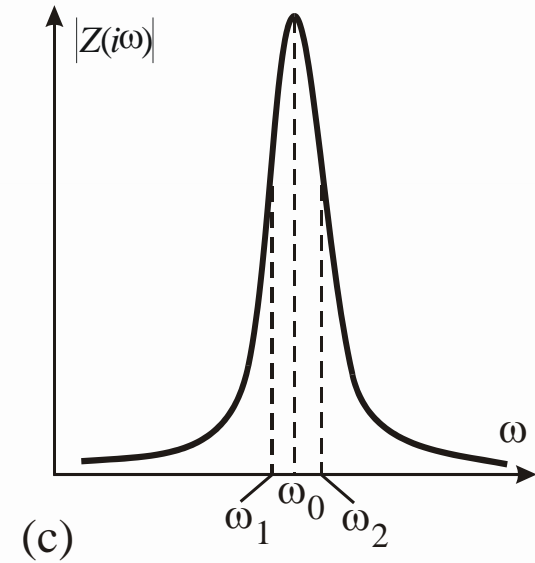
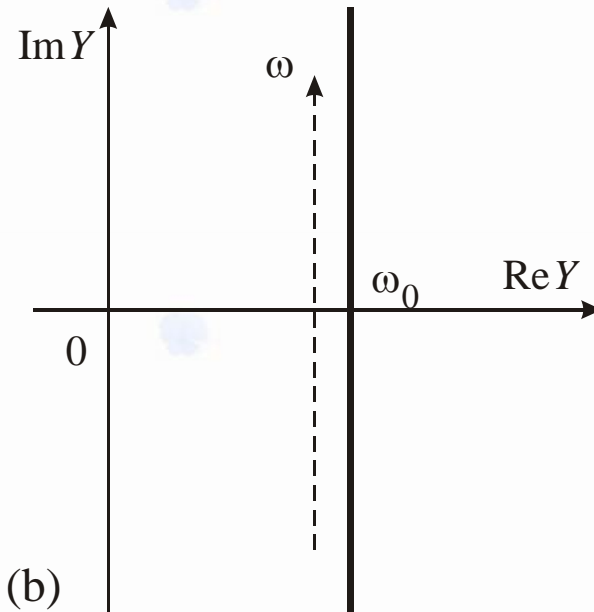
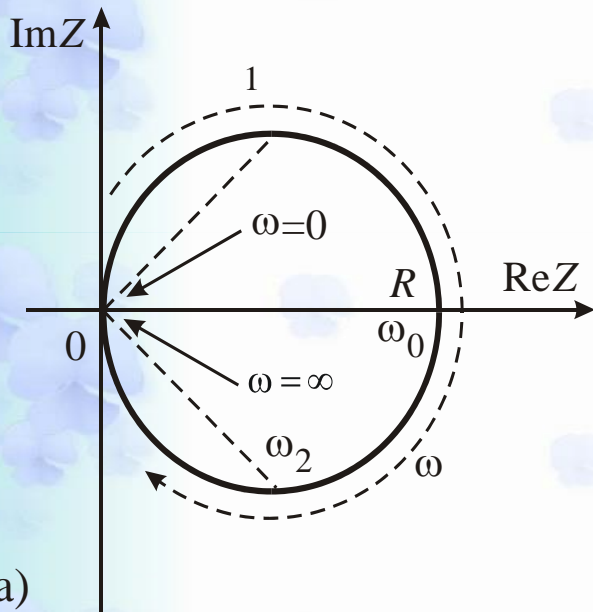
Transfer function, resonance and phase shift

$$Z_{\text{tot}}(i\omega) = \left[\frac{1}{R} + i \left(\omega C - \frac{1}{\omega L} \right) \right]^{-1}$$

