

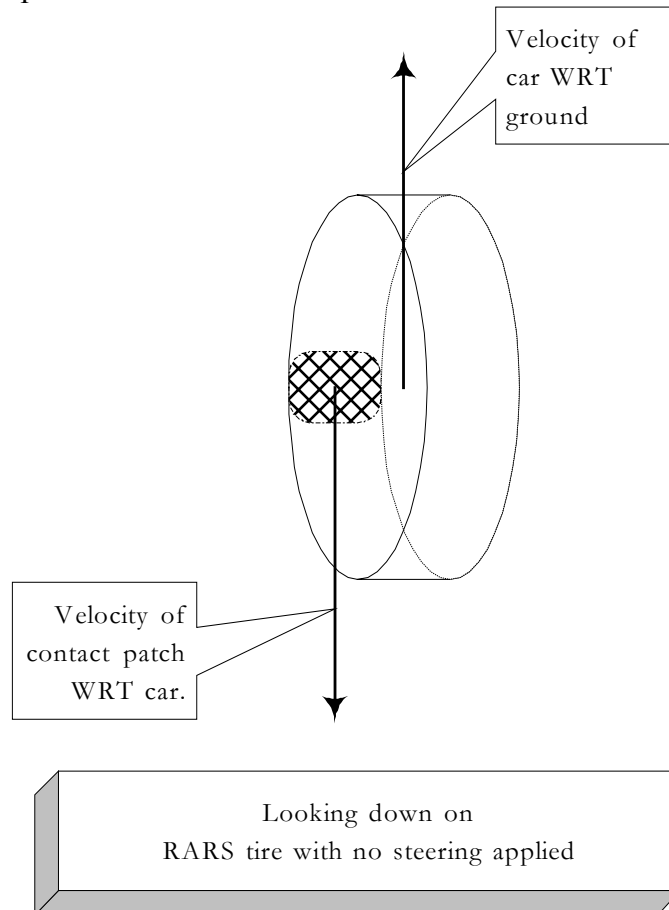
# The Physics of Racing, Part 19: Space, Time, and Rubber

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In part 16, we introduced RARS, the Robot Auto Racing Simulator. We talked about the clever and simple tyre-friction model in RARS and gave a terse presentation of its details in the big table in the article. Here, we'll explain in a little more detail why the model is cool.

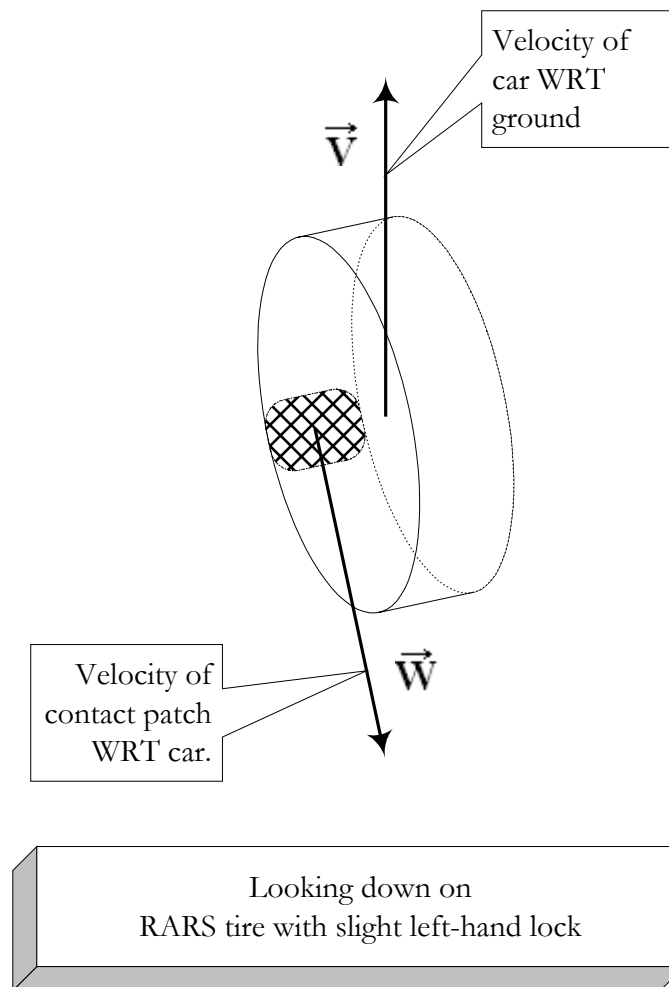
First, consider RARS' idea of a tyre when there is no steering applied. In the following diagram, we look down on a RARS tyre from above, using "X-Ray Vision" to see the contact patch:



