Campi Elettromagnetici

Corso di Laurea in Ingegneria Informatica, Biomedica e delle Telecomunicazioni

a.a. 2023-2024 - Laurea “Triennale” – Secondo semestre - Secondo anno

Università degli Studi di Napoli “Parthenope”

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Color legend

New formulas, important considerations, important formulas, important concepts

Very important for the discussion

Memo

Mathematical tools to be exploited

Mathematics

Mathematical tools that we will exploit today

$$\nabla \cdot \left(\nabla \times \vec{\mathbf{A}}(\vec{\mathbf{r}}) \right) = 0$$

Maxwell equations

Time domain - Differential form

$$
\begin{cases}
\nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\
\nabla \times \vec{\mathbf{h}}(\vec{\mathbf{r}},t) = \dfrac{\partial \vec{\mathbf{d}}(\vec{\mathbf{r}},t)}{\partial t} + \vec{\mathbf{j}}(\vec{\mathbf{r}},t) \\
\nabla \cdot \vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \rho(\vec{\mathbf{r}},t) \\
\nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0
\end{cases}
$$

James Clerk Maxwell 1831-1879

Maxwell equations

Time domain - Differential form

$$\begin{cases} \nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\ \nabla \times \vec{\mathbf{h}}(\vec{\mathbf{r}},t) = \dfrac{\partial \vec{\mathbf{d}}(\vec{\mathbf{r}},t)}{\partial t} + \vec{\mathbf{j}}(\vec{\mathbf{r}},t) + \vec{\mathbf{j}}_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \rho(\vec{\mathbf{r}},t) + \rho_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0 \end{cases}$$

James Clerk Maxwell 1831-1879

Maxwell equations

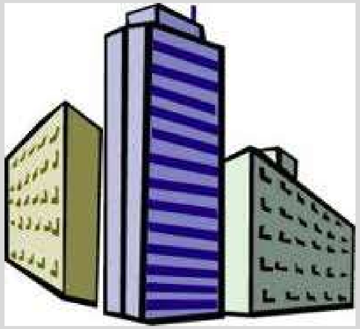
$$\begin{cases} \nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\ \nabla \times \vec{\mathbf{h}}(\vec{\mathbf{r}},t) = \dfrac{\partial \vec{\mathbf{d}}(\vec{\mathbf{r}},t)}{\partial t} + \vec{\mathbf{j}}(\vec{\mathbf{r}},t) + \vec{\mathbf{j}}_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \rho(\vec{\mathbf{r}},t) + \rho_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0 \end{cases}$$

$$\begin{cases} \vec{\mathbf{j}}_0(\vec{\mathbf{r}},t) \\ \rho_0(\vec{\mathbf{r}},t) \end{cases}$$ **Prescribed sources**

$$\begin{cases} \vec{\mathbf{j}}(\vec{\mathbf{r}},t) \\ \rho(\vec{\mathbf{r}},t) \end{cases}$$ **Induced sources**

Complex scenario






The independence of the Maxwell equations

Time domain - Differential form

$$
\begin{cases}
\nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\
\nabla \times \vec{\mathbf{h}}(\vec{\mathbf{r}},t) = \dfrac{\partial \vec{\mathbf{d}}(\vec{\mathbf{r}},t)}{\partial t} + \vec{\mathbf{j}}(\vec{\mathbf{r}},t) + \vec{\mathbf{j}}_0(\vec{\mathbf{r}},t) \\
\nabla \cdot \vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \rho(\vec{\mathbf{r}},t) + \rho_0(\vec{\mathbf{r}},t) \\
\nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0
\end{cases}
$$

$$
\nabla \cdot \left(\nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t)\right) = \nabla \cdot \left(-\frac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t}\right)
$$

$$
\Downarrow \qquad\qquad \Downarrow
$$

$$
0 \qquad = -\frac{\partial \left(\nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t)\right)}{\partial t}
$$

$$
\nabla \cdot \left(\nabla \times \vec{\mathbf{A}}(\vec{\mathbf{r}})\right) = 0
$$

The independence of the Maxwell equations

Time domain - Differential form

$$
\begin{cases}
\nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\
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\nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0
\end{cases}
$$

$$
\nabla \cdot \left(\nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t)\right) = \nabla \cdot \left(-\frac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t}\right)
$$

$$
0 = -\frac{\partial\left(\nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t)\right)}{\partial t}
$$

