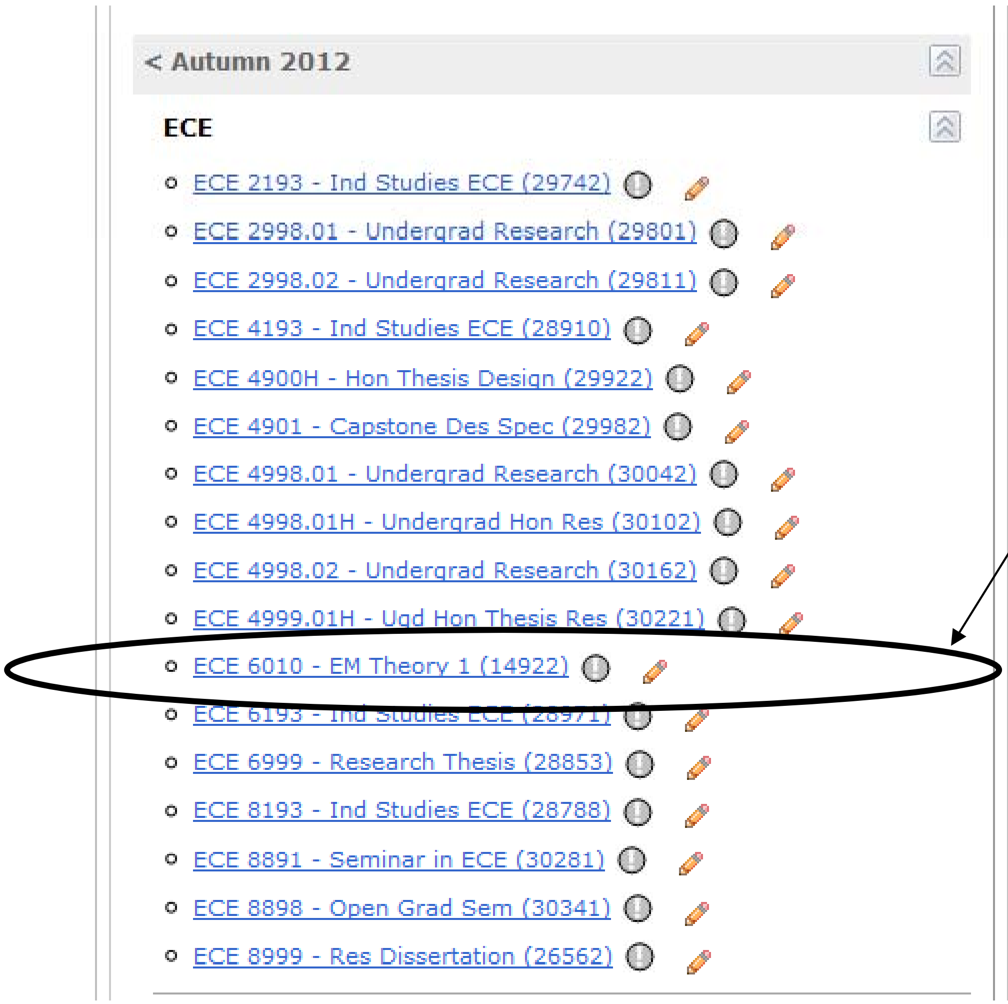
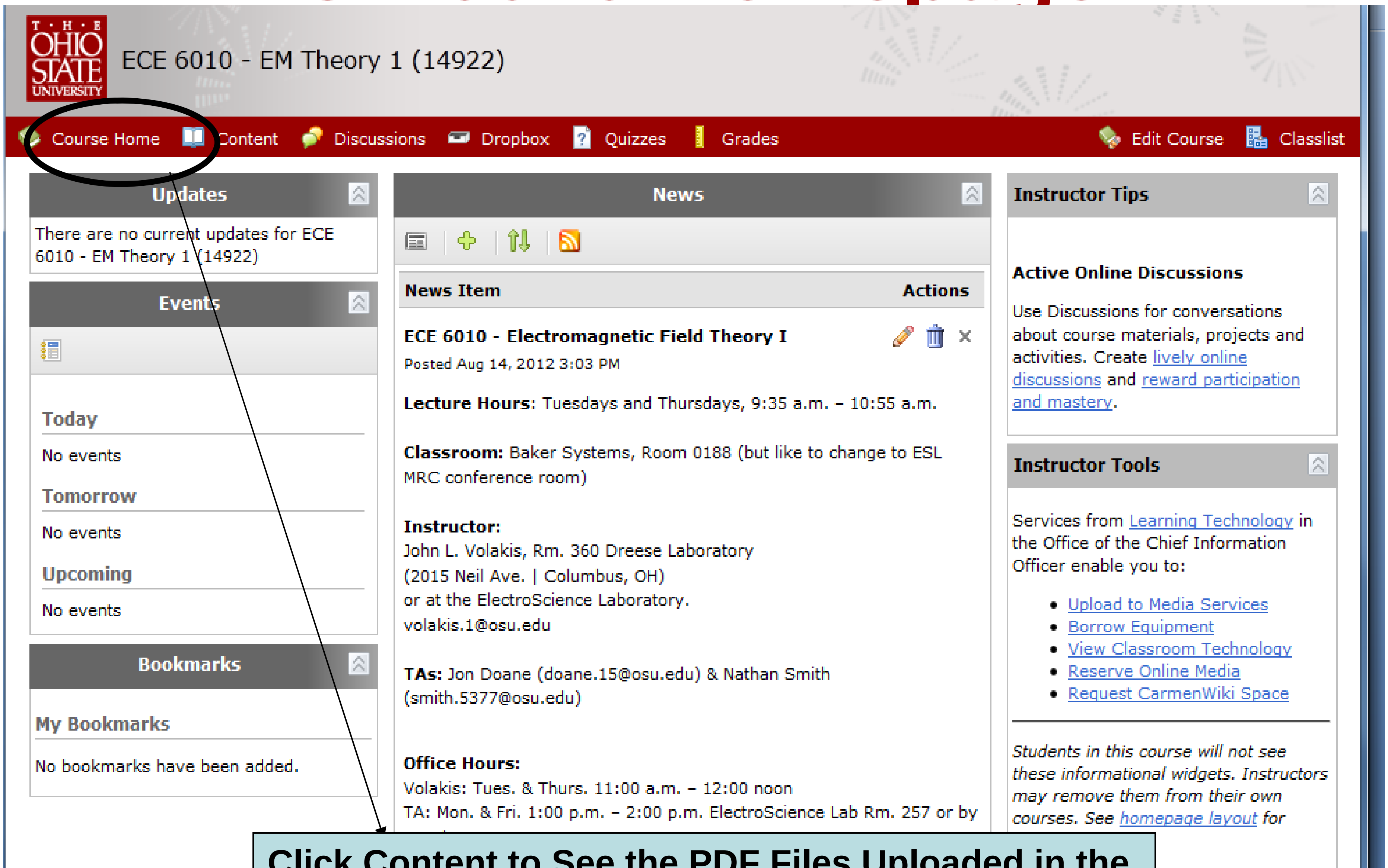
http://carmen.osu.edu

