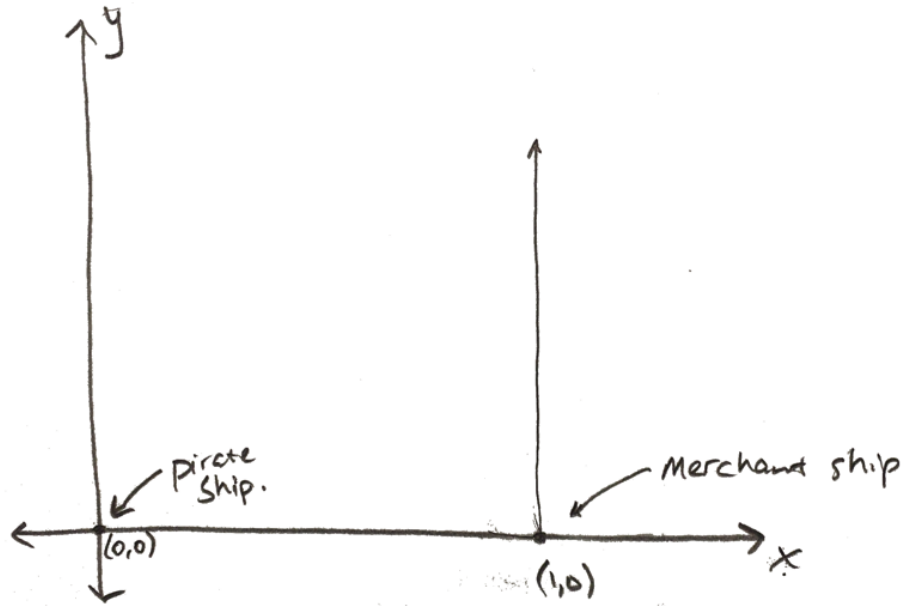


Pursuit Curves

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1.



Sketch of initial ship position and trajectory of merchant ship.

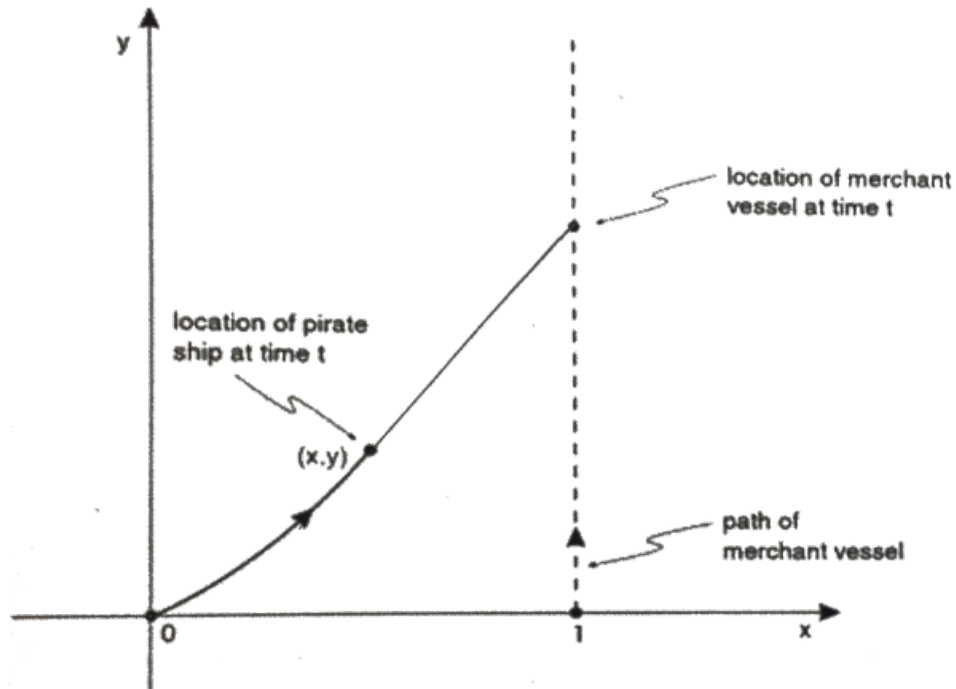
2.

Since both ships begin at the same y coordinate and the merchant ship is constantly traveling due north, it makes sense that the pirate ship's path will be a non-linear, square-looking one.

3.

The merchant ship will have traveled $V_m t$...units... after t hours. At this time, the merchant ship's coordinates will be $(1, V_m t)$.

4.



5.

