Corked Bats, Juiced Balls, and Humidors: The Physics of Cheating in Baseball

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Three separate questions of relevance to Major League Baseball are investigated from a physics perspective. First, can a baseball be hit farther with a corked bat? Second, is there evidence that the baseball is more lively today than in earlier years? Third, can storing baseballs in a temperature- or humidity-controlled environment significantly affect home run production? Each of these questions is subjected to a physics analysis, including an experiment, an interpretation of the data, and a definitive answer. The answers to the three questions are no, no, and yes.

I. INTRODUCTION

Baseball is rich in phenomena that are ripe for a physics analysis. In the last decade this journal has seen an explosion in the number of papers addressing interesting issues in baseball from a physics perspective. In this paper we address three new issues of relevance to Major League Baseball (MLB). While the topics are seemingly separate, they all involve the common physics issue of the ball-bat collision and all are explored using variations of the same experimental technique described in Sec. II. We first investigate whether or not a baseball can be hit harder and therefore farther with an illegally modified corked bat (Sec. III). We next investigate whether there is any direct evidence that the baseball of today is more or less lively than the baseball of yesteryear (Sec. IV). Finally we investigate whether a baseball stored at elevated temperature or humidity will lead to fewer home runs (Sec. V). We conclude the paper with a brief summary in Sec. VI.

II. DESCRIPTION OF THE BAT AND BALL TEST FACILITY

All the experimental work for these studies were done at the bat and ball test facility at the Sports Science Laboratory. The experimental setup is depicted schematically in Fig. 1. The measurements consisted of firing a baseball from a high-speed air cannon onto a stationary impact surface. While inside the barrel of the cannon, the ball traveled in a sabot which allowed control of the ball speed and orientation. An arresting plate at the end of the cannon captured the sabot while allowing the ball to continue unimpeded. Three light screens were placed between the cannon and impact surface to measure the speed of the incident ($v_0$) and rebounding ($v_f$) ball. The location of the impact surface relative to the cannon was adjusted so that the ball rebound path was within 5° of the inbound path. The air pressure to the cannon was adjusted to achieve an incident speed within 1 mph of the target speed. The laboratory was maintained at fixed 72°F temperature and 50% relative humidity for all of the impact measurements.

![Diagram of the bat and ball testing facility]

FIG. 1: Schematic of the bat and ball testing facility at the Sport Science Laboratory with a bat as the impact surface. For some of the studies, the bat was replaced by a fixed rigid surface, either flat or cylindrical.

Three different impact surfaces were used in the studies: a baseball bat shown in Fig. 1] a fixed rigid flat surface, and a fixed rigid cylindrical surface. The bat was used for the corked-bat studies and for some of the juiced-ball studies. The bat was mounted horizontally and supported by clamping it at the handle to a structure that was free to pivot about a vertical axis located six inches from the knob. The collision efficiency $e_A$ is given by

$$e_A = \frac{v_f}{v_0} = \frac{e - m/M_{eff}}{1 + m/M_{eff}}$$

where $e$ is the ball-bat coefficient of restitution (BBCOR).
and \( m \) is the mass of the ball. The effective mass of the bat is \( M_{eff} = I_0/z^2 \), where \( I_0 \) is the moment of inertia of the bat about the pivot, and \( z \) is the distance from the impact location to the pivot. Eq. (1) can be inverted to find the BBCOR value from measurements of \( v_0 \) and \( v_f \).

For the fixed rigid surfaces, \( M_{eff} \rightarrow \infty \), so that the COR is just the ratio of outgoing to incoming speed. Under these conditions, \( e \) is referred to as the ball COR for the flat surface or the ball cylindrical COR, or CCOR, for the cylindrical surface. The flat surface was used for some of the juiced-ball studies to measure the ball COR. The cylindrical surface was used in the humidor studies for determining the ball CCOR, which is a better approximation to the forces and deformation encountered in a ball-bat collision. The 2.63 inch diameter of the impact surface was chosen to closely approximate the diameter of a baseball bat. A relatively slow 60 mph incident speed was used for the CCOR measurements to minimize ball degradation during the study.