$$\omega_0 \equiv \frac{1}{\sqrt{LC}}$$

Resonance: Reactance = 0

Total Phase Shift Change: π

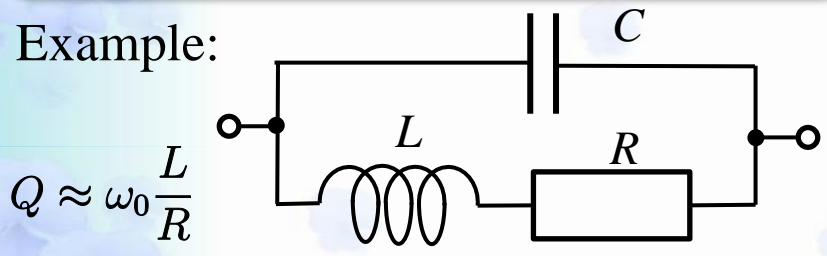


The Bode diagram (plot)

Plot of absolute value and argument of an impedance as a function of frequency.

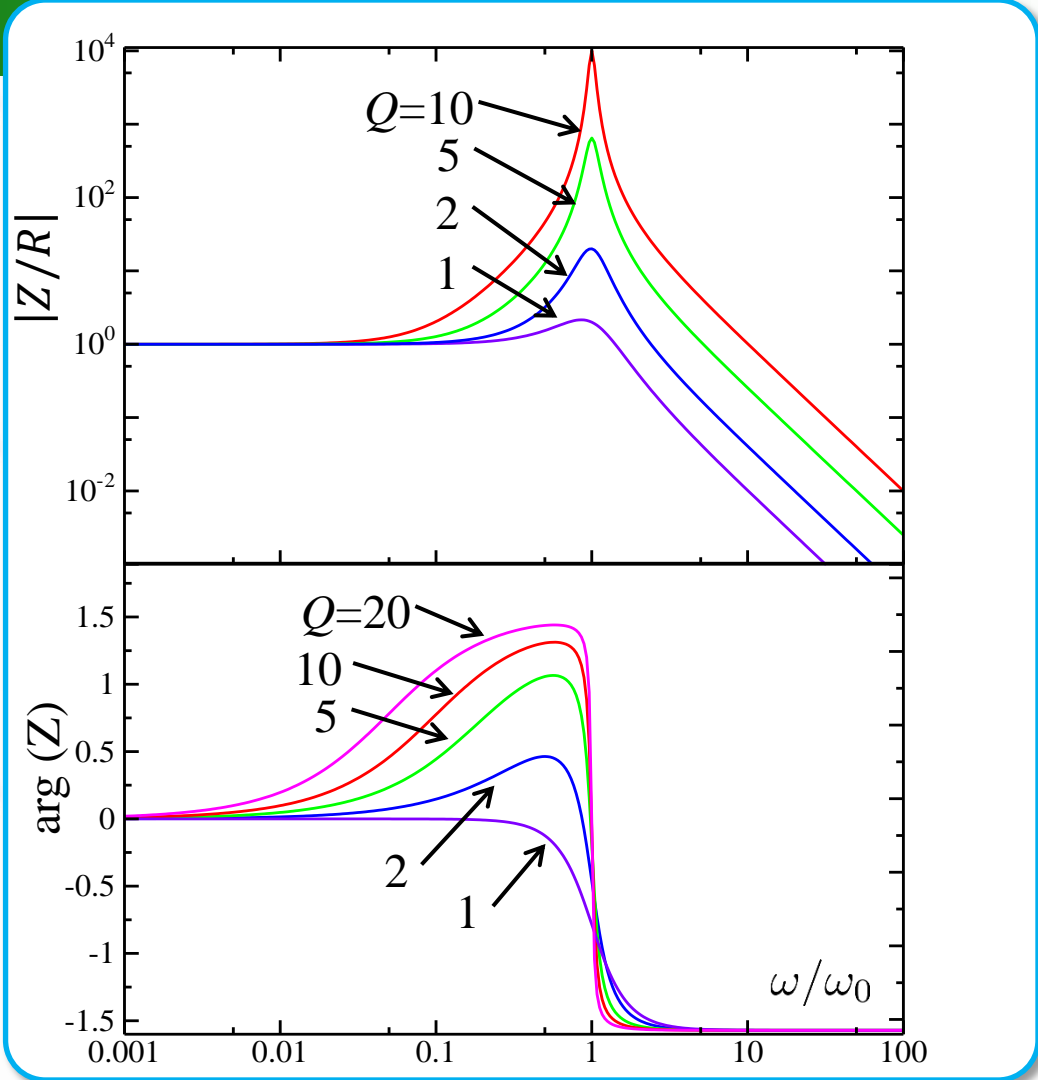
Absolute value: log-log mode
Argument: semi-log mode

