The Basic Physics of ELECTROMAGNETICS WITHOUT ABSTRACT MATHEMATICS

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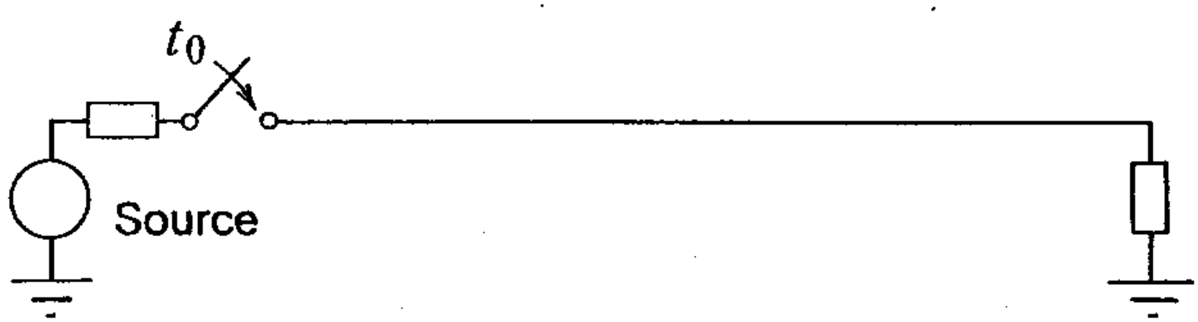
- THE CAUSES OF ELECTROMAGNETIC FIELDS ARE ELECTRIC CURRENTS

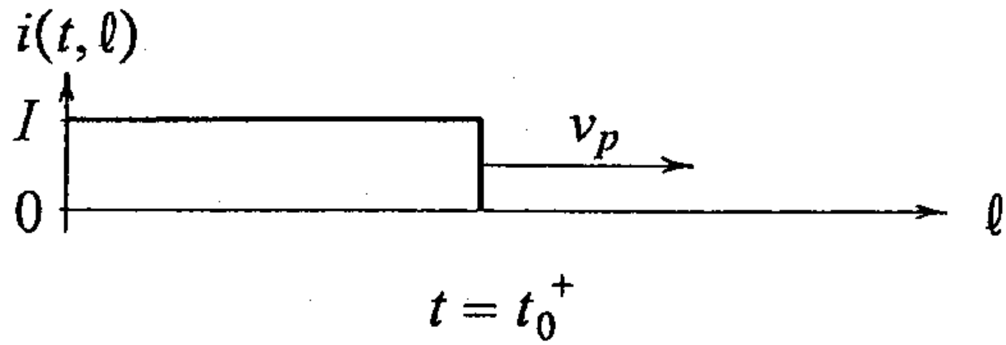
- A TIME-VARYING ELECTRIC CURRENT DIFFERS IN VALUE FROM ONE POINT TO ANOTHER ALONG ITS PATH, AS A RESULT OF PROPAGATION