### III. CAN A BASEBALL BE HIT FARTHER WITH A CORKED BAT?

#### A. Introduction

In early June during the 2003 Major League Baseball season, an event occurred that dominated the sports news for several days. Sammy Sosa, the Chicago Cubs slugger, was caught using an illegally “corked” bat during a game. This event offered a rare opportunity for scientists to comment on events in the world of sports by addressing the question of whether corking a bat gives the batter an advantage.

A corked bat is a wood bat in which a cylindrical cavity is drilled axially into the barrel of the bat. Typically the diameter and length of the cavity are approximately one and ten inches, respectively. The cavity is then filled with a light inert material such as cork (hence, corking), the goal being to disguise the fact that the bat has been illegally modified. By removing weight from the barrel region, the batter can achieve a higher swing speed. However, the lower barrel weight implies a lower collision efficiency. Therefore, if the goal of the batter is to achieve as high a batted-ball speed (BBS) as possible, the increased swing speed is at least partially compensated by the less effective collision. One goal of the present study is to investigate the tradeoff between swing speed and collision efficiency to see whether a batter can achieve a higher BBS with a corked bat.

Corking a bat may offer another advantage, the so-called “trampoline effect,” at least according to anecdotal claims by some batters. The trampoline effect occurs in hollow metal bats due to the ability of the thin wall of the bat to compress when in contact with the ball, thereby increasing the elasticity of the collision. The increased elasticity results in a larger collision efficiency and—all other things equal—a larger BBS. The second goal of this study is to determine whether such a trampoline effect exists for a hollow or corked wood bat.

#### B. Experimental Procedures

These issues were addressed at the ball-bat test facility described in Sec. III. Impact measurements were performed which consisted of firing a baseball from the air cannon at a speed of approximately 110 mph onto a stationary bat. The speed of the incoming and rebounding baseball (\( v_0 \) and \( v_f \), respectively) were measured, and Eq. (1) was used to determine \( e_A \) and the BBCOR. For a given BBCOR reducing the moment of inertia by corking the bat also reduces \( M_{eff} \) and therefore \( e_A \), as discussed earlier.

The properties of the bats used in the study are given in Table I, with the weight, center-of-mass, and moment of inertia measured using standard techniques.  

| BAT   | WEIGHT (OZ) | CM (IN) | \( I_0 \) (OZ-IN^2) | \( m/M_{eff} \) | \( e_A \) | BBCOR |
|-------|-------------|---------|----------------------|-----------------|--------|-------|
| unmodified | 30.6        | 3.5     | 11635                | 0.2269          | 0.214(2)| 0.490(2) |
| hollow   | 27.6        | 2.9     | 10044                | 0.2628          | 0.173(2)| 0.481(2) |
| corked   | 28.6        | 3.2     | 10659                | 0.2477          | 0.193(2)| 0.488(2) |
| control  | 31.1        | 2.6     | 12106                | 0.2181          | 0.227(1)| 0.494(2) |

The modified bat had a length of 34 inches and an unmodified weight of 30.6 oz. First, the unmodified bat was impacted a total of six times. Then a cavity one inch in diameter and ten inches deep was drilled into the barrel of the bat, reducing the weight to 27.6 oz. This “hollow” bat was impacted a total of six times. Then the cavity was filled with crushed-up pieces of cork, raising the weight to 28.6 oz. The corked bat was impacted twelve times. Then the cork was removed and the drilled bat was impacted again five times. Unfortunately, the bat broke at the handle on the last impact. We had intended to fill the cavity with superball material, but that part of the experiment was cut short by breaking the bat. All impacts used the same baseball and all were at the same location, five inches from the barrel end of the bat. A twin “control” bat, with properties nearly identical to those of the unmodified bat, was impacted at various times throughout the measurement cycle to verify that the properties of the ball did not change in the course of the measurements.
C. Results and Discussion