Example:

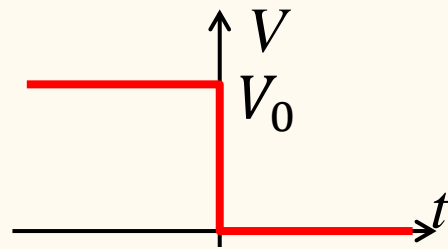
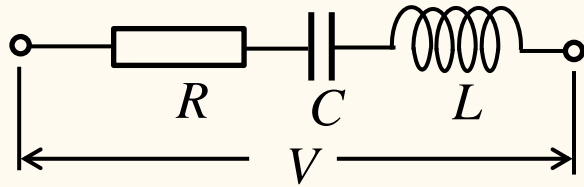


$$Q \approx \omega_0 \frac{L}{R}$$

$$Z(i\omega) = \frac{R + i\omega L}{1 - \omega^2 + i\omega CR}$$
$$= \frac{R + i\omega L}{1 - (\omega/\omega_0)^2 + i\omega CR}$$



Transient response of resonant circuit



$$L \frac{d^2 q}{dt^2} + R \frac{dq}{dt} + \frac{q}{C} = 0 \quad (t > 0),$$

$$q(0) = CV_0$$

$$q(t) = CV_0 e^{st} \rightarrow Ls^2 + Rs + C^{-1} = 0$$

$$s = \left(-\omega_0 \pm \sqrt{\omega_0^2 - 4\alpha^2} \right) \frac{\omega_0}{2\alpha} \quad \alpha \equiv (CR)^{-1}$$

$(\omega_0/2) < \alpha \rightarrow$ imaginary part

$$q(t) = CV_0 \exp[(-\gamma \pm i\omega_s)t], \quad \gamma \equiv \frac{\omega_0^2}{2\alpha}, \quad \omega_s \equiv \omega_0 \left(1 - \frac{\omega_0^2}{4\alpha^2} \right)^{1/2}$$

Damped oscillation with time constant γ^{-1} , frequency ω_s

Transient response of resonance circuit (transfer function)

Synthesized impedance, admittance

$$Z_{\text{tot}}(s) = sL + R + \frac{1}{sC}, \quad Y_{\text{tot}}(s) = Z_{\text{tot}}(s)^{-1}$$

Zero (pole) of $Z_{\text{tot}}(s)$ ($Y_{\text{tot}}(s)$) $s = (-\omega_0 \pm \sqrt{\omega_0^2 - 4\alpha^2}) / (2\alpha)$

$Z_{\text{tot}}(s_0) = 0$ Time constant: $\text{Re}(s_0)$ Frequency: $\text{Im}(s_0)$

Laplace transformation of voltage: $V(s)$

$$\underline{J(t)} = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} Y(s)V(s)e^{st} ds = \sum_i R(s_i)V(s_i)e^{s_i t} \quad (c > 0)$$