There are only two interesting quantities at this point: the velocity of the car with respect to the ground, and the velocity of the contact patch with respect to the car. If there is no power, braking, or cornering applied, then these two vectors are equal and opposite; in other words, the velocity of the contact patch *with respect to the ground* is zero. In general, if you have a velocity of some *thing*, any *thing*, with respect to the **car** and you have the velocity of the car with respect to the **ground**, all you have to do

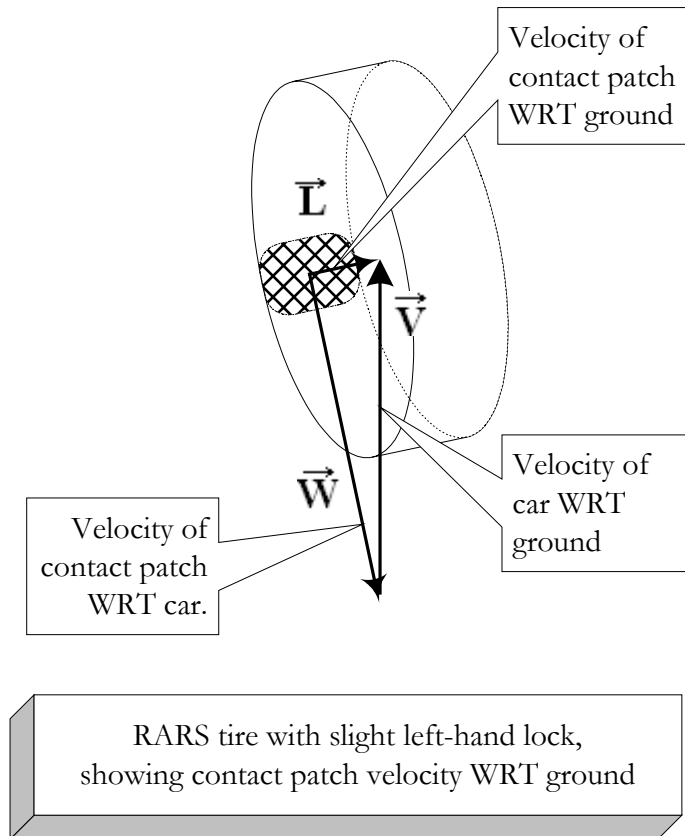
to get the velocity of the thing with respect to the ground is add the vectors, and we show how to add vectors immediately below. You eliminate the middleman—the car—by so doing. This is *relativity*, not the Einstein kind, but the Galileo kind—hence the title of this article. In the Einstein kind of relativity, you correct the vector sum with some quantities depending on the speed of light, a constant, and this is not relevant for auto racing because the speeds are so low compared to the speed of light, which is about 670 million miles per hour.

What happens when you apply a little steering input? Look at the next diagram.