- Go to this web site
- Login using your Ohio State **name.1** username
- You will probably get a list of courses, select and click ECE 6010

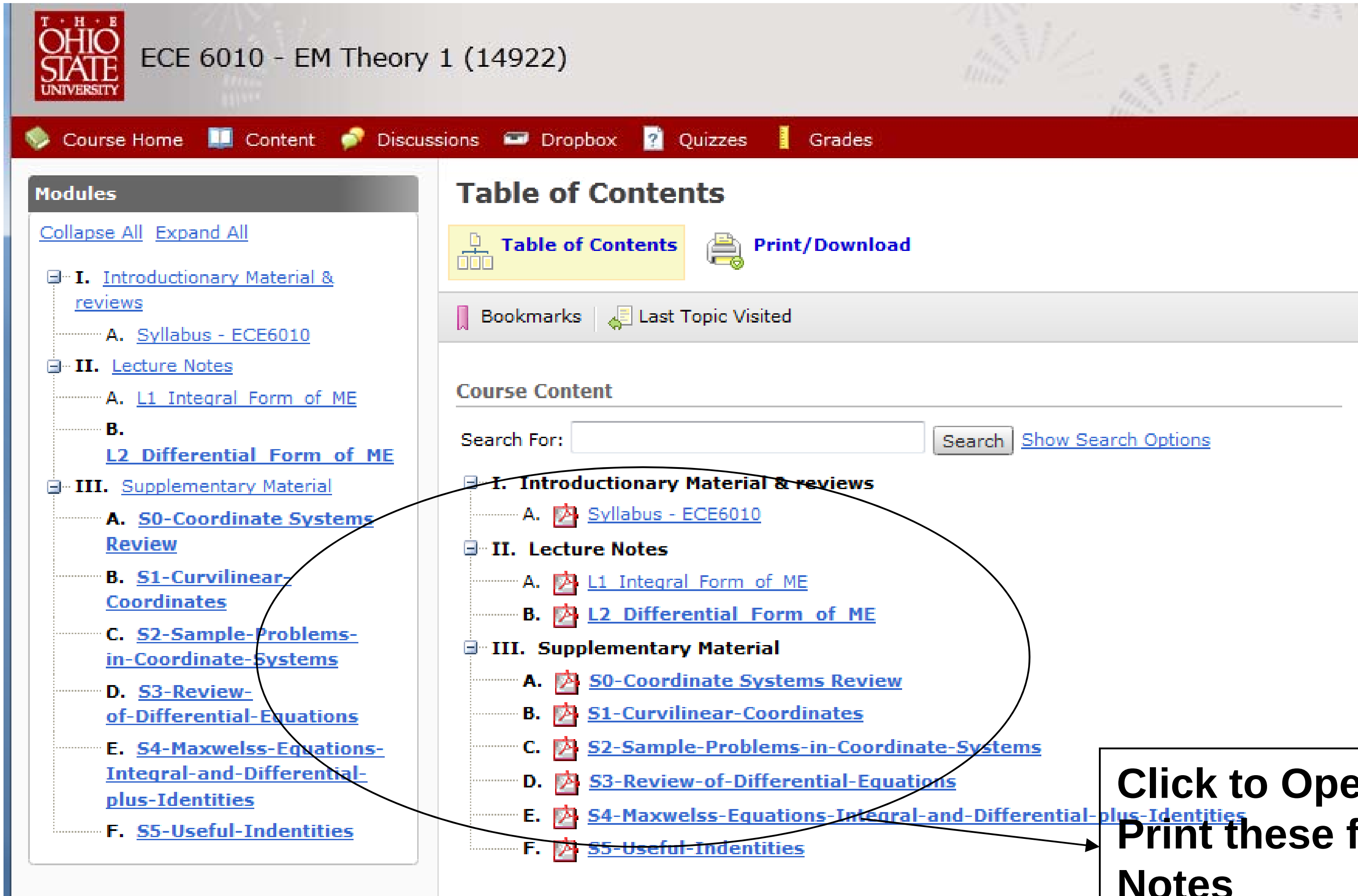


ECE 6010 Homepage



Click Content to See the PDF Files Uploaded in the Class Web Site

Current Course Content in Carmen



Click to Open and then Print these files/Lecture Notes

you will be told or emailed which notes you will need for the next lecture. Bring these notes with you since I will be using these on transparencies for lecturing