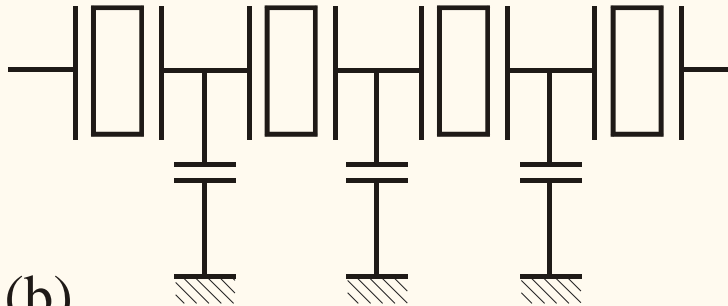
Natural current

s_i : poles of $Y(s)$ $R(s_i) = Y(s)(s - s_i)|_{s=s_i}$

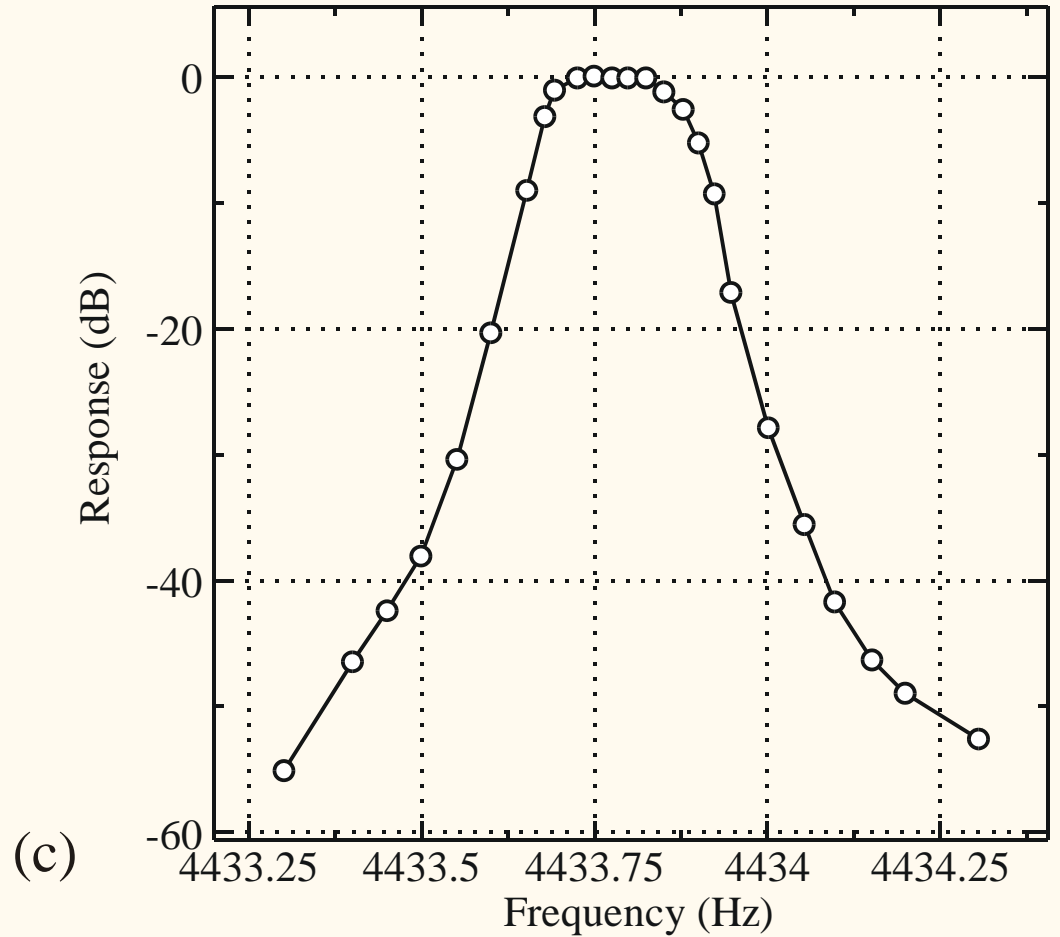
Quartz crystal filter



(a)



(b)

