

## LIÉNARD-WIECHERT POTENTIAL FOR A CHARGE MOVING ON A HYPERBOLIC TRAJECTORY

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References: Griffiths, David J. (2007), Introduction to Electrodynamics, 3rd Edition; Pearson Education - Problems 10.16.

We can now work out the Liénard-Wiechert potentials for a point charge moving on a hyperbolic trajectory. We're trying to find

$$V(\mathbf{r}, t) = \frac{qc}{4\pi\epsilon_0} \frac{1}{(c|\mathbf{r} - \mathbf{w}(t_r)| - (\mathbf{r} - \mathbf{w}(t_r)) \cdot \mathbf{v})} \quad (1)$$

The motion is in one dimension, given by

$$\mathbf{w}(t) = \sqrt{b^2 + c^2 t^2} \hat{\mathbf{x}} \quad (2)$$

It's worth noting here that  $w \geq b > 0$  for all times, and the velocity is

$$\mathbf{v}(t) = \frac{d\mathbf{w}}{dt} = \frac{c^2 t}{\sqrt{b^2 + c^2 t^2}} \hat{\mathbf{x}} \quad (3)$$

which is negative for  $t < 0$  (when the particle is moving in from the right) and positive for  $t > 0$  (when the particle is moving back out again).

We'll consider only observation points  $\mathbf{r}$  that lie on the  $x$  axis to the right of the particle's location, so the separation is

$$d(t) = r - w(t) = x - \sqrt{b^2 + c^2 t^2} > 0 \quad (4)$$

Using this notation, the potential is

$$V(\mathbf{r}, t) = \frac{qc}{4\pi\epsilon_0} \frac{1}{(cd(t_r) - \mathbf{d}(t_r) \cdot \mathbf{v})} \quad (5)$$

The retarded time is given by

$$d(t_r) = c(t - t_r) \quad (6)$$

$$x - \sqrt{b^2 + c^2 t_r^2} = c(t - t_r) \quad (7)$$

We can solve this by isolating the square root on one side and then squaring both sides, to get

$$t_r = \frac{x^2 - 2xct + c^2t^2 - b^2}{2c(ct - x)} \quad (8)$$

Note that for  $t = 0$ , as  $x \rightarrow \infty$ ,  $t_r \rightarrow -\infty$  which makes sense, since the further out on the  $x$  axis we place the observer, the further back in time we need to go to get a signal from the particle. We can substitute this back into 2 to get

$$w(t_r) = \frac{1}{2} \sqrt{\frac{(x^2 - 2xct + c^2t^2 + b^2)^2}{(ct - x)^2}} \quad (9)$$

Although the operand of the square root is a perfect square, we need to be careful when taking the square root to ensure we get the correct sign. Since  $w > 0$  we can look at  $t = 0$  as before, at which point

$$w(t_r) = \frac{1}{2} \sqrt{\frac{(x^2 + b^2)^2}{(-x)^2}} > 0 \quad (10)$$

so we need to take the negative root of the operand to get  $w > 0$ . That is

$$w(t_r) = \frac{x^2 - 2xct + c^2t^2 + b^2}{2(x - ct)} \quad (11)$$

We can now calculate

$$d(t_r) = x - w(t_r) \quad (12)$$

$$= \frac{x^2 - c^2t^2 - b^2}{2(x - ct)} \quad (13)$$

after simplifying.

Now we need to find  $\mathbf{v}(t_r)$ . Substituting 8 into 3

$$\mathbf{v}(t_r) = -\frac{c(b^2 - x^2 + 2xct - c^2t^2)}{2(ct - x) \sqrt{b^2 + \frac{(b^2 - x^2 + 2xct - c^2t^2)^2}{4(-x + ct)^2}}} \quad (14)$$

Simplifying the operand of the square root, we get

$$\mathbf{v}(t_r) = -\frac{c(b^2 - x^2 + 2xct - c^2t^2)}{2(ct - x) \sqrt{\frac{(x^2 - 2xct + c^2t^2 + b^2)^2}{4(ct - x)^2}}} \quad (15)$$

Again, we need to take the correct sign when taking the square root. For  $t = 0$  we get

$$\mathbf{v}(t_r) = c \frac{b^2 - x^2}{2x \sqrt{\frac{(x^2 + b^2)^2}{4(-x)^2}}} \quad (16)$$

For large  $x$ , the signal comes from the particle in the distant past when it was moving to the left, so we should have  $v$  negative in this case. This again requires taking the negative root, so we get

$$\mathbf{v}(t_r) = \frac{c(b^2 - x^2 + 2xct - c^2t^2)}{x^2 - 2xct + c^2t^2 + b^2} \quad (17)$$

Putting it all together, we get

$$cd(t_r) - \mathbf{d}(t_r) \cdot \mathbf{v} = \frac{1}{2} \frac{(-x^2 + c^2t^2 + b^2)c}{-x + ct} - \frac{1}{2} \frac{(-x^2 + c^2t^2 + b^2)c(b^2 - (-x + ct)^2)}{(-x + ct)(b^2 + (-x + ct)^2)} \quad (18)$$

$$= \frac{(-x + ct)(-x^2 + c^2t^2 + b^2)c}{x^2 - 2xct + c^2t^2 + b^2} \quad (19)$$

We've used Maple to do some of the algebra. Therefore the potential is

$$V(\mathbf{r}, t) = \frac{1}{4\pi\epsilon_0} \frac{q(x^2 - 2xct + c^2t^2 + b^2)}{(-x + ct)(-x^2 + c^2t^2 + b^2)} \quad (20)$$

$$= \frac{1}{4\pi\epsilon_0} \frac{q((x - ct)^2 + b^2)}{(x - ct)(x^2 - c^2t^2 - b^2)} \quad (21)$$