Office Hrs/Book/Help

Lecture Hours:	Tuesdays and Thursdays, 9:35 a.m. – 10:55 p.m.
Classroom:	Baker Systems, Room 0188 (but like to change to ESL MRC conference room)
Instructor:	John L. Volakis, Rm. 360 Dreese Laboratory (2015 Neil Ave. | Columbus, OH) or at the ElectroScience Laboratory. volakis.1@osu.edu
TAs:	Jon Doane (doane.15@osu.edu) & Nathan Smith (smith.5377@osu.edu)
Office Hours:	Volakis: Tues. & Thurs. 11:00 a.m. – 12:00 noon TA: Mon. & Fri. 1:00 p.m. – 2:00 p.m. ElectroScience Lab Rm. 257 or by appointment
Make-up Class:	**TBD**
Text:	C.A. Balanis, *Advanced Engineering Electromagnetics*, 2nd ed., J. Wiley and Sons, New York, NY, 2012 (Chapters 1-11, 14)

Lecture Notes will Be Placed on Carmen and will be complete Use Book for further reading

The great majority of the class lectures will be given as handouts; these handouts will be posted on the Web: https://carmen.osu.edu/. You are expected to print these notes and bring them to class. Lectures will mostly follow these handouts. Handout notes and homework assignments are expected to serve as a guideline for the covered material. The book covers the same material but will only serve as reference and will not be followed during lectures.

Homework

Approximately 8-10 homework sets will be given. Regardless of the day of assignment, homework is **due exactly one week after the date of assignment unless noted otherwise.** Delayed homeworks cause substantial inconvenience to the grader schedules. You must turn in homeworks by 5:00 p.m. the day they are due. **Place them in my faculty mailbox by 5:00 p.m. or under my office door, if not delivered in class on the due date.** Please do not use any other mailbox. If you deliver late homework, you run the risk of your homework not being graded. Most definitely, it will not be graded if the solution has already been posted on the web. Homework solutions will be posted on the web within approximately one week from assignment. If you choose to place your homework in my faculty mailbox (instead of delivering it in class), I cannot be responsible if your homework is lost.

Grading and Reference Books

Homework	30%	
Midterm	30%	(on a date to be announced –early Nov)
Final	40%	(Fri., Dec. 7, 2012, 10:00am – 11:45am.)
TOTAL	100%	

Books for reference. The following books are additional references for the course:

1. Harrington, *Time Harmonic Electromagnetic Fields*, 1961 (the classic first-year graduate EM book, a concise version of Balanis)
2. Collin, *Field Theory of Guided Waves*, 2nd ed., 1992 (excellent source for waves propagation in guided structures and related Green's functions)
3. Stratton, *Electromagnetic Theory*, McGraw-Hill, 1941 (a classic, most often referenced book in EM theory)
4. Cheng, *Fundamentals for Engineering Electromagnetics* (a popular basic undergrad textbook)
5. Ulaby, *Fundamentals of Applied Electromagnetics*