$\nabla \cdot \vec{\mathbf{b}}$ is independent of time. If the fields are equal to zero before a given time, then $\nabla \cdot \vec{\mathbf{b}} = 0$ for all times, thus recovering the last Maxwell equation

The independence of the Maxwell equations

Time domain - Differential form

$$
\begin{cases}
\nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\
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\nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0
\end{cases}
$$

Number of independent scalar equations:

3+3+1=7

Let us assume knowledge of the impressed sources $\vec{\mathbf{j}}_0(\vec{\mathbf{r}},t); \rho_0(\vec{\mathbf{r}},t)$

Number of unknown scalar quantities:

$\vec{\mathbf{e}}(\vec{\mathbf{r}},t); \vec{\mathbf{d}}(\vec{\mathbf{r}},t); \vec{\mathbf{h}}(\vec{\mathbf{r}},t); \vec{\mathbf{b}}(\vec{\mathbf{r}},t); \vec{\mathbf{j}}(\vec{\mathbf{r}},t); \rho(\vec{\mathbf{r}},t)$

3 +3 +3 +3 +3 +1

16

The independence of the Maxwell equations

Time domain - Differential form

$$\begin{cases} \nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\ \nabla \times \vec{\mathbf{h}}(\vec{\mathbf{r}},t) = \dfrac{\partial \vec{\mathbf{d}}(\vec{\mathbf{r}},t)}{\partial t} + \vec{\mathbf{j}}(\vec{\mathbf{r}},t) + \vec{\mathbf{j}}_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \rho(\vec{\mathbf{r}},t) + \rho_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0 \end{cases}$$

Even assuming knowledge of the impressed sources $\vec{\mathbf{j}}_0(\vec{\mathbf{r}},t); \rho_0(\vec{\mathbf{r}},t)$

Number of independent scalar equations: 7

Number of unknown scalar quantities: 16

Maxwell equations involve a number of unknowns larger than the number of equations!

Constitutive relationships

Time domain - Differential form

$$\begin{cases} \nabla \times \vec{\mathbf{e}}(\vec{\mathbf{r}},t) = -\dfrac{\partial \vec{\mathbf{b}}(\vec{\mathbf{r}},t)}{\partial t} \\ \nabla \times \vec{\mathbf{h}}(\vec{\mathbf{r}},t) = \dfrac{\partial \vec{\mathbf{d}}(\vec{\mathbf{r}},t)}{\partial t} + \vec{\mathbf{j}}(\vec{\mathbf{r}},t) + \vec{\mathbf{j}}_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \rho(\vec{\mathbf{r}},t) + \rho_0(\vec{\mathbf{r}},t) \\ \nabla \cdot \vec{\mathbf{b}}(\vec{\mathbf{r}},t) = 0 \end{cases}$$

Even assuming knowledge of the impressed sources $\vec{\mathbf{j}}_0(\vec{\mathbf{r}},t); \rho_0(\vec{\mathbf{r}},t)$

Number of independent scalar equations: 7

Number of unknown scalar quantities: 16

Maxwell equations involve a number of unknowns larger than the number of equations!

The additional missing equations are provided by the **constitutive relationships**, which describe interaction of fields and matter from a macroscopic point of view

Memo

Vacuum

$$\vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \varepsilon_0 \vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

$$\vec{\mathbf{b}}(\vec{\mathbf{r}},t) = \mu_0 \vec{\mathbf{h}}(\vec{\mathbf{r}},t)$$

$$\vec{\mathbf{j}}(\vec{\mathbf{r}},t) = \sigma \vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

$\mu_0 = 4\pi \times 10^{-7}$ *Permeability* $[Henry/m]$

$\varepsilon_0 = 8.8 \times 10^{-12}$ *Permittivity* $[Farad/m]$

$\sigma = 0$ *Conductivity* $[Siemens/m]$

These relationships depend on the particular medium that we have considered, that is, the vacuum.
More generally, similar relationships, can be found also in other media. They depend upon the characteristics of the medium in which the electromagnetic field is considered, and are called **CONSTITUTIVE RELATIONSHPS**