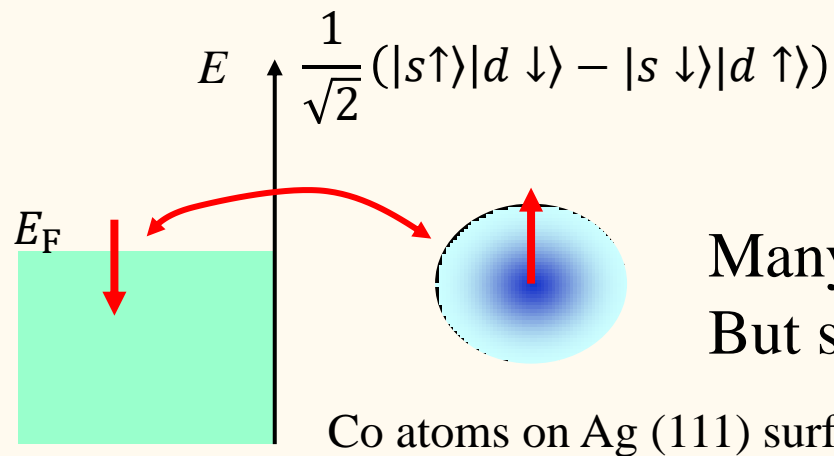


(c)

Kondo Resonance and Phase shift

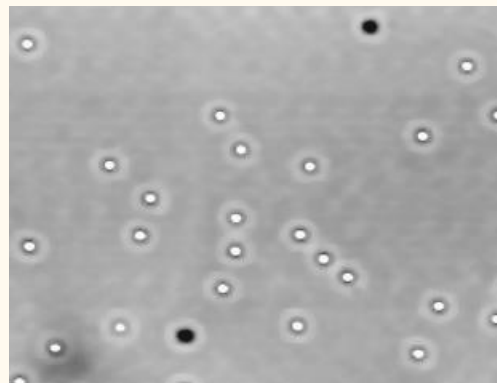


Jun Kondo



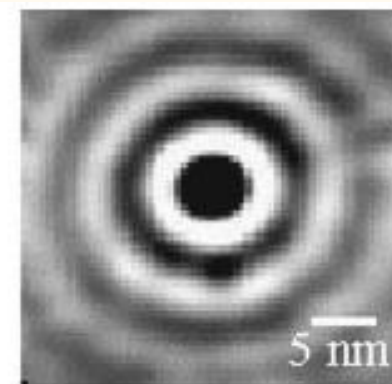
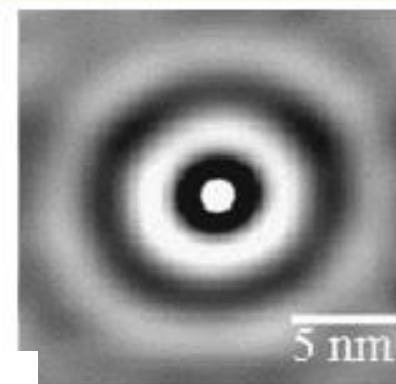
Many body resonance.

But still has the phase shift of $\pi/2$!



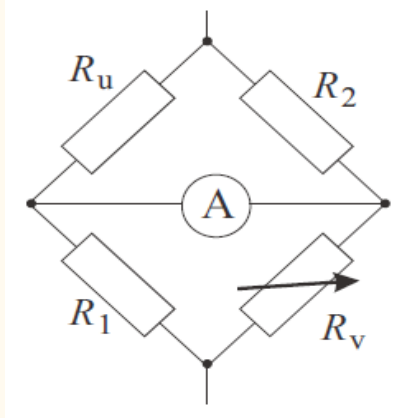
Co (magnetic)

Defect (non-magnetic)



Schneider et al., Phys. Rev. B65, 121406 (2002).