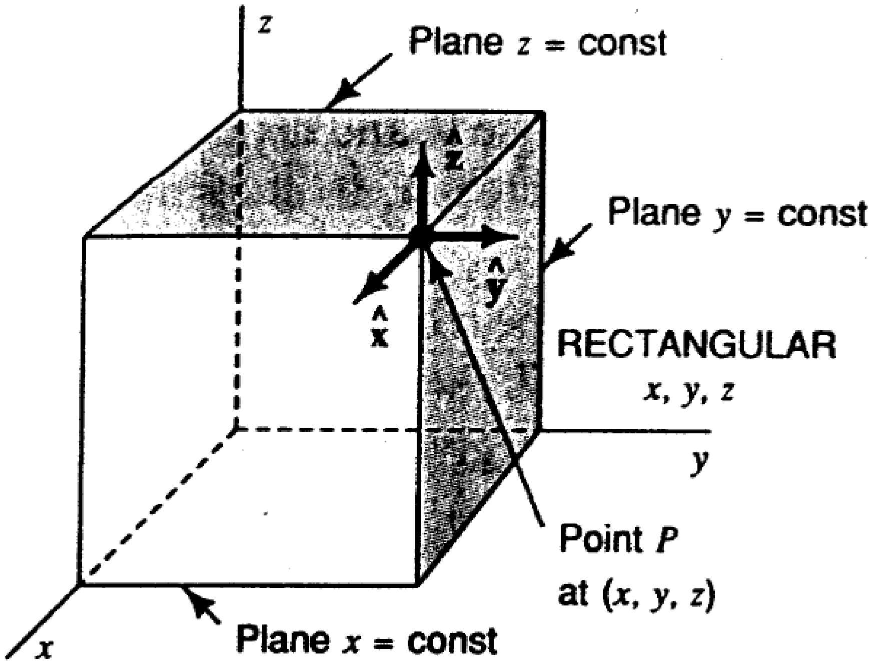
ECE 6010 COURSE OUTLINE

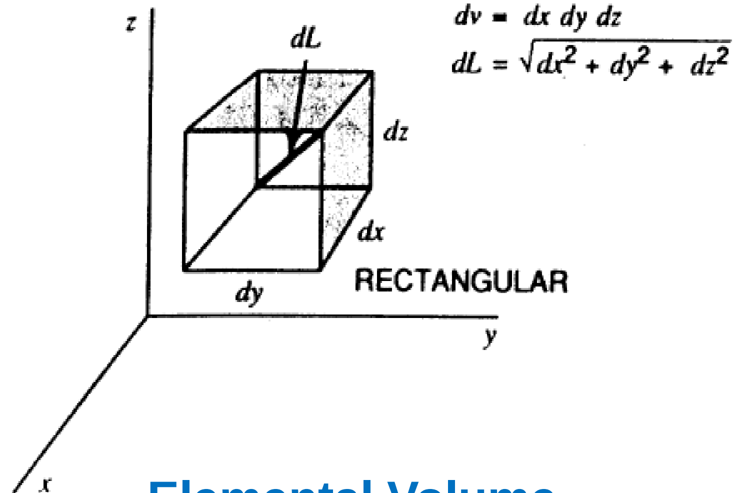
1. **Maxwell's Equations**
   (Balanis, Ch. 1, 2 and 3) and handouts
   Differential and integral forms; continuity equation; constitutive relations; media classification; Poynting theorem; time harmonic fields; complex Poynting vector, homogeneous wave equation and its solution.
2. **Plane Waves**
   (Balanis, Ch. 4 and 5) and handouts
3. **Field Representations and Wave Solution in Unbounded Space**
   (Balanis, Ch. 6 and 14) and handouts
   Electromagnetic sources, solutions of 2D and 3D inhomogeneous wave equation, vector and scalar potentials, Hertz potentials, potentials for static fields, near zone and far zone representations

4. **Waveguides and Guided Waves**
   (Balanis, Ch. 8) and handouts
   Parallel plate waveguide, grounded dielectric slab, rectangular waveguide and cavity.
5. **Green's Functions and Waveguide Excitation**
   (Balanis Ch. 14) and handouts
   Green's functions and their construction, sources in waveguides and cavities, Green's identities, integral equations.
6. **Cylindrical Waves and Structures**
   (Balanis, Ch. 9 and 11)
   Cylindrical wave functions, circular metallic guide, dielectric rod, cylindrical wave transformations, scattering by metallic cylinder.
7. **Spherical Waves**
   (Balanis, Ch. 10)
   Spherical waves and spherical cavity.
8. **Electromagnetic Theorems**
   (Balanis, Ch. 7)
   Duality, uniqueness, image theory, equivalence principle, reciprocity and reaction theorem, Babinet's principle.
9. **Applications to Radiation, Scattering and Propagation**
   Antennas, aperture radiation, scattering and radar cross section of metallic, dielectric modeling, waveguide perturbations.