The slope of this tangent line between the pirate and merchant ships is:

$$\frac{y_p - y_m}{x_p - x_m} \rightarrow \frac{y_p - V_m t}{x_p - 1}$$

This is the instantaneous slope of the pirate ship, so:

$$\frac{dy}{dx} = \frac{y_p - V_m t}{x_p - 1}$$

Solving for t :

$$\frac{dy}{dx}(x_p - 1) = y_p - V_m t$$

$$\frac{dy}{dx}(x_p - 1) - y_p = -V_m t$$

$$\frac{\frac{dy}{dx}(x_p - 1) - y_p}{-V_m} = t$$

$$t = \frac{-\frac{dy}{dx}(x_p - 1) + y_p}{V_m}$$

6.

We're given this equality, which makes enough sense:

$$V_p t = \int_0^x \sqrt{1 + \left(\frac{dy}{dz}\right)^2} dz$$

Solving for t :

$$t = \frac{1}{V_p} \int_0^x \sqrt{1 + \left(\frac{dy}{dz}\right)^2} dz$$

7.

Using the results from #5 and #6 as well as letting $p(x) = \frac{dy}{dx}$,
show that $\frac{1}{V_p} \int_0^x \sqrt{1 + p^2(z)} dz = \frac{y}{V_m} - \frac{(x-1)}{V_m} \cdot p(x)$.

First, we define p :

$$p(x) = \frac{dy}{dx}$$

Our conclusion from #6:

$$t = \frac{1}{V_p} \int_0^x \sqrt{1 + \left(\frac{dy}{dz}\right)^2} dz$$

becomes

$$t = \frac{1}{V_p} \int_0^x \sqrt{1 + p^2(z)} dz$$

Recalling our conclusion from #5:

$$t = \frac{-\frac{dy}{dx}(x_p - 1) + y_p}{V_m}$$

This can be reorganized to:

$$t = \frac{-p(x)(x - 1)}{V_m} + \frac{y}{V_m}$$

$$t = p(x) \cdot \frac{-(x - 1)}{V_m} + \frac{y}{V_m}$$

$$t = \frac{y}{V_m} - \frac{(x - 1)}{V_m} \cdot p(x)$$

So,

$$\frac{1}{V_p} \int_0^x \sqrt{1 + p^2(z)} dz = \frac{y}{V_m} - \frac{(x - 1)}{V_m} \cdot p(x)$$

8.

Using some ideas from the FTC, take a derivative in terms of x on both sides of the equation in #7 [...].

Left-hand side:

$$\frac{d}{dx} \left(\frac{1}{V_p} \int_0^x \sqrt{1 + p^2(z)} dz \right) \rightarrow \frac{1}{V_p} \cdot \frac{d}{dx} \left(\int_0^x \sqrt{1 + p^2(z)} dz \right)$$

Applying FTC₂ our LHS becomes:

$$\frac{1}{V_p} \cdot \sqrt{1 + p^2(x)}$$

Now, the RHS:

$$\frac{d}{dx} \left(\frac{y}{V_m} - \frac{x - 1}{V_m} \cdot p(x) \right)$$

$$\frac{1}{V_m} \left(\frac{dy}{dx} - \frac{d}{dx} \left((x-1) \cdot p(x) \right) \right)$$

$$\frac{1}{V_m} \left(\frac{dy}{dx} - \left(p(x) + (x-1) \cdot p'(x) \right) \right) \rightarrow \frac{1}{V_m} \left(\frac{dy}{dx} - \left(\frac{dy}{dx} + (x-1) \cdot \frac{dp}{dx} \right) \right)$$

$$\frac{1}{V_m} \left(- (x-1) \cdot \frac{dp}{dx} \right)$$

$$- \frac{(x-1)}{V_m} \cdot \frac{dp}{dx}$$

Since we've just taken the derivative of both sides, they're still equal, and we get the desired equality:

$$\frac{1}{V_p} \sqrt{1 + p^2(x)} = - \frac{(x-1)}{V_m} \frac{dp}{dx}$$

Simplify this further by multiplying both sides by $-V_m$.

$$(-V_m) \frac{1}{V_p} \sqrt{1 + p^2(x)} = (-V_m) \frac{-(x-1)}{V_m} \frac{dp}{dx}$$

$$\frac{-V_m}{V_p} \sqrt{1 + p^2(x)} = (x-1) \frac{dp}{dx}$$

...and let $n = \frac{V_m}{V_p}$, the ratio of the merchant ship's velocity to the pirate ship's velocity.

$$-n \sqrt{1 + p^2(x)} = (x-1) \frac{dp}{dx}$$

When $n > 1$, the merchant ship is moving faster than the pirate ship.

When $n = 1$, the ships are traveling at the same velocity.

When $n < 1$, the pirate ship is moving faster than the merchant ship.

The case when $n < 1$ is the most important to us, because the pirates will potentially be closing in on the merchants.

(Note that since the merchant ship is traveling in a "bee" line and the pirate ship is following some curve, the ratio n will have to be some amount *under* 1 in order for the pirate ship to actually get closer to the merchant ship.)

9.