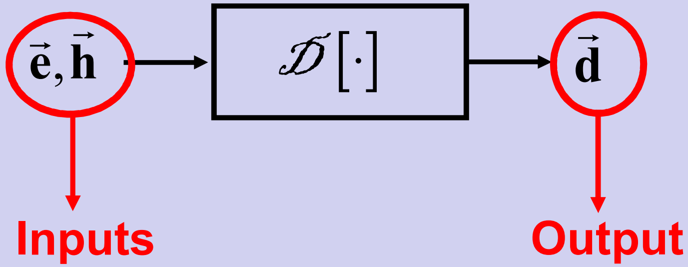
Constitutive relationships

Inductions and currents must be represented in terms of fields

$$\vec{\mathbf{d}} = \mathscr{D}\left[\vec{\mathbf{e}},\vec{\mathbf{h}}\right]$$

$$\vec{\mathbf{b}} = \mathscr{B}\left[\vec{\mathbf{e}},\vec{\mathbf{h}}\right]$$

$$\vec{\mathbf{j}} = \mathscr{J}\left[\vec{\mathbf{e}},\vec{\mathbf{h}}\right]$$



$\mathscr{D}[\cdot]$, $\mathscr{B}[\cdot]$ and $\mathscr{J}[\cdot]$ are functionals which depend upon the medium in which the electromagnetic field is considered and upon the fields themselves.

Constitutive relationships

Linear media

$$\vec{\mathbf{d}}_1 = \mathscr{D}\left[\vec{\mathbf{e}}_1, \vec{\mathbf{h}}_1\right]$$

$$\vec{\mathbf{d}}_2 = \mathscr{D}\left[\vec{\mathbf{e}}_2, \vec{\mathbf{h}}_2\right]$$

$$\Rightarrow \quad \vec{\mathbf{d}}_1 + \vec{\mathbf{d}}_2 = \mathscr{D}\left[\vec{\mathbf{e}}_1 + \vec{\mathbf{e}}_2, \vec{\mathbf{h}}_1 + \vec{\mathbf{h}}_2\right]$$

Constitutive relationships

In the following we will consider linear media

Constitutive relationships

Linear media

Example 1

$$\vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \boldsymbol{\varepsilon} \cdot \vec{\mathbf{e}}(\vec{\mathbf{r}},t) + \boldsymbol{\chi} \cdot \vec{\mathbf{h}}(\vec{\mathbf{r}},t)$$

where

$\vec{\mathbf{d}}(\vec{\mathbf{r}},t); \vec{\mathbf{e}}(\vec{\mathbf{r}},t); \vec{\mathbf{h}}(\vec{\mathbf{r}},t):$ 3x1 column vectors

$\boldsymbol{\varepsilon}$ and $\boldsymbol{\chi}:$ 3x3 matrices

- **Local (nondispersive) media**
- **Bianisotropic media**

Constitutive relationships

Linear media

Example 2

$$\vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \boldsymbol{\varepsilon} \cdot \vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

where

$\vec{\mathbf{d}}(\vec{\mathbf{r}},t); \vec{\mathbf{e}}(\vec{\mathbf{r}},t); \vec{\mathbf{h}}(\vec{\mathbf{r}},t):$ 3x1 column vectors

$\boldsymbol{\varepsilon}:$ 3x3 matrix

- **Local (nondispersive) media**
- **Anisotropic media**

Constitutive relationships

Linear media

Example 2

$$\vec{\mathbf{d}}(\vec{\mathbf{r}},t)=\boldsymbol{\varepsilon}\cdot\vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$
$$\vec{\mathbf{b}}(\vec{\mathbf{r}},t)=\boldsymbol{\mu}\cdot\vec{\mathbf{h}}(\vec{\mathbf{r}},t)$$
$$\vec{\mathbf{j}}(\vec{\mathbf{r}},t)=\boldsymbol{\sigma}\cdot\vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

- **Local (nondispersive) media**
- **Anisotropic media**

where

$\vec{\mathbf{d}}(\vec{\mathbf{r}},t);\vec{\mathbf{b}}(\vec{\mathbf{r}},t);\ \vec{\mathbf{j}}(\vec{\mathbf{r}},t);\vec{\mathbf{e}}(\vec{\mathbf{r}},t);\ \vec{\mathbf{h}}(\vec{\mathbf{r}},t):$ 3x1 column vectors

$\boldsymbol{\varepsilon};\ \boldsymbol{\mu};\ \boldsymbol{\sigma}:$ 3x3 matrices

$\boldsymbol{\varepsilon}$:permittivity [Farad/m]
$\boldsymbol{\mu}$:permeability [Henry/m]
$\boldsymbol{\sigma}$:conductivity [Siemens/m]