- THEREFORE, EVERY POINT ALONG A TIME-VARYING ELECTRIC CURRENT'S PATH IS A FUNDAMENTAL SOURCE OF ELECTROMAGNETIC FIELDS

Point-to-Point Circuit-Current Variations



DC Source



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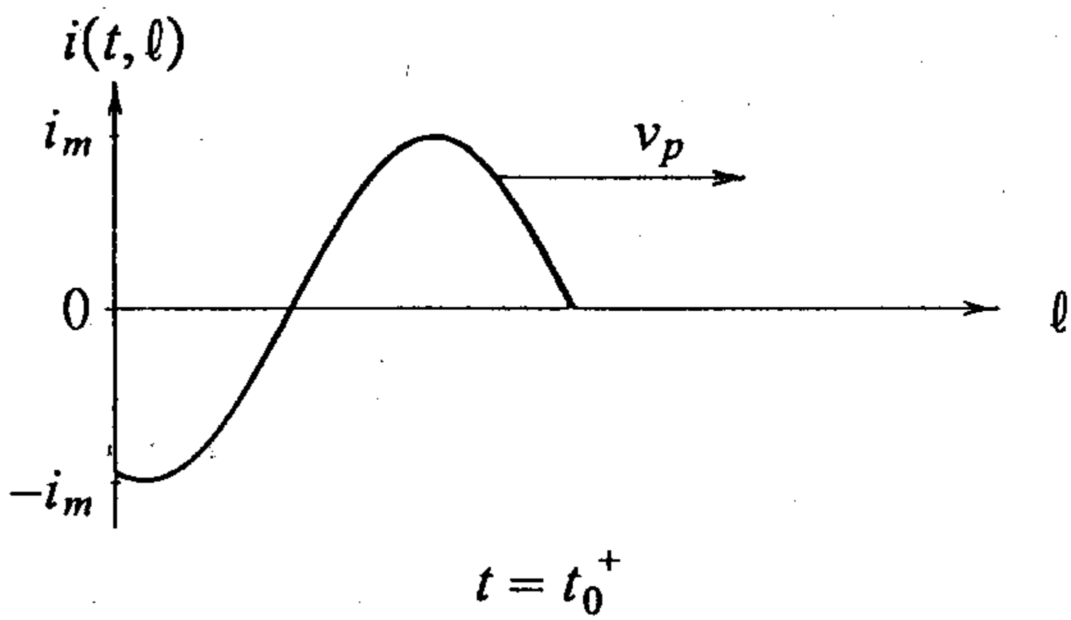
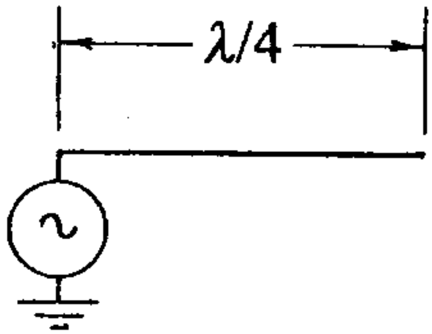
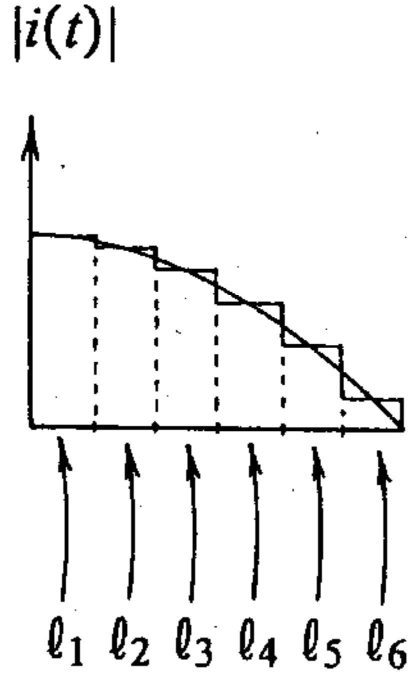
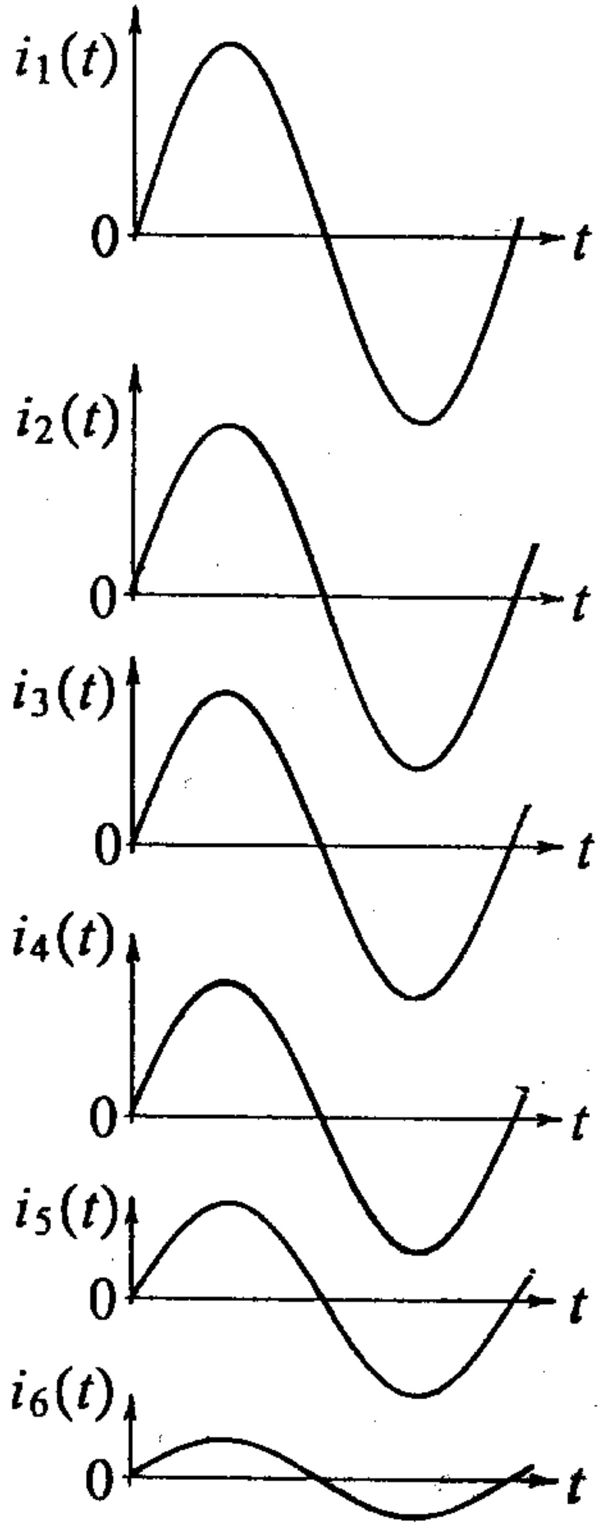


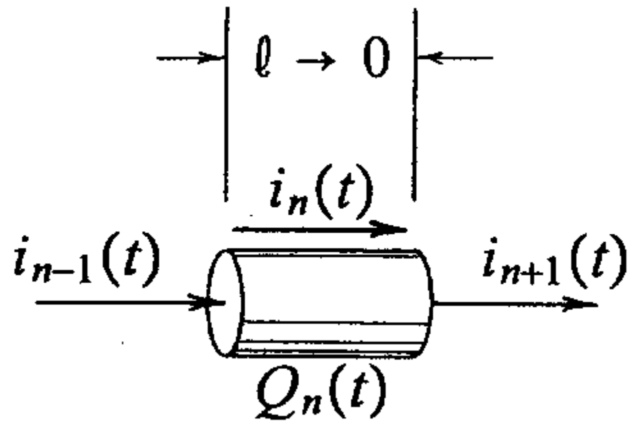
Point Current Variations: $\lambda/4$ Monopole







THE CHARGE ELEMENT



Point Current:

$$\ell i_n(t) = \ell \frac{dq_n(t)}{dt} = \frac{d}{dt}[\ell q_n(t)]$$

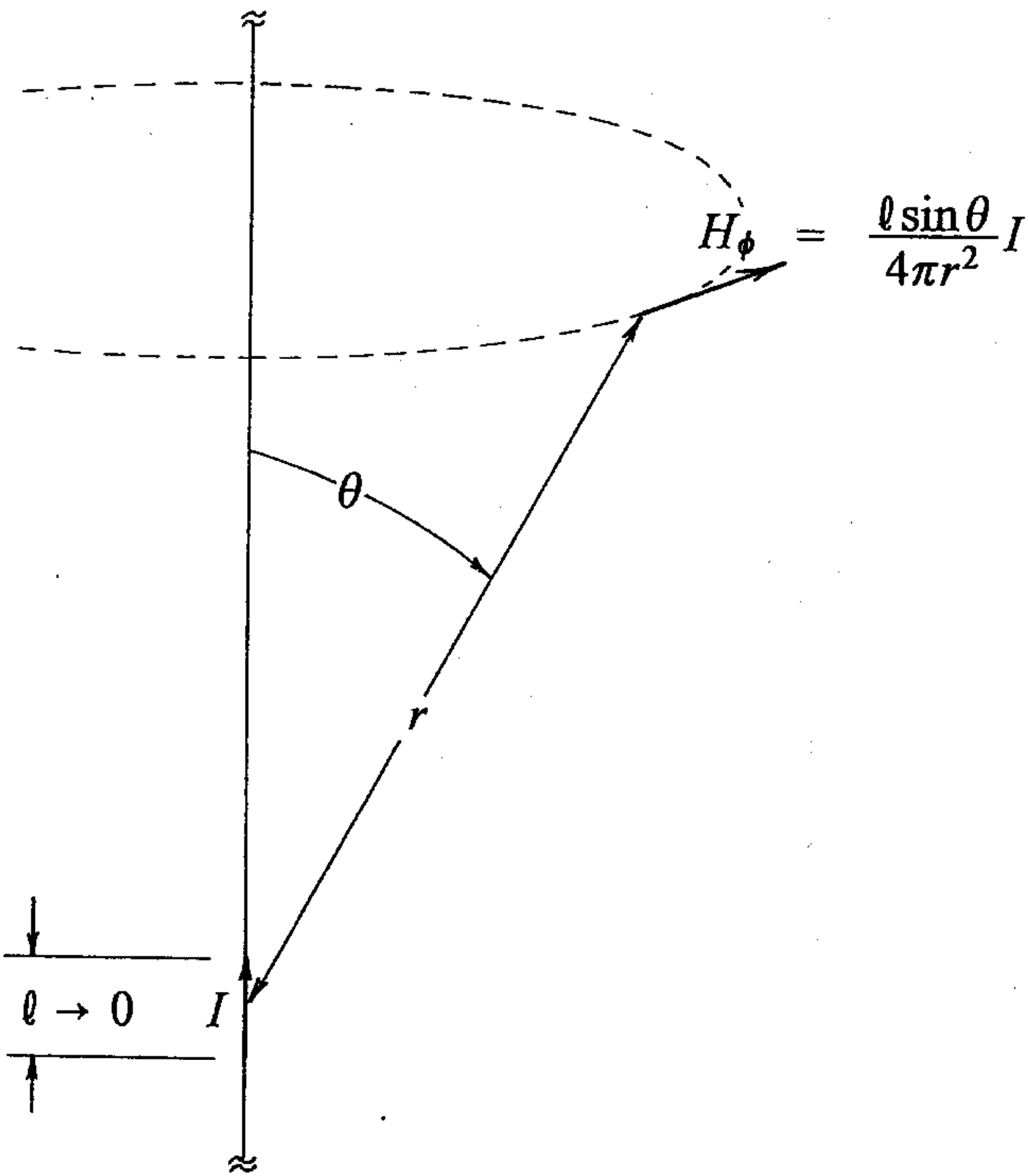
$$= q_n(t)\frac{d\ell}{dt} = q_n(t)\bar{v}$$

Point Charge:

$$Q_n(t) = \int_0^t [i_{n-1}(t) - i_{n+1}(t)]dt$$

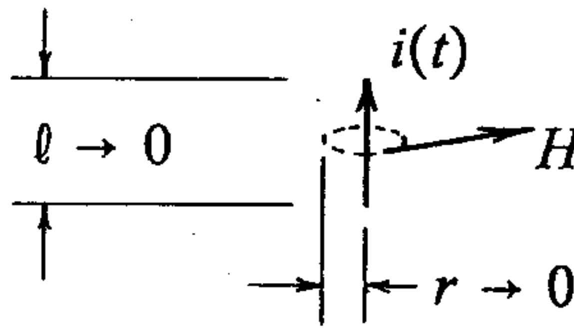
Point Current Fields

The Biot-Savart Law:



Point Current Fields

Also, for $r \to 0$, the Biot-Savart law implies



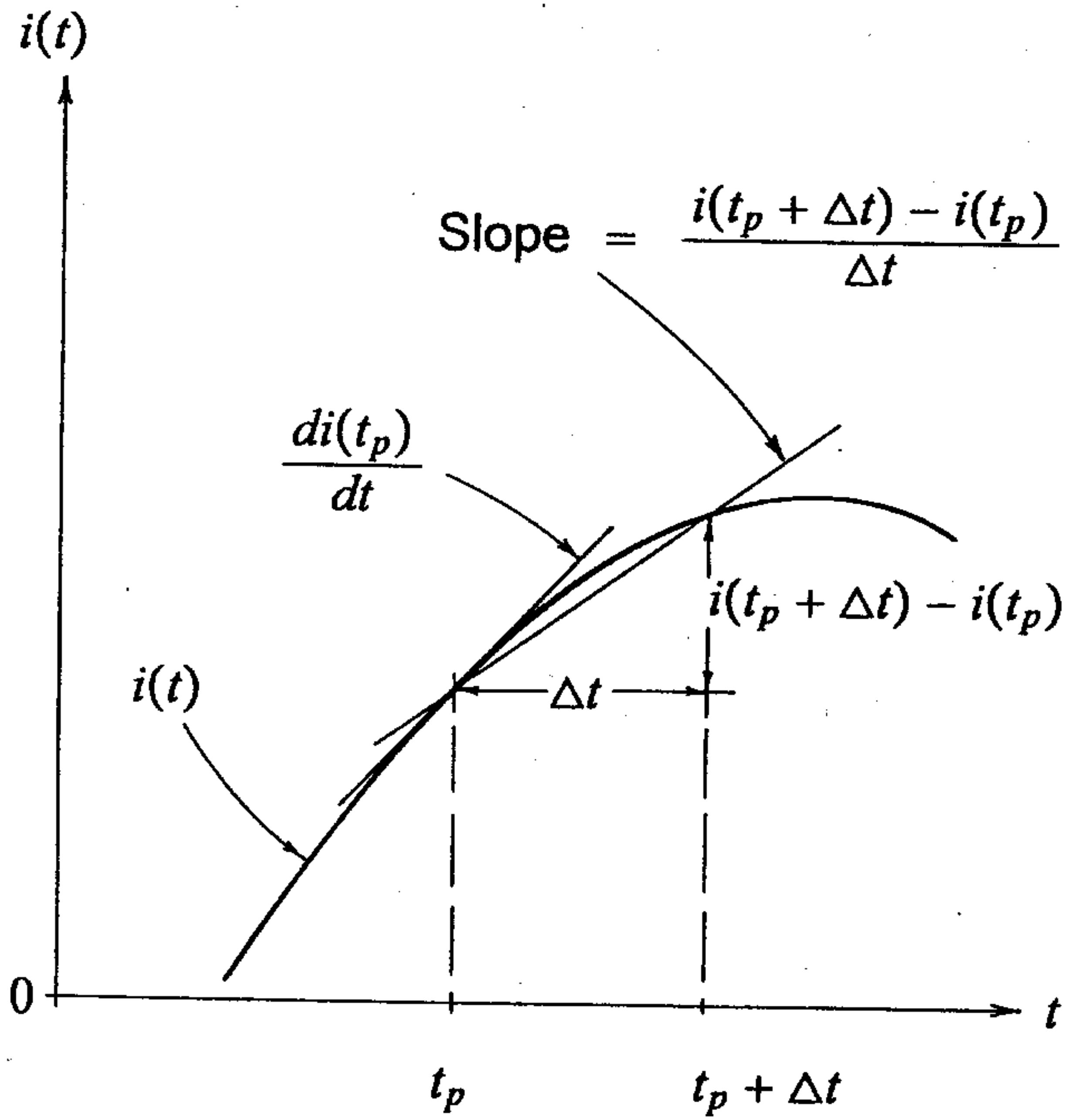
$$H_\phi(t) = \frac{\ell \sin\theta}{4\pi r^2} i(t)$$