Coordinate Systems

Rectangular



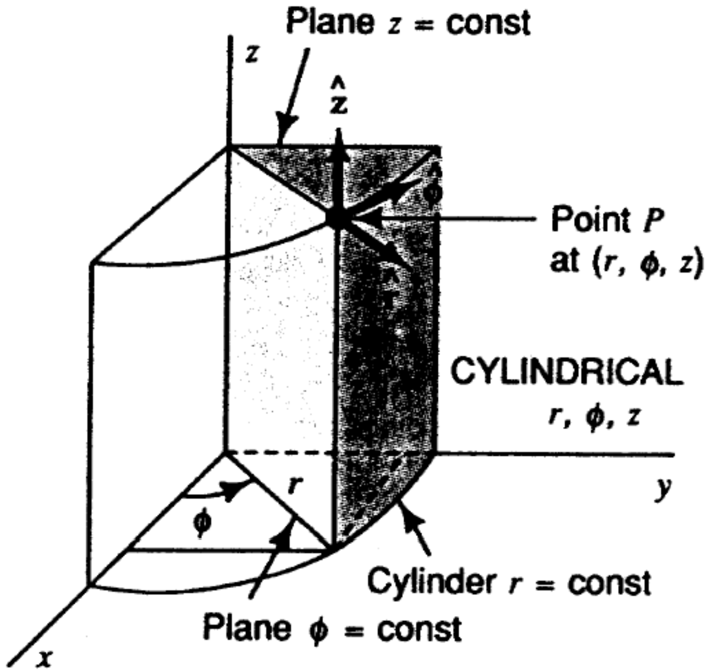


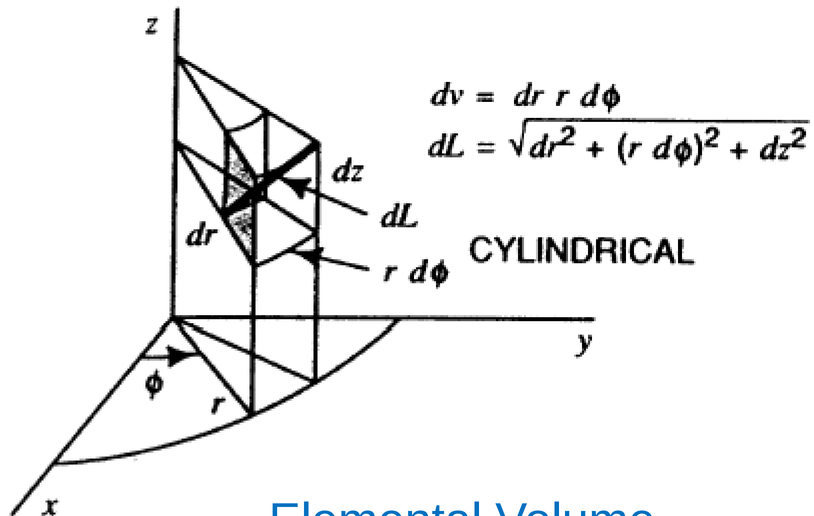
Elemental Volume

$$\vec{dL} = \hat{x}dx + \hat{y}dy + \hat{z}dz$$

$$\vec{ds} = \hat{x}dydz + \hat{y}dxdz + \hat{z}dxdy$$

Cylindrical



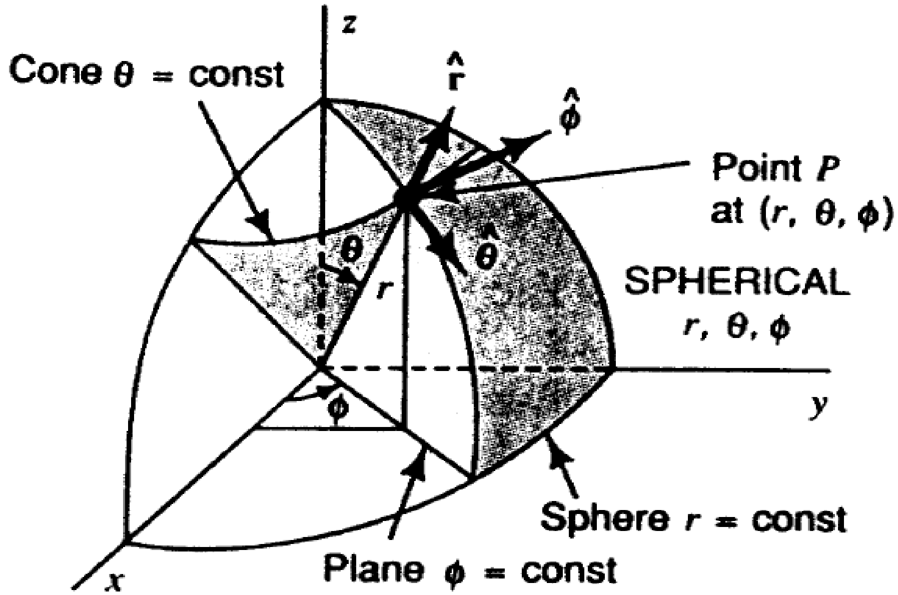


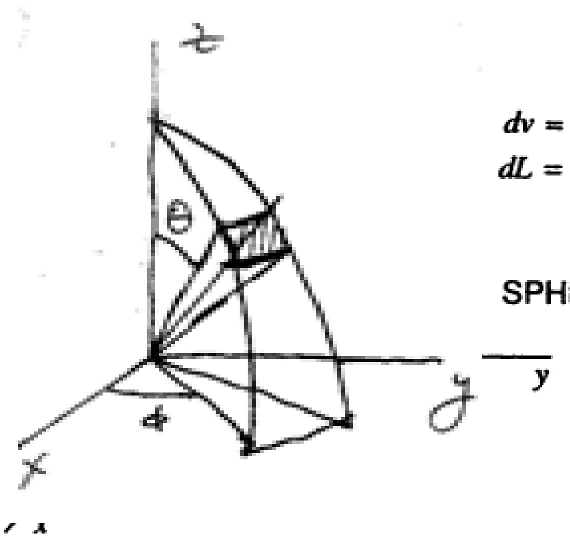
Elemental Volume

$$\vec{dL} = \hat{r}\,dr + \hat{\phi}\,r\,d\phi + \hat{z}\,dz$$

$$\vec{dS} = \hat{r}\,r\,d\phi\,dz + \hat{\phi}\,dr\,dz + \hat{z}\,r\,dr\,d\phi$$

Spherical





$$dv = dr\, r^2 \sin\theta\, d\theta\, d\phi$$

$$dL = \sqrt{dr^2 + (r\, d\theta)^2 + (r \sin\theta\, d\phi)^2}$$

SPHERICAL (c)

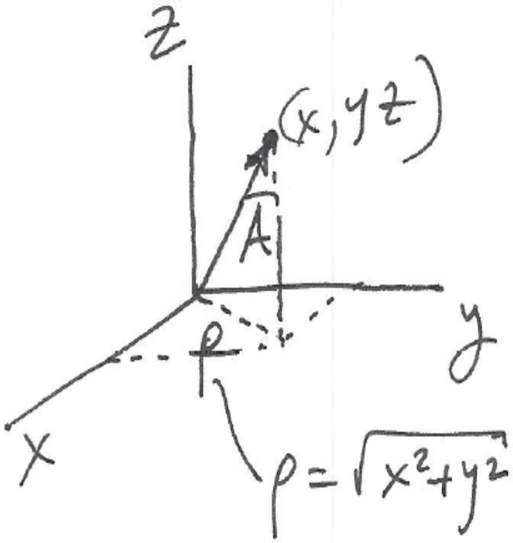
$$\vec{dL} = \hat{r}\,dr + \hat{\theta}\,r\,d\theta + \hat{\phi}\,r\sin\theta\,d\phi$$

$$\vec{dS} = \hat{r}\,r^2\sin\theta\,d\phi\,d\theta + \hat{\theta}\,r\sin\theta\,d\phi\,dr + \hat{\phi}\,r\,dr\,d\theta$$