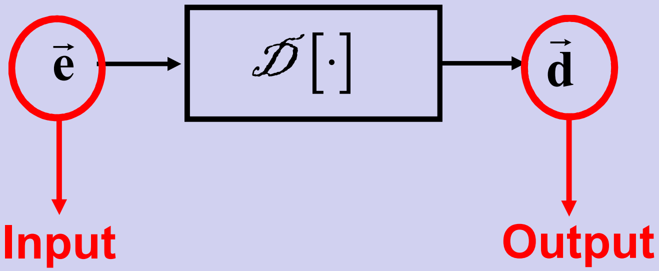
Constitutive relationships

Linear & Anisotropic media

$$\vec{\mathbf{d}} = \mathscr{D}\left[\vec{\mathbf{e}}\right]$$

$$\vec{\mathbf{b}} = \mathscr{B}\left[\vec{\mathbf{h}}\right]$$

$$\vec{\mathbf{j}} = \mathscr{J}\left[\vec{\mathbf{e}}\right]$$



Constitutive relationships

Linear media

$$\vec{\mathbf{d}}(\vec{\mathbf{r}},t) = \boldsymbol{\varepsilon} \cdot \vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

$\boldsymbol{\varepsilon}$: 3x3 matrix

- **Local (nondispersive) media**
- **Anisotropic media**

Class	**Property**	**Effect on the I-O relation**
Isotropic	A **rotation** of the input implies **the same rotation** of the output	$\boldsymbol{\varepsilon}$ becomes scalar. It is not a matrix anymore!

Constitutive relationships

Linear media

- **Local (non-dispersive) media**
- **Anisotropic media**

$$\vec{\mathbf{d}}(\vec{\mathbf{r}},t)=\boldsymbol{\varepsilon}\cdot\vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

$$\vec{\mathbf{b}}(\vec{\mathbf{r}},t)=\boldsymbol{\mu}\cdot\vec{\mathbf{h}}(\vec{\mathbf{r}},t)$$

$$\vec{\mathbf{j}}(\vec{\mathbf{r}},t)=\boldsymbol{\sigma}\cdot\vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

$\boldsymbol{\varepsilon};\ \boldsymbol{\mu};\ \boldsymbol{\sigma}:$ 3x3 matrices

- **Local (non-dispersive) media**
- **Isotropic media**

$$\vec{\mathbf{d}}(\vec{\mathbf{r}},t)=\varepsilon\,\vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

$$\vec{\mathbf{b}}(\vec{\mathbf{r}},t)=\mu\,\vec{\mathbf{h}}(\vec{\mathbf{r}},t)$$

$$\vec{\mathbf{j}}(\vec{\mathbf{r}},t)=\sigma\,\vec{\mathbf{e}}(\vec{\mathbf{r}},t)$$

$\varepsilon;\mu;\sigma:$ scalars

Constitutive relationships

Linear media

Class	Property	Effect on the I-O relation

Constitutive relationships

Linear media

Class	Property	Effect on the I-O relation
Time-dispersive Time-nondispersive Time-variant Time-invariant		

Constitutive relationships

Linear media

Class	Property	Effect on the I-O relation
Space-dispersive		
Space-nondispersive		
Space-variant		
Space-invariant		

Constitutive relationships

Linear media

Class	Property
Time-dispersive	
Time-nondispersive	The output **at time *t* depends only** on the value of the input **at the same time *t***
Time-variant	
Time-invariant	

Constitutive relationships

Linear media

Class	**Property**
Time-dispersive	The output **at time t depends** on the values of the input **throughout a time-interval**.
Time-nondispersive	
Time-variant	
Time-invariant	

Constitutive relationships

Linear media

Class

Time-dispersive

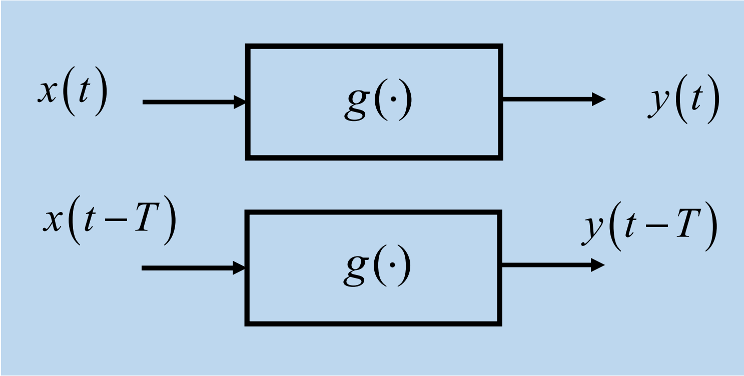
Time-nondispersive

Time-variant

Time-invariant

Property

A **time translation** of the input implies **the same translation** of the output