And, with a propagation rate equal to c, the speed of light, it would seem that, if $r >> 0$

$$H_\phi(t) = \frac{\ell \sin\theta}{4\pi r^2} i(t - r/c)$$

BUT, if a current is time-varying, $di(t)/dt \neq 0$, so charge flow increases and decreases. And that causes *radiation*. SO, when $r >> 0$, there must be a second component of $H_\phi(t)$ that is proportional to $1/r$, and to $di(t - r/c)/dt$.

The Derivative of $i(t_p)$ and Its Definition



Point Current Fields

The derivative of $i(t)$ at t is defined to be

$$\frac{di(t)}{dt} \equiv \lim_{\Delta t \to 0}\left[\frac{i(t+\Delta t) - i(t)}{\Delta t}\right]$$

So, the derivative of $i(t)$ when $t = t - r/c$ is

$$\frac{di(t-r/c)}{dt} \equiv \lim_{\Delta t \to 0}\left[\frac{i(t-r/c+\Delta t) - i(t-r/c)}{\Delta t}\right]$$

And, replacing Δt with $r/c \to 0$, that becomes

$$\frac{di(t-r/c)}{dt} = \frac{i(t) - i(t-r/c)}{r/c}$$

which says, so long as $r/c \to 0$, or $r \to 0$,

$$i(t) = i(t-r/c) + \frac{r}{c}\frac{di(t-r/c)}{dt}$$

Point Current Fields

So, it is clear that so long as $r \to 0$,

$$H_\phi(t) = \frac{\ell \sin\theta}{4\pi r^2} i(t)$$

$$= \frac{\ell \sin\theta}{4\pi r^2}\left[i(t - r/c) + \frac{r}{c}\frac{di(t - r/c)}{dt} \right]$$

However, there is not one reason – physical, or mathematical – for the description of $H_\phi(t)$ to change as further propagation occurs and makes $r >> 0$.

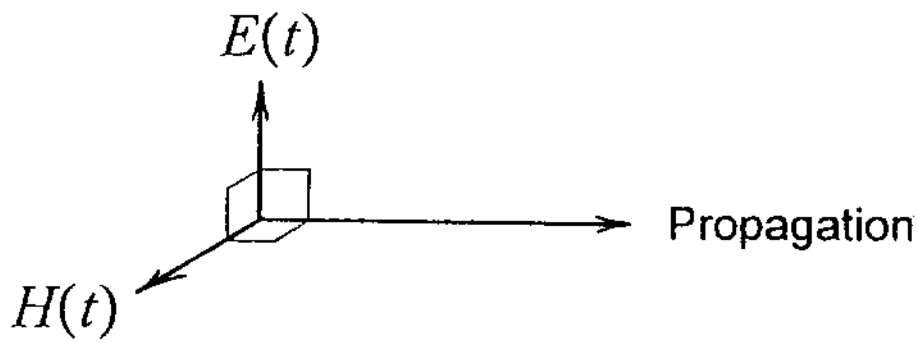
In other words, <u>for all r from 0 to ∞</u>,

$$H_\phi(t) = \frac{\ell \sin\theta}{4\pi r^2}\left[i(t - r/c) + \frac{r}{c}\frac{di(t - r/c)}{dt} \right]$$

Point Current Fields

Poynting's theorem says a radiated H-field will always be accompanied by a radiated E-field. And, those fields will be related to each other as follows:

(a)