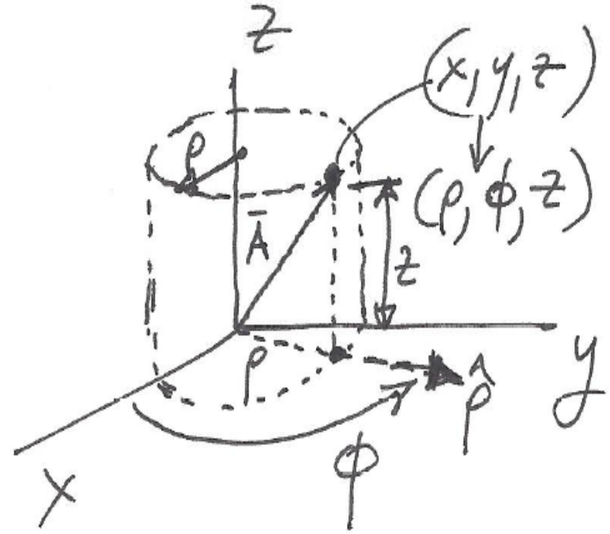
Elemental Volume

Vectors in Different Coordinate Systems

from rectangular to cylindrical

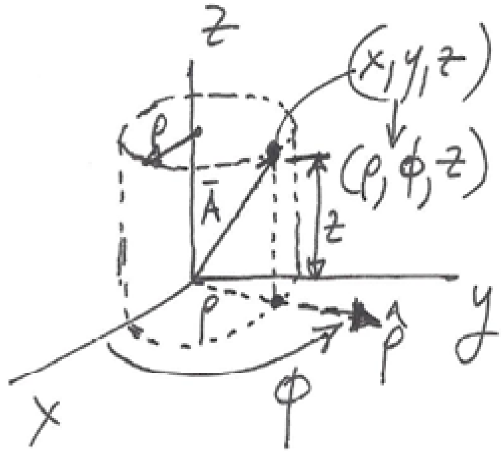


$$\bar{A} = \hat{x}A_x + \hat{y}A_y + \hat{z}A_z$$



$$\hat{\rho} = \hat{x}\cos\phi + \hat{y}\sin\phi$$

$$\bar{A} = \hat{\rho}A_\rho + \hat{\phi}A_\phi + \hat{z}A_z$$



$\hat{\rho} = \hat{x}\cos\phi + \hat{y}\sin\phi$

$\bar{A} = \hat{\rho}A_\rho + \hat{\phi}A_\phi + \hat{z}A_z$

$$A_\rho = \hat{\rho}\cdot\bar{A}$$
$$= (\hat{\rho}\cdot\hat{x})A_x + (\hat{\rho}\cdot\hat{y})A_z$$
$$= A_x\cos\phi + A_y\sin\phi$$

$$A_\phi = \hat{\phi}\cdot\bar{A} = (\hat{\phi}\cdot\hat{x})A_x + (\hat{\phi}\cdot\hat{y})A_y$$

$$\hat{\phi} = -\sin\phi\,\hat{x} + \cos\phi\,\hat{y}$$

since $\hat{\phi}\cdot\hat{x} = -\sin\phi$, $\hat{\phi}\cdot\hat{y} = \cos\phi$ (from Table)

Thus,

$$A_\phi = -\sin\phi A_x + \cos\phi A_y$$

Consequently

$$\boxed{\bar{A} = \hat{\rho}(A_x\cos\phi + A_y\sin\phi) + \hat{\phi}(-A_x\sin\phi + A_y\cos\phi) + \hat{z}A_z}$$

from Rectangular to Spherical

Show that

$$A_x = A_r \sin\theta\cos\phi + A_\theta \cos\theta\cos\phi - A_\phi \sin\phi$$

Solution:

$$\bar{A} = \hat{r} A_r + \hat{\phi} A_\phi + \hat{\theta} A_\theta$$

$$A_x = \hat{x}\cdot\bar{A} = (\hat{x}\cdot\hat{r})A_r + (\hat{x}\cdot\hat{\theta})A_\theta + (\hat{x}\cdot\hat{\phi})A_\phi$$

From Table,

$$\hat{x}\cdot\hat{r} = \sin\theta\cos\phi$$

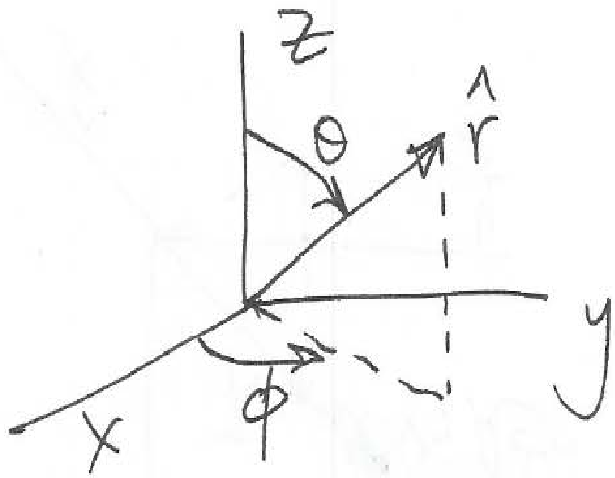
$$\hat{x}\cdot\hat{\theta} = \cos\theta\cos\phi$$

$$\hat{x}\cdot\hat{\phi} = -\sin\phi$$

Therefore,

$$A_x = \sin\theta\cos\phi\, A_r + \cos\theta\cos\phi\, A_\theta - \sin\phi\, A_\phi$$

Memorize this



$$\hat{r} = \hat{x}\cos\phi\sin\theta + \hat{y}\sin\phi\sin\theta + \hat{z}\cos\theta.$$

Memorize this one!