Constitutive relationships

Linear media

Class

Time-dispersive

Time-nondispersive

Time-variant

Time-invariant

Property

A **time translation** of the input **does not** imply **the same translation** of the output

Constitutive relationships

Linear media

Class	Property
Space-dispersive	
Space-nondispersive	The output **at space $\vec{r}$ depends only** on the value of the input **at the same space $\vec{r}$**
Space-variant	
Space-invariant	

Constitutive relationships

Linear media

Class	Property
Space-dispersive	The output **at space $\vec{\mathbf{r}}$ depends** on the values of the input **throughout a space-interval**
Space-nondispersive	
Space-variant	
Space-invariant	

Constitutive relationships

Linear media

Class

Space-dispersive

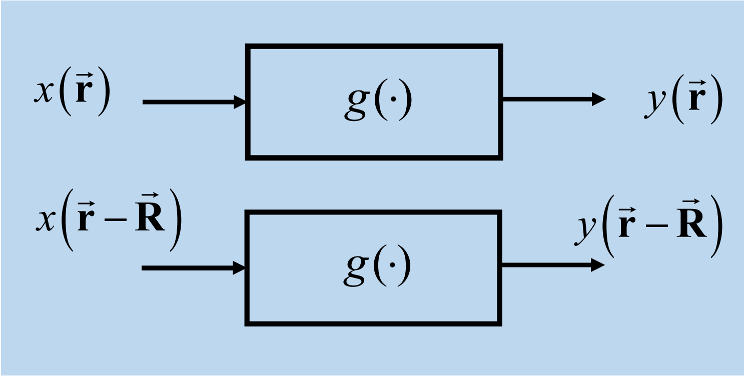
Space-nondispersive

Space-variant

Space-invariant

Property

A **space translation** of the input implies **the same translation** of the output



Constitutive relationships

Linear media

Class	Property
Space-dispersive Space-nondispersive Space-variant Space-invariant	A **space translation** of the input **does not** imply **the same translation** of the output

Constitutive relationships

Linear media

Class	Property	Effect on the I-O relation

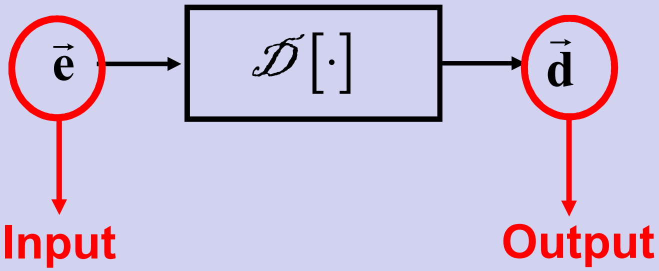
Constitutive relationships

Linear & Anisotropic media

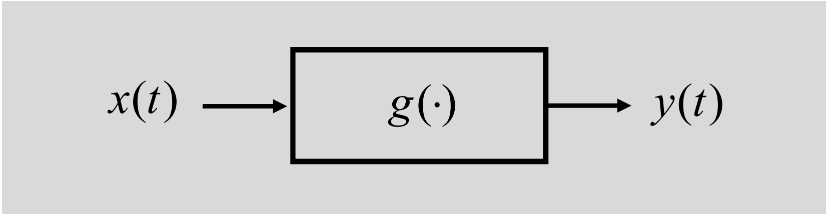
$$\vec{\mathbf{d}} = \mathscr{D}\left[\vec{\mathbf{e}}\right]$$

$$\vec{\mathbf{b}} = \mathscr{B}\left[\vec{\mathbf{h}}\right]$$

$$\vec{\mathbf{j}} = \mathscr{J}\left[\vec{\mathbf{e}}\right]$$



Linear systems: effect on the I-O relation



$x(t)$ and $y(t)$ are scalar

	Time-dispersive (TD)	**Time-nondispersive (TND)**
Time-variant (TV)	$y(t)=\int dt'\, g(t,t')\, x(t')$	$y(t)=\tilde{g}(t)\, x(t)$
Time-invariant (TI)	$y(t)=\int dt'\, g(t-t')\, x(t')$	$y(t)=\tilde{g}\, x(t)$