We now have a differential equation that looks like:

$$(x - 1) \frac{dp}{dx} = -n \sqrt{1 + p^2(x)}$$

We use separation of variables to take the integrals:

$$\int \frac{1}{\sqrt{1 + p^2(x)}} dp = \int \frac{-n}{x - 1} dx$$

For the LHS, my computer gives me:

$$\int \frac{1}{\sqrt{1 + p^2(x)}} dp = \sinh^{-1}(p) + C$$

Per the definition of \sinh^{-1} :

$$\sinh^{-1}(p) = \ln(p + \sqrt{p^2 + 1})$$

For the RHS:

$$\begin{aligned} \int \frac{-n}{x - 1} dx &\rightarrow n \cdot \int \frac{1}{1 - x} dx \\ &= -n \cdot \ln(1 - x) + C \end{aligned}$$

Altogether:

$$\ln(p + \sqrt{p^2 + 1}) + C = -n \cdot \ln(1 - x)$$

10.

When $t = 0$, x is also 0. At this time, the instantaneous value of p , which was defined as $\frac{dy}{dx}$, will be $\frac{0}{\text{something}}$. That is, at this time the pirate ship will be proceeding due west directly at the merchant ship. p_x will be changing and p_y will not.

Recalling our previous equation:

$$\ln(p + \sqrt{p^2 + 1}) + C = -n \cdot \ln(1 - x)$$

We can plug in some values since we know that when $x = 0$, p is also 0:

$$\ln(0 + \sqrt{0^2 + 1}) + C = -n \cdot \ln(1 - 0)$$

$$\ln(1) + C = -n \cdot \ln(1)$$

$$C = 0$$

11.

Rearranging using various natural log rules:

$$\ln(p + \sqrt{p^2 + 1}) = -n \cdot \ln(1 - x)$$

$$\ln(p + \sqrt{p^2 + 1}) = -\ln((1 - x)^n)$$

$$\ln(p + \sqrt{p^2 + 1}) + \ln((1 - x)^n) = 0$$

$$\ln\left((p + \sqrt{p^2 + 1})(1 - x)^n\right) = 0$$

$$e^{\ln((p + \sqrt{p^2 + 1})(1 - x)^n)} = e^0$$

$$(p + \sqrt{p^2 + 1})(1 - x)^n = 1$$

12.

Letting $q = (1 - x)^{-n}$:

$$(p + \sqrt{p^2 + 1}) \frac{1}{q} = 1$$

$$p + \sqrt{p^2 + 1} = q$$

$$\sqrt{p^2 + 1} = q - p$$

$$p^2 + 1 = (q - p)^2$$

$$p^2 + 1 = q^2 + p^2 - 2qp$$

$$p^2 - p^2 = q^2 - 2qp - 1$$

$$2qp = q^2 - 1$$

$$p = \frac{q^2 - 1}{2q}$$

$$p = \frac{1}{2} \left(q - \frac{1}{q} \right)$$

Since $p = \frac{dy}{dx}$ and $q = (1 - x)^{-n}$:

$$\frac{dy}{dx} = \frac{1}{2} \left((1 - x)^{-n} - (1 - x)^n \right)$$

13.

Integrate our result from #12 in terms of x :

$$\int \frac{dy}{dx} dx = \int \frac{1}{2} \left((1 - x)^{-n} - (1 - x)^n \right) dx$$

LHS:

$$\int \frac{dy}{dx} dx = y$$

RHS:

$$\int \frac{1}{2} \left((1-x)^{-n} - (1-x)^n \right) dx$$
$$\frac{1}{2} \left(\int (1-x)^{-n} dx - \int (1-x)^n dx \right)$$

Integrate the first term, $\int (1-x)^{-n} dx$. Let $u = 1-x$, $du = -dx$, $dx = -du$:

$$- \int u^{-n} du = \frac{-u^{1-n}}{1-n}$$

Back-substituting for u :

$$\frac{-(1-x)^{1-n}}{1-n}$$

Integrate the second term, $\int (1-x)^n dx$. Again, let $u = 1-x$, $du = -dx$, $dx = -du$:

$$- \int u^n du = \frac{-u^{n+1}}{1+n}$$

Back-substituting for u :

$$\frac{-(1-x)^{n+1}}{1+n}$$

Our RHS expression becomes:

$$\frac{1}{2} \left(\frac{(1-x)^{n+1}}{1+n} - \frac{(1-x)^{1-n}}{1-n} \right)$$

Factor a $(1-x)$ out of the interior:

$$\frac{1}{2} (1-x) \left(\frac{(1-x)^n}{1+n} - \frac{(1-x)^{-n}}{1-n} \right)$$

Altogether:

$$y = \frac{1}{2} (1-x) \left(\frac{(1-x)^n}{1+n} - \frac{(1-x)^{-n}}{1-n} \right) + C$$