The velocity of propagation in free space is

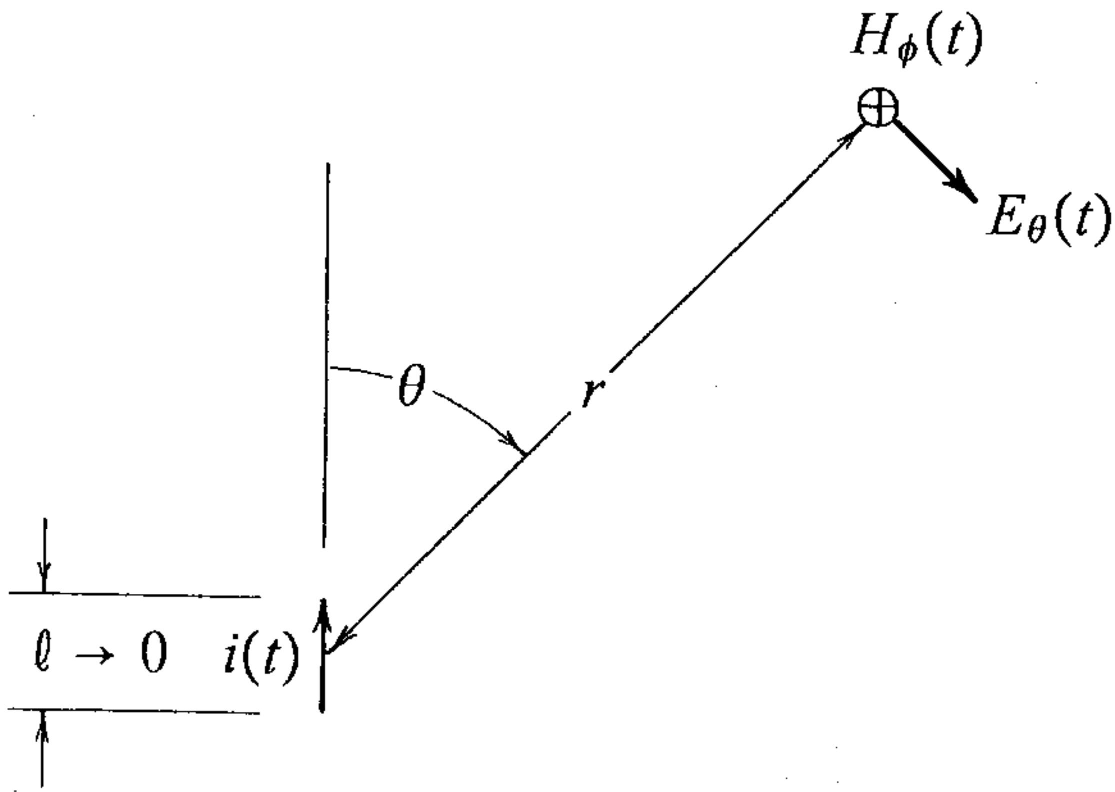
$$c = 3 \times 10^8 \quad \text{meters/second}$$

(b)

$$E(t) = Z_0 H(t)$$

where $Z_0 = 120\pi$ ohms, the characteristic impedance of free space.

THE FIELDS OF A POINT CURRENT

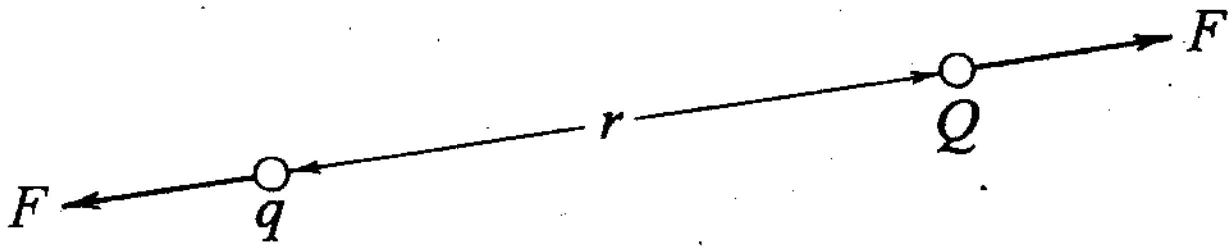


$$H_\phi(t) = \frac{\ell \sin\theta}{4\pi r^2}\left[i(t - r/c) + \frac{r}{c}\frac{\partial i(t - r/c)}{\partial t} \right]$$

$$E_\theta(t) = Z_0 \frac{\ell \sin\theta}{4\pi r^2}\left[\frac{r}{c}\frac{\partial i(t - r/c)}{\partial t} \right]$$

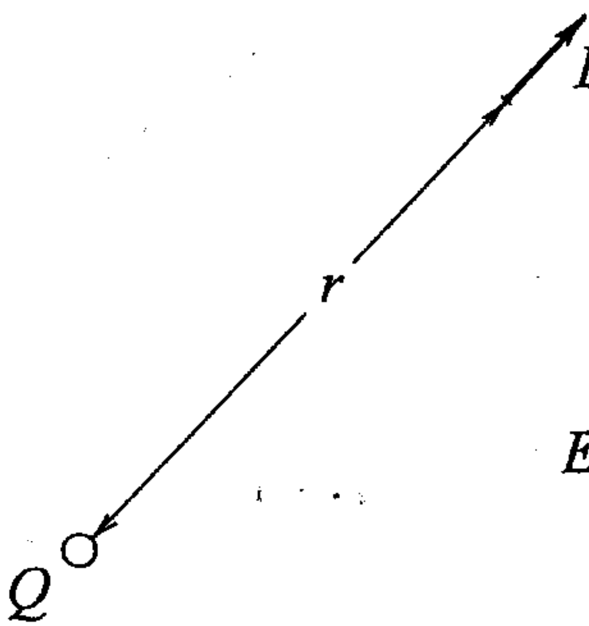
Point Charge Fields

Coulomb's Law:



$$F = \frac{1}{\varepsilon_0}\frac{qQ}{4\pi r^2} = Z_0 c\frac{qQ}{4\pi r^2}$$

And, the E-field of Q is



$$E_r = \frac{F}{q} \quad \frac{\text{newtons}}{\text{coulomb}}$$

Or,

$$E_r = Z_0 c\frac{Q}{4\pi r^2} \quad \frac{\text{volts}}{\text{meter}}$$

Point Charge Fields

So, for $r \to 0$, the time-varying point charge $Q_n(t)$ has the E-field

$$E_r(t) = \frac{Z_0 c}{4\pi r^2} Q_n(t)$$

where

$$Q_n(t) = \int [i_{n-1}(t) - i_{n+1}(t)] dt$$

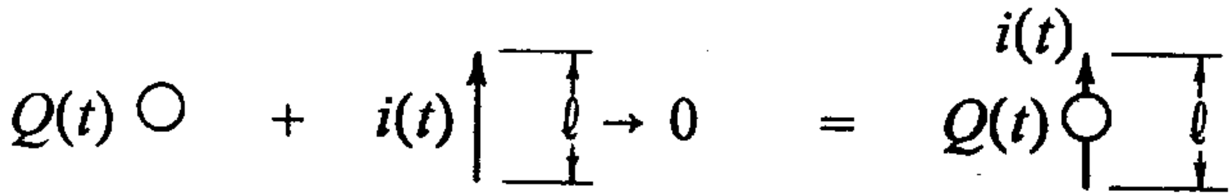
BUT, as with $H_\phi(t)$ and $i(t)$, if $r >> 0$, then

$$Q_n(t) \leftarrow Q_n(t - r/c) + \frac{r}{c} \frac{\partial Q_n(t - r/c)}{\partial t}$$