The velocity of the contact path with respect to the car,  $\vec{W}$ , gets a little angle—the slip angle or the grip angle, as I called it in part 10 of the *Physics of Racing*.  $\vec{W}$  still points directly back along the plane of the tyre, and the velocity of the car with respect to the ground,  $\vec{V}$ , still heads forward, that is, *up* on the page, at least for an instant. To find out the velocity of the contact patch with respect to the ground,  $\vec{L}$ , we add the vectors  $\vec{W}$  and  $\vec{V}$ , just as before, but now there's an intervening angle. Here's the procedure for adding the vectors:

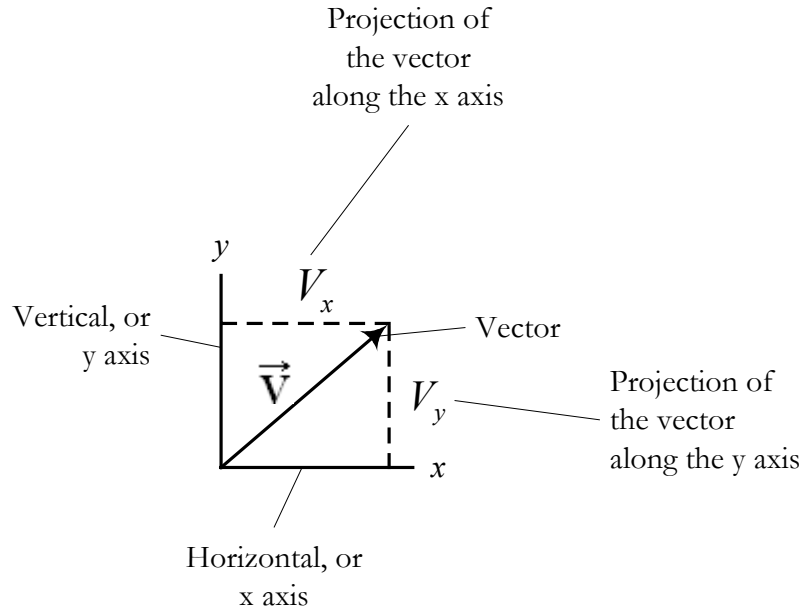
Transport one of them, without changing its direction, so that its tail touches the head of the other one. It turns out that not all kinds of vectors can be transported like this, but velocity in this context is one of the kinds that we *can* freely transport. We'll transport  $\vec{V}$  over to the head of  $\vec{W}$ , as in the following diagram:



Draw a new vector from the tail of  $\vec{W}$  to the head of  $\vec{V}$  in its new location. This new, little vector is *defined as* the **vector sum**,  $\vec{L}$ , drawn from the tail of one to the head of the other. Note it would have the same direction and length if it were drawn from the tail of  $\vec{V}$  to the head of  $\vec{W}$ . Because of this fact, we can write the following equation:

$$\vec{L} = \vec{V} + \vec{W} = \vec{W} + \vec{V}$$

This procedure for adding vectors works even when the vectors are colinear, in which case the triangle is flat, the opposite corners coincide, and the vector sum is zero—the mathematically unique **vector zero**. It also turns out that this procedure has a very simple equivalent in algebraic form. To do computations, we need to represent vectors with numbers. To do so, we measure the length of the projection of the vector against the axes of a coordinate frame, as in the following diagram:

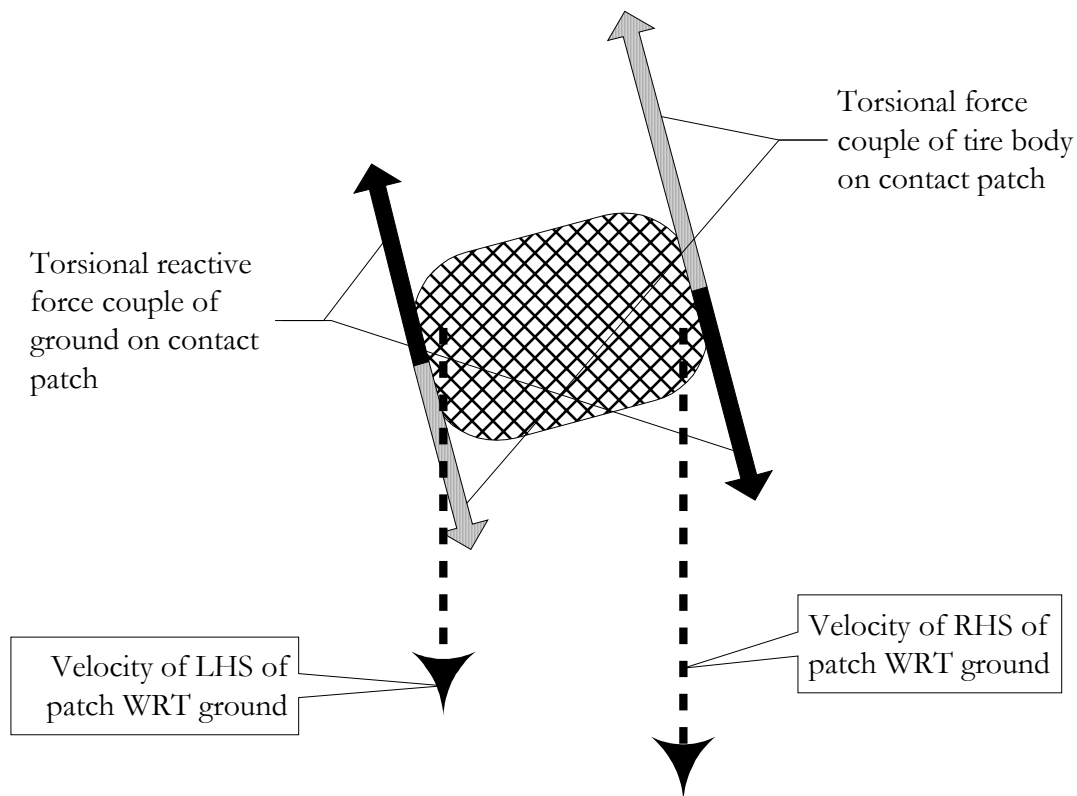


So, we get just what we need: numbers, also called **components** because they are the component parts that make up the perpendicular, independent projections of the vector. Numbers, in general, are also called *scalars* since they can be used to scale vectors. In general, we'll get three numbers for any vector in a 3D world, and two numbers in a 2D world. In either case, adding vectors is trivial. If we write  $\vec{V} = V_x, V_y, V_z$  and  $\vec{W} = W_x, W_y, W_z$ ,

then  $\vec{V} + \vec{W} = V_x + W_x + V_y + W_y + V_z + W_z$

Just add them up componentwise. Couldn't be easier. I'll leave it to you to show that the head-to-tail method is equivalent to the numerical add-'em-up-componentwise method.

Let's go back to the tyres. Here's what makes RARS' model so clever: It's undeniable that the contact patch moves with respect to the ground if we assume that it continues to move in the circumferential direction with respect to the wheel and the car. We can summarize all the complex motion of the contact patch in a single velocity  $\vec{L}$  and we can approximate our friction model so that it depends only on the magnitude of  $\vec{L}$ . This is a simpler model than the one presented in part 10, but also potentially less accurate. Let's review that one briefly. Again, looking at the contact patch from above, as if by X-Ray vision:



In the diagram above, we're looking at a wheel steered slightly to the left of the direction of travel. Assuming that there's a little acceleration in addition to the steering, both sides of the contact patch move backwards with respect to the ground. The left-hand side (LHS) of the patch moves a little more slowly than the right-hand side (RHS) because the RHS crabs around the corner. The wheel, through the carcass of the tyre, twists the patch to the left, generating a force couple illustrated by the grey arrows. The ground resists, through friction, producing the right-twisting, restoring, force couple in black. Since the patch continues to twist leftward with respect to an inertial reference frame in a steady-state turn, the grey couple must be a little larger than the black one.

This model is not by any means complete, and it's already MUCH more complex than the RARS model, which does a decent job in practice. RARS computes just *one* quantity, the vector  $\vec{L}$ , and accounts for all forces and torques on the tyre through that one variable. The advantages of the approach, when it comes to computer simulation, are

- very simple math, easy to code and debug
- very fast conversion from velocity to force
- one table lookup and one interpolation

The limitations, of course, are that RARS cannot account for detailed tyre physics and important effects like suspension geometry and dynamics, so the whole scheme trades off accuracy for simplicity. However, as a quick-and-dirty approximation, it's remarkably effective.