Table for coordinate transformations

Dot products of unit vectors in three coordinate systems

	$\cdot$	Rectangular $\hat{\mathbf{x}}$	$\hat{\mathbf{y}}$	$\hat{\mathbf{z}}$	Cylindrical $\hat{\mathbf{r}}$	$\hat{\boldsymbol{\phi}}$	$\hat{\mathbf{z}}$	Spherical $\hat{\mathbf{r}}$	$\hat{\boldsymbol{\theta}}$	$\hat{\boldsymbol{\phi}}$
Rectangular	$\hat{\mathbf{x}}$	1	0	0	$\cos\phi$	$-\sin\phi$	0	$\sin\theta\cos\phi$	$\cos\theta\cos\phi$	$-\sin\phi$
	$\hat{\mathbf{y}}$	0	1	0	$\sin\phi$	$\cos\phi$	0	$\sin\theta\sin\phi$	$\cos\theta\sin\phi$	$\cos\phi$
	$\hat{\mathbf{z}}$	0	0	1	0	0	1	$\cos\theta$	$-\sin\theta$	0
Cylindrical	$\hat{\mathbf{r}}$	$\cos\phi$	$\sin\phi$	0	1	0	0	$\sin\theta$	$\cos\theta$	0
	$\hat{\boldsymbol{\phi}}$	$-\sin\phi$	$\cos\phi$	0	0	1	0	0	0	1
	$\hat{\mathbf{z}}$	0	0	1	0	0	1	$\cos\theta$	$-\sin\theta$	0
Spherical	$\hat{\mathbf{r}}$	$\sin\theta\cos\phi$	$\sin\theta\sin\phi$	$\cos\theta$	$\sin\theta$	0	$\cos\theta$	1	0	0
	$\hat{\boldsymbol{\theta}}$	$\cos\theta\cos\phi$	$\cos\theta\sin\phi$	$-\sin\theta$	$\cos\theta$	0	$-\sin\theta$	0	1	0
	$\hat{\boldsymbol{\phi}}$	$-\sin\phi$	$\cos\phi$	0	0	1	0	0	0	1

Note that the unit vectors $\hat{\mathbf{r}}$ in the cylindrical and spherical systems are *not* the same. Example:

$$\hat{\mathbf{r}}\cdot\hat{\mathbf{x}} = \sin\theta\cos\phi$$

$$\hat{\mathbf{r}}\cdot\hat{\mathbf{y}} = \sin\theta\sin\phi$$

$$\hat{\mathbf{r}}\cdot\hat{\mathbf{z}} = \cos\theta$$

Using the Coordinate Transformation Table

		Rectangular			Cylindrical			Spherical		
	$\cdot$	$\hat{x}$	$\hat{y}$	$\hat{z}$	$\hat{\rho}$	$\hat{\phi}$	$\hat{z}$	$\hat{r}$	$\hat{\theta}$	$\hat{\phi}$
Rectangular	$\hat{x}$	1	0	0	$\cos\phi$	$-\sin\phi$	0	$\sin\theta\cos\phi$	$\cos\theta\cos\phi$	$-\sin\phi$
	$\hat{y}$	0	1	0	$\sin\phi$	$\cos\phi$	0	$\sin\theta\sin\phi$	$\cos\theta\sin\phi$	$\cos\phi$
	$\hat{z}$	0	0	1	0	0	1	$\cos\theta$	$-\sin\theta$	0
Cylindrical	$\hat{\rho}$	$\cos\phi$	$\sin\phi$	0	1	0	0	$\sin\theta$	$\cos\theta$	0
	$\hat{\phi}$	$-\sin\phi$	$\cos\phi$	0	0	1	0	0	0	1
	$\hat{z}$	0	0	1	0	0	1	$\cos\theta$	$-\sin\theta$	0
Spherical	$\hat{r}$	$\sin\theta\cos\phi$	$\sin\theta\sin\phi$	$\cos\theta$	$\sin\theta$	0	$\cos\theta$	1	0	0
	$\hat{\theta}$	$\cos\theta\cos\phi$	$\cos\theta\sin\phi$	$-\sin\theta$	$\cos\theta$	0	$-\sin\theta$	0	1	0
	$\hat{\phi}$	$-\sin\phi$	$\cos\phi$	0	0	1	0	0	0	1

Note that the unit vectors $\hat{r}$ in the cylindrical and spherical systems are *not* the same. Example:

Examples

$$\hat{r} = \hat{x}\sin\theta\cos\phi + \hat{y}\sin\theta\sin\phi + \hat{z}\cos\theta$$

$$\hat{\rho} = \hat{x}\cos\phi + \hat{y}\sin\phi$$

$$\hat{x} = \hat{\rho}\cos\phi - \hat{\phi}\sin\phi$$

$$\hat{r}\cdot\hat{x} = \sin\theta\cos\phi$$

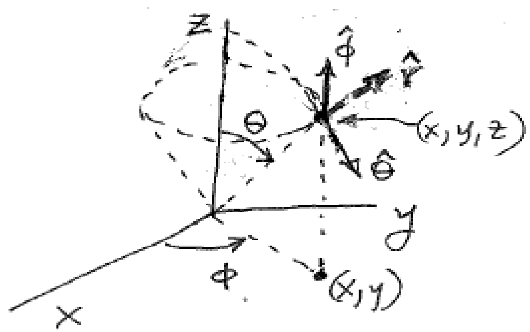
$$\hat{r}\cdot\hat{y} = \sin\theta\sin\phi$$

$$\hat{r}\cdot\hat{z} = \cos\theta$$

$$\hat{\rho} = \hat{r}\sin\theta + \hat{\theta}\cos\theta$$

$$\hat{z} = \hat{r}\cos\theta - \hat{\theta}\sin\theta.$$

Example uses of the table



$$\bar{E} = \nabla(\nabla \cdot \bar{\pi}_e) + k^2 \bar{\pi}_e \quad , k^2 = \omega^2 \mu \epsilon$$

$$\bar{H} = j\omega\epsilon \nabla \times \bar{\pi}_e$$

ω = frequency , ϵ = permittivity
μ = permeability

k = propagation Constant

$$\bar{\pi}_e = A \frac{e^{-jkr}}{4\pi r} \hat{z} \quad , \quad r = \sqrt{x^2 + y^2 + z^2}$$

A = Constant

- Carry out the required operations to find an explicit expression for $\bar{H}$ in Cartesian coordinates:

- Find the spherical components of $\bar{H}$.

