A POINT OF PHYSICS

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A Motorcycle is a Gyroscope
or,
Two ways of Steering a Motorcycle Without Turning the Handlebars

The wheels of a motorcycle form a splendid gyroscope. The next time you ride a motorcycle (or a bicycle, although the effects are smaller because of the lower mass and velocity), you can study the gyroscopic effects of steering in two different ways—*without* turning the handlebars, but making of the motorcycle a *precessing* gyroscope.[1]

Angular momentum, like linear momentum and energy, is *additive*: the angular momentum of a system is the *sum* of the angular momenta of all the bits and particles that make it up. In general physics we derive a little theorem that shows how a system's total angular momentum splits into the sum of two terms: the "orbital angular momentum," which is the angular momentum *of* the center of mass (CM) relative to one's chosen origin; plus the "spin angular momentum," the sum of the particles' angular momentum *relative to* the CM.[2] For example, a precessing gyroscope has spin angular momentum of the wheel about its axle, and orbital angular momentum as the wheel's CM orbits the pivot point.

Consider a motorcycle moving along a straight horizontal highway. Both wheels spin in the same vertical plane. Thus each contributes a spin angular momentum to give an angular momentum vector **L** that points horizontally to the rider's left. When I ride my motorcycle, I imagine this angular momentum as an arrow sticking out of the machine's axles. These vectors grow longer when I speed up, and shorten when I slow down.

For discussing the dynamics of this vector **L**, let's refer to the axis defined by the two points where the motorcycle tires touch the road. Call this the "tire patch axis." When I ride in a straight line, the weight of the CM, and the normal forces on the tires, pass through the tire patch axis, producing zero torque. This torqueless gyroscope gives a moving motorcycle its stability. But what happens to the total **L** when I need to turn?

At low speeds (as in parking lot maneuvers) one steers the machine by turning the handlebars and leaning into the turn. Turning the handlebars is necessary here because the radius of curvature of the bike's path is so small that both wheels cannot be coplanar *and* tangent to it. But at highway speeds, when you must go around a curve or change lanes, the path's radius of curvature is so large compared to the bike's length that both wheels can be coplanar and tangent to the trajectory. Here one can initiate a turn two ways, without turning the handlebars: (a) leaning, or (b) pushing with slight pressure on one handlebar grip (not enough to turn the handlebars—which would be disastrous at high speed—just a gentle nudge).

First, let's consider leaning the machine. If you lean to the left, the motorcycle turns left (likewise on bicycles). Why is this so? By leaning left the center of mass shifts to left of the tire patch axis. This induces a nonzero torque, $\mathbf{r}\times(m\mathbf{g})$, that points horizontally towards

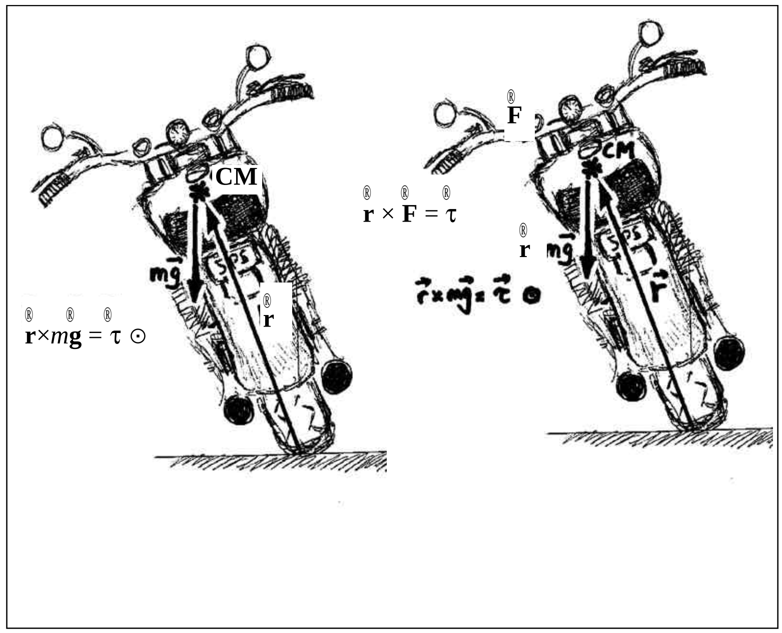

Fig. 1: The torque produced by leaning (left), and the torque produced by exerting a gentle pressure on the handlebar (right). In both cases the machine will turn left.

the rear of the motorcycle (see Fig. 1). According to Newton's Second Law in its rotational form, a torque τ produces a changing angular momentum given by the rate equation

$$\tau = d\mathbf{L}/dt .$$

This means that $d\mathbf{L}$ is proportional to τ: the angular momentum vector must acquire a component $d\mathbf{L}$ that, in our case, points backwards, in the same direction as the torque. Hence the angular momentum vector **L** rotates about a *vertical* axis, and the motorcycle precesses to my left.

Incidentally, we can also see why motorcyclists must lean into a crosswind. If I'm going straight but the wind comes from my left, the wind pressure exerted on me and the machine produces a clockwise torque (as viewed by an observer following me). To restore zero net torque, I must compensate by leaning to the left. This shift provides the necessary counter-clockwise torque to cancel the wind's torque.

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More subtly, if you apply a small but steady horizontal force *forward* on, say, the left handlebar grip, the motorcycle swerves (counterintuitively) to the *left*. When I apply the force gently forward on the left grip, I am producing a torque about the tire patch axis (or, if you prefer, the steering axis) that has a vertical downward component. To the horizontal angular momentum vector **L** is therefore added an increment *d***L** with a vertically downward component. Now the motorcycle rotates counter-clockwise (seen from behind), about the *horizontal* tire patch axis. In addition, when this happens the plane of the wheels tips to my left, so now I also have induced the CM to shift to the left of the tire patch axis. Result: now the vector **L** is rotating down *and* back.

You will notice that the handlebar pressure *initiates* a lean. Good riding technique consists in using handlebar pressure to initiate turns. By exerting forward handlebar pressure on the side where you want to go, the downward torque makes the bike lean, which further enhances the turn with the rearward torque. The gentle handlebar pressure also gives the quicker response for slight course corrections (such as lane changes or armadillo avoidance), but in the sweeping graceful curves of the Ozarks or the Rockies one sometimes deliberately leans into a turn, besides exerting the handlebar pressure. Hmmm... further research is needed.... One cannot do too much research on the two ways of steering a motorcycle!

When riding a motorcycle, one must pay sharp attention (e.g., you are invisible). However, in the back of your mind, when the traffic is minimal and no deer are foraging by the road, you can meditate on some interesting physics. Ride joyfully, and ride safely!

The author's present rides include a Kawasaki Vulcan 1500 and a Suzuki GS 1100.

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[1] Practically any general physics text will include a section of gyroscopes and their precession.
[2] See "Elegant Connections in Physics: Angular Momentum and Spin," *SPS Observer*, Fall 2000, pp. 10-14.