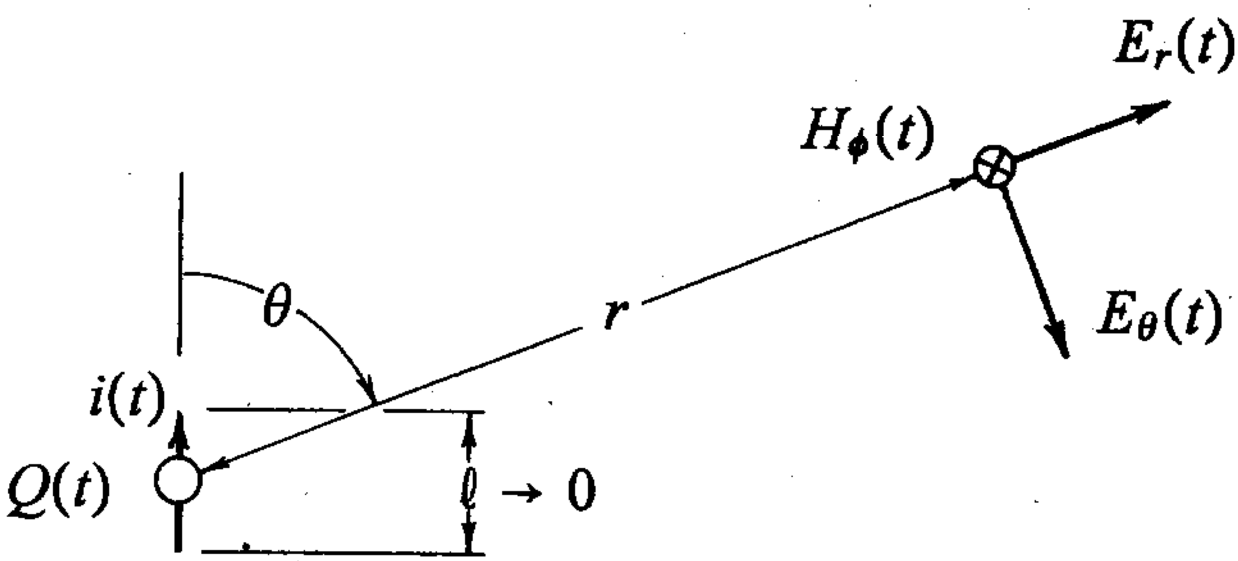
and, <u>for all r from 0 to ∞</u>,

$$E_r(t) = \frac{Z_0 c}{4\pi r^2} \left[Q_n(t - r/c) + \frac{r}{c} \frac{\partial Q_n(t - r/c)}{\partial t} \right]$$

THE CHARGE ELEMENT



AND ITS FIELDS



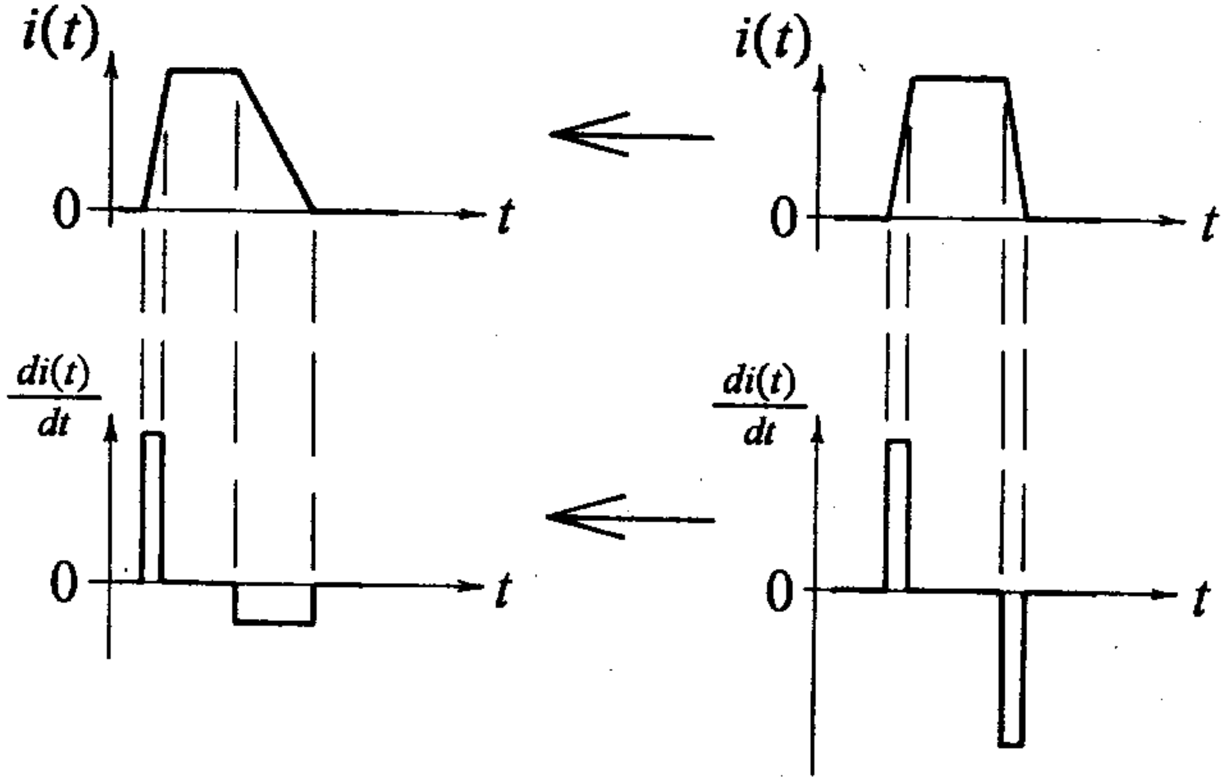
$$E_r(t) = \frac{Z_0 c}{4\pi r^2}\left[Q(t - r/c) + \frac{r}{c}\frac{\partial Q(t - r/c)}{\partial t} \right]$$

$$H_\phi(t) = \frac{\ell \sin\theta}{4\pi r^2}\left[i(t - r/c) + \frac{r}{c}\frac{\partial i(t - r/c)}{\partial t} \right]$$