The results from each part of the measurement cycle are shown in Fig. 2. Average values of both $e_A$ and BBCOR for each bat are given in Table I. A histogram of the measured BBCOR for 54 total impacts, including all bats, is shown in Fig. 3 where we see that the mean BBCOR is 0.489 and the standard deviation is 0.009. From these results, we conclude that to within about 0.01 (or about 2%), the BBCOR is identical for all four bats listed in Table I, despite the fact that the spread in $e_A$ values is considerably larger, of order 0.05 (or over 20%). The BBCOR values for the corked and unmodified bats are even closer in value and are statistically indistinguishable to better than 0.6%. By comparison, the BBCOR of a typical hollow aluminum bat exceeds that of a wood bat of comparable dimensions by at least 10%. We conclude that there is no evidence for a trampoline effect in a corked bat.

\[ BBS = e_A v_{pitch} + (1 + e_A) v_{bat}, \]

which relates the BBS to the pitch speed, the bat speed, and the collision efficiency. To compare a corked and unmodified bat, we use the measured values of the collision efficiencies (Table I), along with a typical pitch speed $v_{pitch} = 90 \text{ mph}$ and the prescription for bat speed $v_{bat} = 70 \text{ mph} \left( \frac{I_0}{I_{knob}} \right)^n$, (3)

where $I_{knob}$ is the moment of inertia of the bat about the knob and $I_0$ is a reference moment of inertia. The value of $I_{knob}$ is determined from $I_0$, the location of the center of mass (see Table I), and the parallel axis theorem. We take $I_0$ to be the moment of inertia about the knob of the unmodified bat (19213 oz-in²). The rationale behind Eq. 3 comes from the observation that the rotation axis of the bat just prior to meeting the ball is about a point very close to the knob, so it is natural to expect the bat speed to depend on $I_{knob}$. The exponent $n$, which characterizes how the bat speed depends on $I_{knob}$, is not known from any first principles. However, as discussed by Adair, one can confidently set two extreme limits for $n$. A lower limit $n = 0$ is realized when the batter swings the bat at the same speed, independent of $I_{knob}$; the limit $n = 0.5$ is realized when the kinetic energy imparted to the bat is independent of $I_{knob}$. Experimental data from baseball and slow-pitch softball seem to be consistent with $n \approx 0.25$, or halfway between the extreme limits.

Fig. 4 shows the computed BBS for the unmodified, hollow, and corked bats for $n = 0, 0.25,$ and 0.50. Note that since the moment of inertia of the unmodified bat was taken as $I_0$, the BBS for that bat is independent of $n$. This figure shows that for all but the most extreme value $n \approx 0.5$, the BBS of the unmodified bat exceeds that of the hollow or corked bat. We conclude that there is no advantage to corking a bat if the goal is for the BBS to be as large as possible, as is the case for a home run hitter. Said a bit differently, a baseball cannot be hit farther by corking a bat. Indeed, one actually draws the opposite conclusion, namely that corking almost always results in a lower BBS and therefore a shorter fly ball distance.

It is worthwhile pointing out, however, that there are other reasons why a batter might choose to cork a bat. The smaller moment of inertia results not only in a higher bat speed but most likely in a higher bat acceleration; that is, in the parlance of baseball, the batter can “get around quicker.” If a batter is not a home run hitter but mainly a contact hitter, getting around quicker offers a distinct advantage, since the batter can wait longer on the pitch as well as more easily adjust the swing after the swing has already begun. So, while corking may not allow a batter to hit the ball farther, it may well allow...
home runs might be hit more often with a corked bat. Indeed, while the present study shows that corked bats do not result in a batter to hit the ball solidly more often. Therefore, the underlying issue is one that periodically arises in the game of baseball, usually during periods when there is a marked increase in the rate of home run production. The rules of MLB do not seem to be very discriminating regarding the COR. Those rules specify that the COR of official baseballs must lie in the range of 0.514–0.578 when the ball is impacted on a flat plate at an incident speed of 58 mph. That range of acceptable values of ±6% leads to significant difference in performance when extrapolated to the higher speed that are relevant to the game. Our own estimate is that such a range would amount to a spread of approximately 35 ft on the distance of a long fly, in agreement with an earlier estimate by Kagan.