Wheatstone bridge

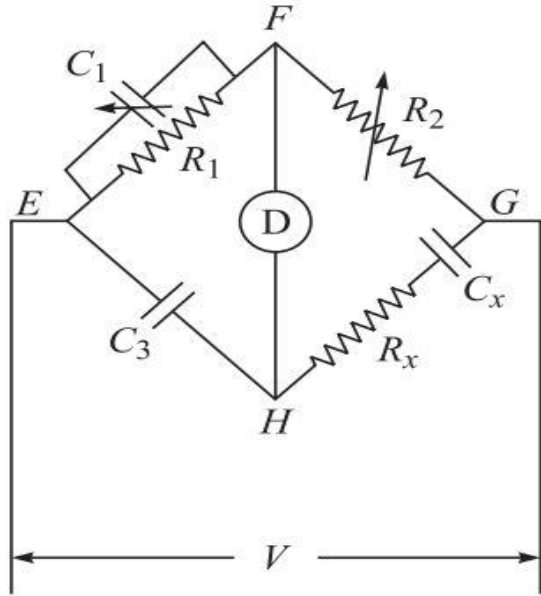


AVS-47 Resistance bridge

Not a “bridge” circuit!



Schering Bridge



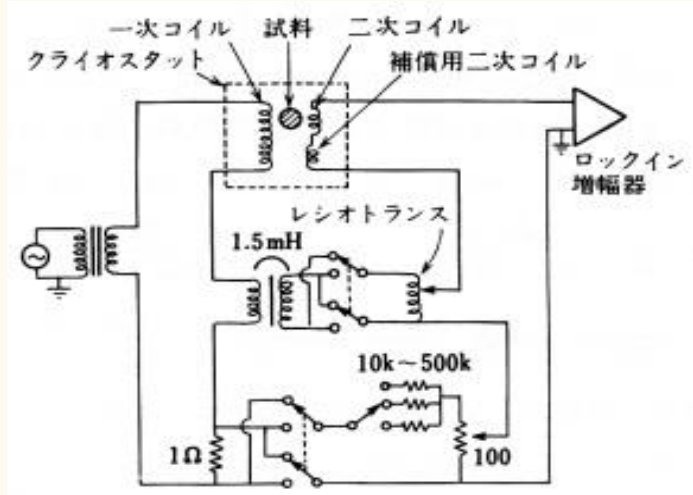
$$Z_1 Z_x = Z_2 Z_3, \quad Z_x = Z_2 Z_3 Y_1$$

$$Z_x = R_x + \frac{1}{i\omega C_x}, \quad Z_2 = R_2, \quad Z_3 = \frac{1}{i\omega C_3}, \quad Y_1 = \frac{1}{R_1} + i\omega C_1$$

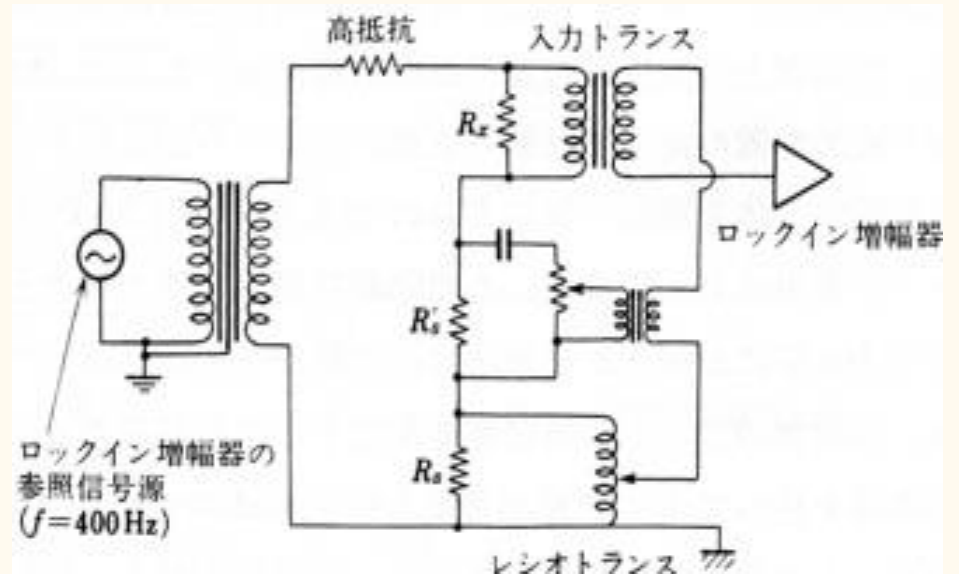
$$R_x + \frac{1}{i\omega C_x} = R_2 \frac{1}{i\omega C_3} \left(\frac{1}{R_1} + i\omega C_1 \right)$$