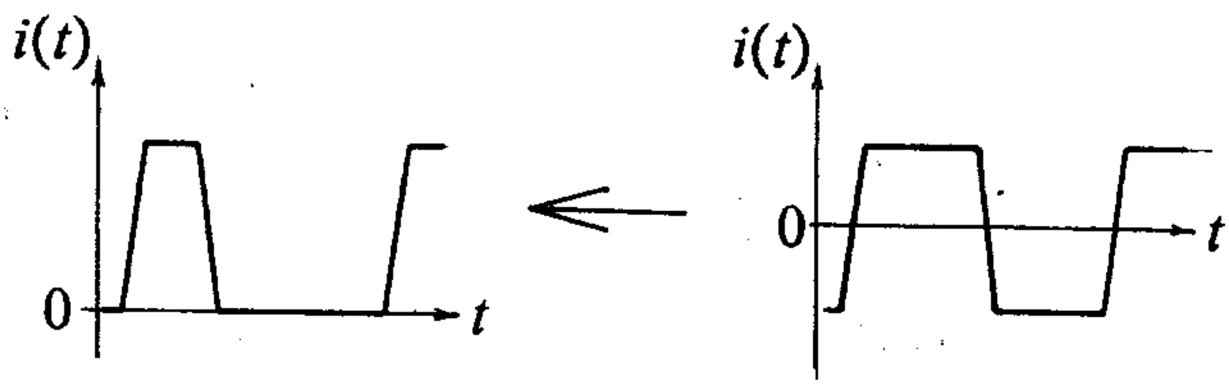
$$E_\theta(t) = Z_0 \frac{\ell \sin\theta}{4\pi r^2}\left[\frac{r}{c}\frac{\partial i(t - r/c)}{\partial t} \right]$$

Example: Minimizing Clock-Pulse EMI

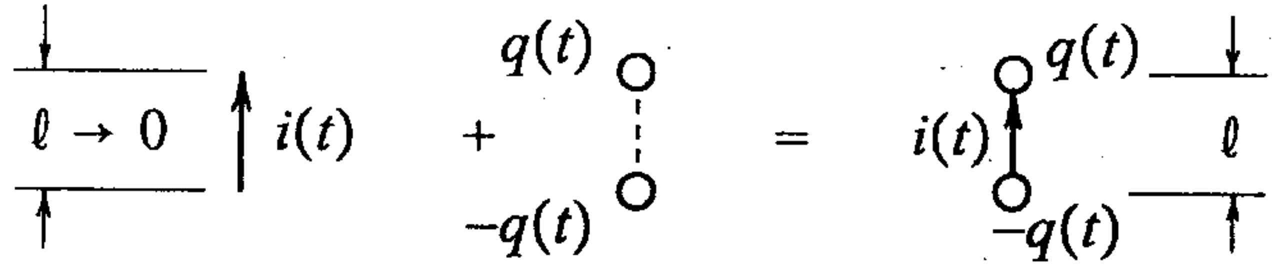
(1) Equalize the clock current rise and fall times to minimize radiated fields.



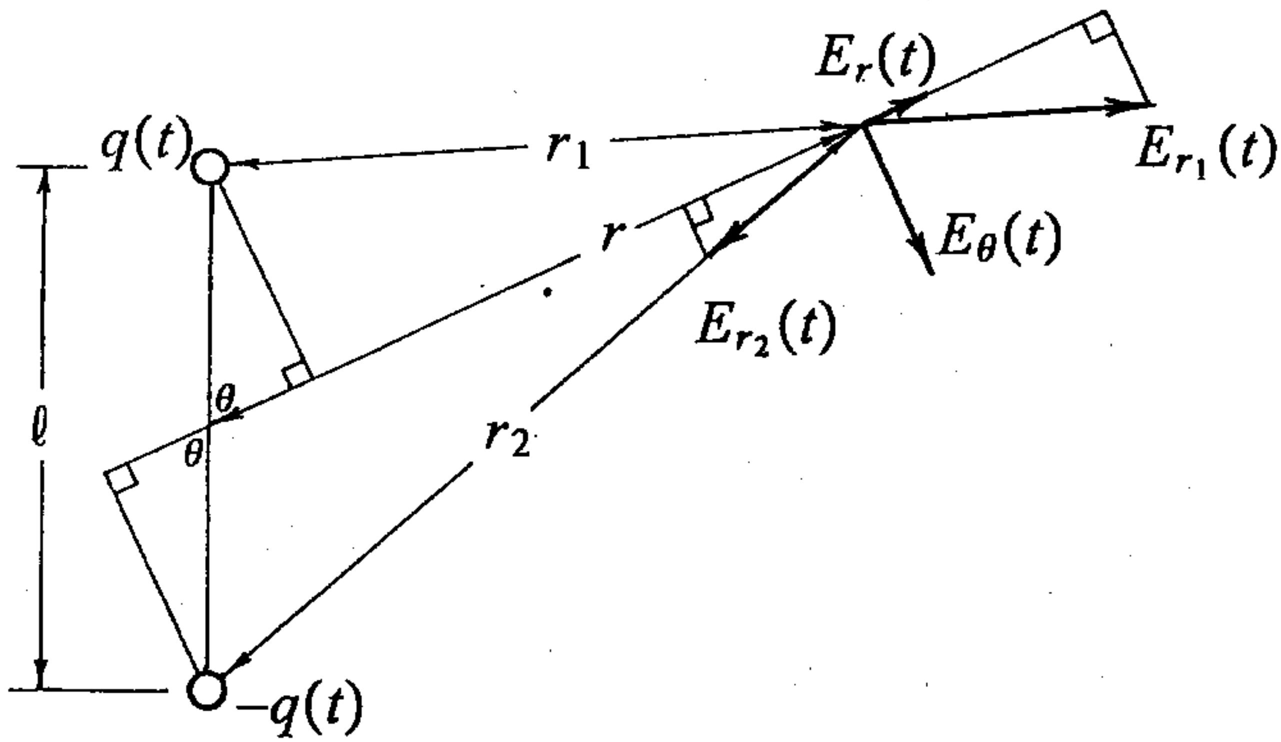
(2) Symmetrize the current to minimize the inductive H-field.