Most recently the issue of juiced baseballs attracted widespread attention during the early part of the 2000 MLB season. During April and May of that season, home runs were hit at a rate markedly higher than the rate over the same time period in the previous year. There was much speculation in the baseball-observing community that the increase was due to the juicing of the ball. As a result, MLB commissioned a study by the Baseball Research Center at University of Massachusetts at Lowell to compare the COR of baseballs from years 1998, 1999, and 2000. Although not published in the refereed literature, the report was widely disseminated. Interestingly, the measurements done at 58 mph were clustered at the upper end of the range allowed by MLB. The principal conclusion of the study was that there were no significant performance difference among the three sets of baseballs. A subsequent study commissioned by the Cleveland Plain Dealer (CPD) reached the same conclusion. However, the CPD study reported that the COR of present-day baseballs is significantly larger than the COR measured at the National Bureau of Standards in 1945. This conclusion was based on a comparison of the COR of 2000 balls at 89 mph (0.54, according to their measurements) to the value of 0.46 for 1938 balls from the NBS study, which was done at a slightly higher speed of 104 mph.

There are only two systematic studies of baseball COR of which we are aware in the scientific literature. First is that of Hendee, et al. who measured the COR of various baseballs up to speeds of 90 mph. Second is that of Chauvin and Carlson who measured up to 150 mph. The results of both studies are quite interesting in that they show that baseballs with nearly identical COR’s at the MLB-specified testing speed of 58 mph can have considerably different COR’s at higher speeds. This result suggests that COR measurements at 58 mph might have little relevance for the relative performance of baseballs at the higher speeds at which the game is played.

The purpose of the present study is to compare the COR of baseballs from different eras at as high a speed as practical. The main difficulty in any measurement of this type is finding a supply of unused baseballs from earlier years. Serendipitously we were able to find unopened boxes of baseballs from the late 1970’s. These baseballs were provided to us by the family of Charlie Finley, then-owner of the Oakland A’s, and were official American League baseballs bearing the facsimile signature of then-AL President Lee MacPhail and manufactured by Rawlings. These facts constrain the baseballs to the period 1976-1980. The present-day baseballs were purchased directly from Rawlings in 2004, the year the measurements were actually performed.

B. Experimental Procedures

In the present study, the ball-bat test facility at the Sports Science Laboratory was used to fire baseballs at speeds in the range 60-125 mph onto either a massive and rigid flat steel plate or onto a wood bat. For the massive plate, the COR is just the ratio of rebound to incident speed, both of which were measured. For the bat, the same techniques described in the corked bat study were used to extract the BBCOR. It was assumed that the COR is essentially identical to the peak BBCOR, where energy losses due to bat vibrations are minimal. The peak location was found in a supplemental experiment.
using a different set of baseballs to scan across the barrel of the bat. All baseballs used in this study were conditioned by storing them in a controlled 50% relative humidity environment for at least two weeks prior to the measurements.

The study was conducted in three parts. First, the COR of three baseballs from each set was measured by impacting the flat plate at incident speeds of 60, 90, and 120 mph. The results are presented in Fig. 5, where each point is an average over four impacts. Second, the COR of three additional balls from each set were measured in the same manner at the fixed incident speed of 120 mph, each ball being impacted four times. The results are presented in Fig. 6, which also includes the 120 mph results from the first part. Third, the same balls tested in the second part were tested again by impacting a wood bat with a 125 mph initial speed. The results of the ball-bat impact study are presented in Fig. 7, where each point again represents an average over three impacts.