* Cartesian Coordinates :

Write $\bar{H}$ in terms of x, y, and z:

$$\bar{H} = j\omega\epsilon\, \nabla\times\left(A\,\frac{e^{-jkr}}{4\pi r}\,\hat{z}\right) = j\omega\epsilon\,\nabla\times\left(A\,\frac{e^{-jk\sqrt{x^2+y^2+z^2}}}{4\pi\sqrt{x^2+y^2+z^2}}\,\hat{z}\right)$$

$\nabla\times\bar{H}$ in Cartesian Coordinates is:

$$\nabla\times\bar{H} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ \cancel{H_x}^{\,0} & \cancel{H_y}^{\,0} & H_z \end{vmatrix} = \hat{x}\left(\frac{\partial H_z}{\partial y} - \cancel{\frac{\partial H_y}{\partial z}}^{\,0}\right) - \hat{y}\left(\frac{\partial H_z}{\partial x} - \cancel{\frac{\partial H_x}{\partial z}}^{\,0}\right) + \hat{z}\left(\cancel{\frac{\partial H_y}{\partial x}}^{\,0} - \cancel{\frac{\partial H_x}{\partial y}}^{\,0}\right)$$

$$= \hat{x}\frac{\partial H_z}{\partial y} - \hat{y}\frac{\partial H_z}{\partial x}$$

Noting that

$$\frac{\partial}{\partial x}\left(\frac{e^{-jkr}}{r}\right) = \frac{\partial}{\partial r}\left(\frac{e^{-jkr}}{r}\right)\frac{\partial r}{\partial x} = -\frac{e^{-jkr}}{r^3}(1+jkr)\,x, \quad r = \sqrt{x^2+y^2+z^2}$$

$$\frac{\partial}{\partial y}\left(\frac{e^{-jkr}}{r}\right) = \cdots$$

$$\nabla H_z = \hat{r}\frac{\partial H_z}{\partial r} = j\omega\varepsilon A\left[-(1+jkr)\frac{e^{-jkr}}{4\pi r}\right]$$

↑ only function of r

$$\frac{\partial H_z}{\partial y} = \frac{\partial H_z}{\partial r}\frac{\partial r}{\partial y} = \nabla H_z \cdot \hat{y}$$

$$\bar{H} = \hat{x}\frac{\partial H_z}{\partial y} - \hat{y}\frac{\partial H_z}{\partial x}$$

$$\frac{\partial H_z}{\partial x} = \nabla H_z \cdot \hat{x}$$

$$-A\frac{e^{-jkr}}{r^3}(1+jkr)y\,\hat{x} + A\frac{e^{-jkr}}{r^3}(1+jkr)x\,\hat{y}$$

$$\boxed{\bar{H} = \frac{j\omega\epsilon A}{4\pi}\frac{e^{-jkr}}{r^3}(1+jkr)(-y\hat{x} + x\hat{y})}$$

Spherical Coordinates

Start with the cylindrical expression and replace all rectangular coordinates:

$$\boxed{\bar{H} = \frac{j\omega\epsilon A}{4\pi}\,\frac{e^{-jkr}}{r^3}\,(1+jkr)\,(-y\,\hat{x} + x\,\hat{y})}$$

we already know that: $y = r\sin\theta\sin\varphi$

$x = r\sin\theta\cos\varphi$

<u>Note:</u>

$$\hat{r} = \hat{x}\cos\phi\sin\theta + \hat{y}\sin\phi\sin\theta + \hat{z}\cos\theta$$

(see table)

and

$$\hat{x} = \hat{r}\,\overbrace{\boxed{\sin\theta\cos\varphi}}^{\hat{r}\cdot\hat{x}} + \hat{\theta}\cos\theta\cos\varphi - \hat{\varphi}\sin\varphi$$

$$\hat{y} = \hat{r}\sin\theta\sin\varphi + \hat{\theta}\,\underbrace{\cos\theta\sin\varphi}_{\hat{y}\cdot\hat{\theta}} + \hat{\varphi}\cos\varphi$$

(refer to the table)

after some algebraic manipulation :

$$\boxed{\bar{H} = j\omega\epsilon \frac{A}{4\pi r^2} \sin\theta \, e^{-jkr} (1 + jkr) \, \hat{\varphi}}$$

$$\bar{H} = j\omega\epsilon \nabla \times \bar{\pi}_e = j\omega\epsilon \; \nabla \times \left(\frac{A}{4\pi r} e^{-jkr} \hat{z} \right)$$

refer to the table

$$= j\omega\epsilon \; \nabla \times \left[\left(\frac{A \, e^{-jkr}}{4\pi r} \right) \left(\hat{r} \cos\theta - \hat{\theta} \sin\theta \right) \right]$$

$$\nabla \times \bar{H} = \begin{vmatrix} \hat{r} & r\hat{\theta} & r\sin\theta\hat{\varphi} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial \varphi} \\ H_r & r H_\theta & r\sin\theta H_\varphi \end{vmatrix} \times \frac{1}{r^2 \sin\theta}$$