$$R_x = \frac{R_2 C_1}{C_3}, \quad C_x = \frac{R_1}{R_2} C_3$$

Magnetic moment measurement



Resistance measurement



Capacitance bridge キャパシタンスブリッジ



General Radio
3-terminal
Capacitance bridge

Agilent E4981A



What is Spice?

SPICE: Simulation Program with Integrated Circuit Emphasis

A language which describes electronic circuits (corresponding to circuit diagrams).

ex) a CR circuit and a dc power source

```
* 0---R1---1---C1---2---V1---0
```

```
R1 0 1 10
```

```
C1 1 2 20
```

```
V1 2 0 5
```

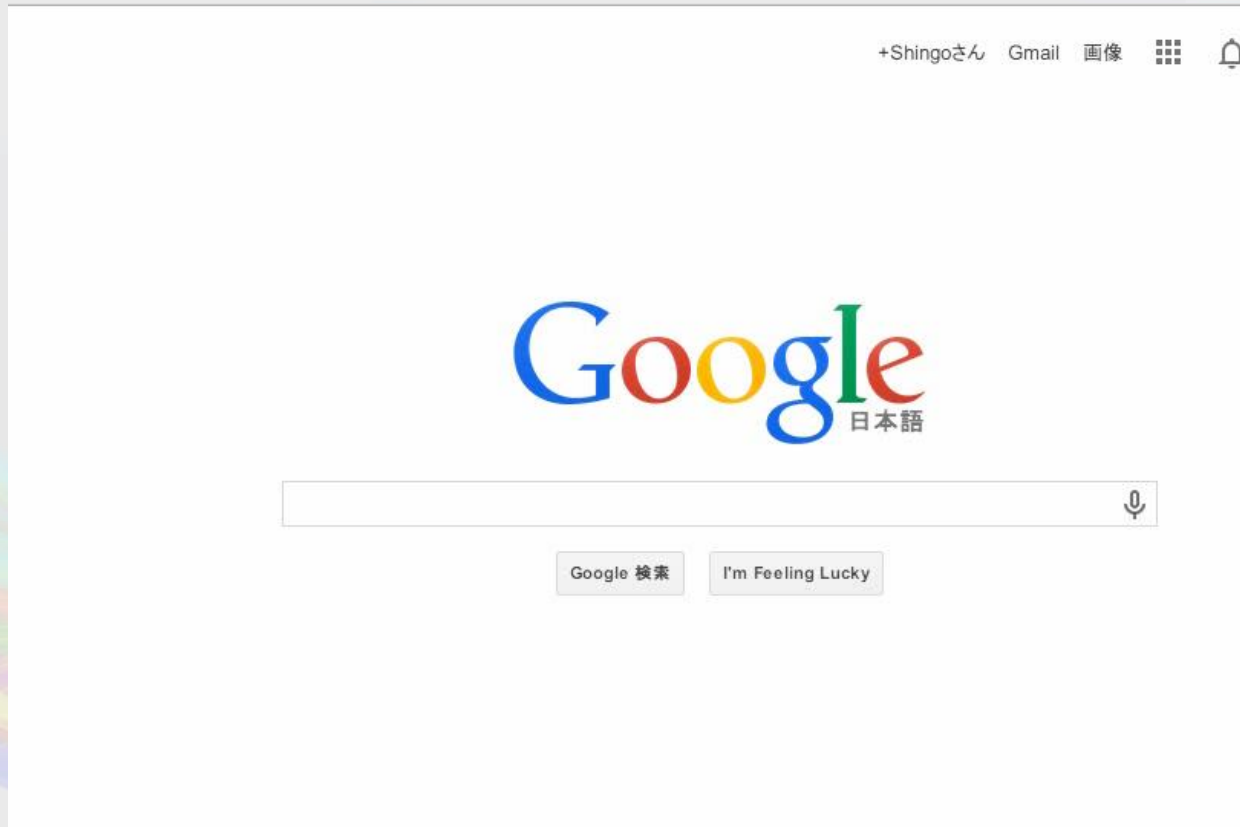
```
.END
```

Graphical user interface: Circuit diagram

Linear Technology
web site



The screenshot displays the Linear Technology website interface. At the top, there is a search bar and navigation links for '国内ニュースサイト', 'ENGLISH', '中文网站', '品質', '採用', '問い合わせ', and 'MyLinear'. Below this, a main navigation menu includes '製品', 'ソリューション', 'デザインサポート', '購入', and '会社概要'. The main content area features a product spotlight for the LTC6430, which includes a circuit diagram icon and a list of key features: '利得ブロック: 15dB', 'OIP3: +50dBm', and '3.3dB NF'. To the right of the product spotlight, there is a section for 'LTSPICE IV' with links for 'ダウンロード LTspice IV', 'LTspice デモ回路', and 'LTspice 資料'. Below the product spotlight, there is a '製品リリース' (Product Releases) section listing various LT products and their descriptions. On the far right, there is a 'ビデオ' (Video) section with a video thumbnail and a link to 'LT4321 PoE 理想ダイオード・ブリッジコントローラ - 製品概要ビデオ'.