THE CURRENT ELEMENT



. . . AND IT'S FIELDS



Since $\ell \to 0$ and $r >> \ell$, $\quad r_1 \cong r - \frac{\ell}{2}\cos\theta$,

$r_2 \cong r + \frac{\ell}{2}\cos\theta$, $\quad 1/r_1^n \cong 1/r^n$, $\quad 1/r_2^n \cong 1/r^n$,

and $\quad r_2^2 - r_1^2 \;=\; (r_2 - r_1)(r_2 + r_1) \;\cong\; 2r\ell\cos\theta.$

Therefore, $E_r(t) \cong E_{r_1}(t) + E_{r_2}(t)$

$$= \frac{Z_0 c}{4\pi}\left[\frac{q(t)}{r_1^2} + \frac{-q(t)}{r_2^2} \right]$$

$$= \frac{Z_0 c}{4\pi}\left[\frac{r_2^2 - r_1^2}{r_1^2 r_2^2} \right] q(t)$$

$$\cong Z_0 c \frac{2r\ell\cos\theta}{4\pi r^4} q(t)$$

So,

$$E_r(t) = Z_0 c \frac{\ell\cos\theta}{2\pi r^3}\left[q(t - r/c) + \frac{r}{c}\frac{\partial}{\partial t} q(t - r/c) \right]$$

And,

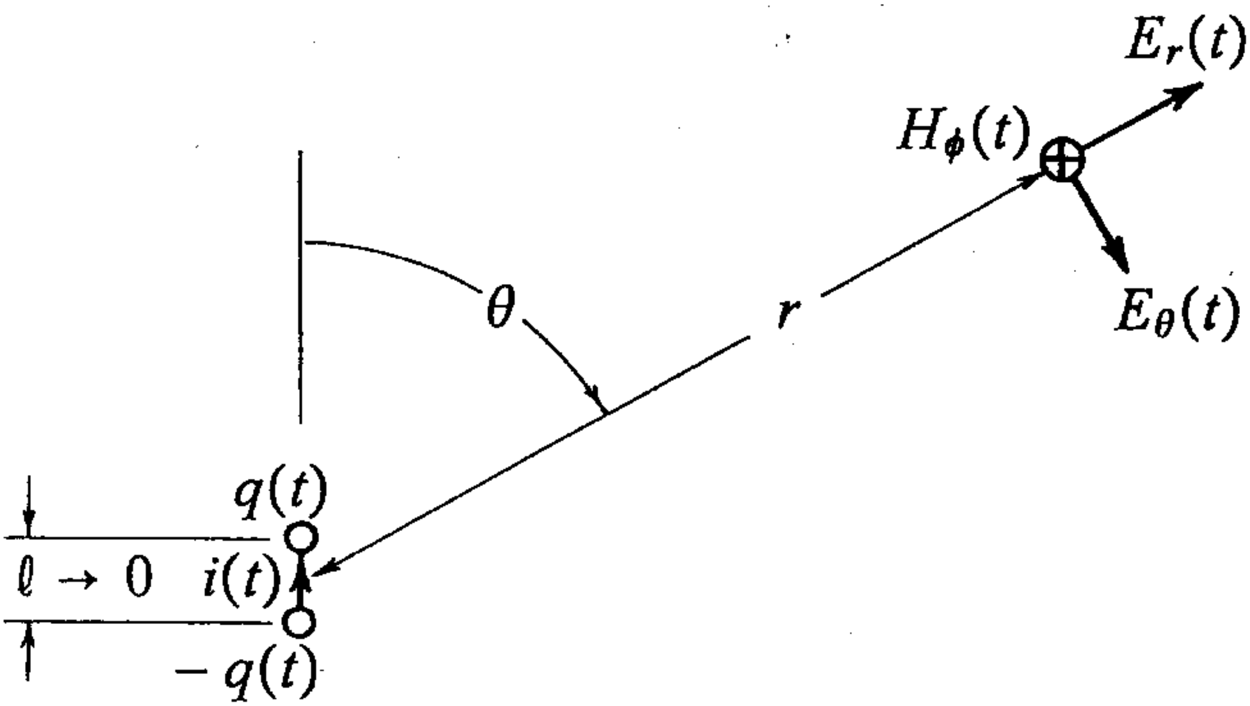
$$E_\theta(t) = \frac{\ell\sin\theta}{2r_1} E_{r_1}(t) + \frac{\ell\sin\theta}{2r_2} E_{r_2}(t)$$

$$= Z_0 c \frac{\ell\sin\theta}{2}\left[\frac{q(t)}{4\pi r_1^3} + \frac{q(t)}{4\pi r_2^3} \right]$$

So,

$$E_\theta(t) = Z_0 c \frac{\ell\sin\theta}{4\pi r^3}\left[q(t - r/c) + \frac{r}{c}\frac{\partial}{\partial t} q(t - r/c) \right]$$

THE CURRENT ELEMENT'S FIELDS



$$E_r(t) = Z_0 \frac{2\ell\cos\theta}{4\pi r^2}\left[\frac{c}{r} q(t - r/c) + \frac{\partial}{\partial t} q(t - r/c) \right]$$

$$H_\phi(t) = \frac{\ell\sin\theta}{4\pi r^2}\left[i(t - r/c) + \frac{r}{c}\frac{\partial}{\partial t} i(t - r/c) \right]$$

$$E_\theta(t) = Z_0 \frac{\ell\sin\theta}{4\pi r^2}\left[\frac{c}{r} q(t - r/c) + \frac{\partial}{\partial t} q(t - r/c) \right] + Z_0 \frac{\ell\sin\theta}{4\pi r^2}\left[\frac{r}{c}\frac{\partial}{\partial t} i(t - r/c) \right]$$

EQUIVALENCE OF CHARGE ELEMENTS AND CURRENT ELEMENTS