Download LTSpice from
the web site of Linear
Technology

Operation example

Home > デザインサポート > ソフトウェア

Design Simulation and Device Models

リニアテクノロジーは高性能なスイッチング・レギュレータやアンプ、データ・コンバータ、フィルターなどを使用した回路を、初めての設計者でも短時間に容易に評価できるよ
ムデザイン・シミュレーション・ツールを提供しています。


- LTspice IV
- LTpowerCAD
- LTpowerPlay
- Amplifier Simulation & Design
- Filter Simulation & Design
- Timing Simulation & Design
- Data Converter Evaluation Software
- Dust Networks Starter Kits


LTSPICE IV

LTspice IV

LTspice IVは高性能なSpice IIIシミュレータと回路図入力、波形ビューワに改善を加え、スイッチング・レギュレータのシミュレーションを容易にするためのモデルを搭載しています。Spiceの改善により、スイッチング・レギュレータのシミュレーションは、通常のSpiceシミュレータ使用時に比べて著しく高速化され、ほとんどのスイッチング・レギュレータにおいて波形表示をほんの数分で行なうことができます。Spiceとリニアテクノロジーのスイッチング・レギュレータの80%に対応するMacro Model、200を超えるオペアンプ用モデルならびに抵抗、トランジスタ、MOSFETモデルをここからダウンロードできます。

- [LTspice IV \(Windows用\)をダウンロード\(2014年5月5日更新\)](#)
- [LTspice IV \(Mac OS X 10.7+用\)をダウンロード](#)
- [関連情報 & ショートカット](#)
- [Mac OS X用ショートカット](#)
- [スタート・ガイド](#)
- [ユーザ・ガイド\(ヘルプ・ファイル参照\)](#)
- [トランスの使用](#)
- [デモ回路集](#)
- [セミナーの開催予定を見る](#)

LTspiceのツイッターをフォロー 

LTspiceに関するビデオを見る 

LTPOWERCAD

MYLINEAR ログイン



Summary

Theorems for paired terminal circuits

Superposition, Ho-Thevenin, Reciprocity

Duality

Passive devices (elements) and active devices

Transfer function and transient response

Transfer function of single-pair terminal circuits

Resonance circuit

Bode plot

General properties