FIG. 5: Measured values of the ball COR vs incident speed for the three 1970’s balls (red) and the three 2004 balls (blue), with different plotting symbols corresponding to different balls. The vertical line at 58 mph is the range of COR specified by MLB. The diamond at 104 mph is the measurement of Briggs on 1938 baseballs.

FIG. 6: Measured values of the COR of different balls at an incident speed of 120 mph. The red points (balls 1-3 and 5-7) are from the 1970’s and the blue points (balls 11-16) are from 2004. The diamonds at 0 and 10 are averages over the six balls from each era (0.470 and 0.468, respectively, for the 1970’s and 2004 balls). The “7 ft” label is an estimate of the change in a long fly ball distance due to a change in COR given by the length of the double arrow (0.01).

FIG. 7: Measured values of the COR of different balls at an incident speed of 125 mph on a bat. The red points (balls 5-7) are from the 1970’s and the blue points (balls 14-16) are from 2004. The diamonds at 0 and 10 are averages over the three balls from each era (0.487 and 0.491, respectively, for the 1970’s and 2004 balls). The “7 ft” label is an estimate of the change in a long fly ball distance due to a change in COR given by the length of the double arrow (0.01).

C. Results and Discussion

We start this discussion with the primary conclusion evident from an inspection of Fig. 5-7. There is nothing in the current measurements to suggest any significant difference in COR of the baseballs tested from the two different eras. Indeed, averaging the 120-mph results from the ball-flat plate collisions yields nearly identical results for the two sets of balls (0.470 and 0.468). Similarly, averaging the 125-mph ball-bat collision results yields 0.487 and 0.491 for the older and newer balls, respectively.

Some interesting secondary conclusions emerge from the data. Referring to Fig. 5 we see that all baseballs fall within the rather broad range allowed by MLB at 60 mph. Indeed, with one exception, the COR of the baseballs tested at 60 mph fall within 0.01 of each other, a spread significantly smaller than the 0.064 range allowed by MLB. The spread in values approximately doubles at 120 mph, confirming the effect found by Hendee et al. 15. The data also confirm the result from the CPD study regarding the comparison with the NBS measurement (see Fig. 5). If the present data are interpolated to find an expected result at 104 mph, that result is larger than the Briggs result by about 0.03. One interesting observation...
from Fig. 6 is that the 2004 balls show much more uniformity than the 1970’s balls, perhaps pointing to better quality control during the manufacturing process of today’s baseballs.

While our principal finding is the lack of evidence that today’s baseball is any more or less lively than that of an earlier time, we caution the reader that this result applies only to the very small sample of balls that we tested. It is not possible to extrapolate this result to make more general statements about the relative liveliness of baseballs without more extensive testing. Given the difficulty of obtaining older unused baseballs, we will likely never be able to make such statements.

VI. WHAT’S THE DEAL WITH THE HUMIDOR?

A. Introduction

Coors Field, home of the Colorado Rockies in mile-high Denver, is well-known to be a pitcher’s nightmare and a batter’s paradise. Because the air density in Denver is approximately 80% of that at sea level, fly balls carry farther and there is less movement on pitches, both of which contribute to an increase in a variety of offensive statistics. However, starting in 2002 the Colorado Rockies started storing their baseballs in a humidor, which was kept at a constant 70°F temperature and 50% relative humidity (RH). Since that time, various offensive statistics have dropped, such as home runs or total runs per game. So the question posed in the title to this section arises. Rephrasing the question in a more scientific way, is it plausible that the humidor could account for the decrease in offensive statistics at Coors Field since 2002?

Two recent studies have addressed this question. Meyer and Bohn investigated the effect of the humidor on the aerodynamics of official MLB baseballs, specifically on the flight of a fly ball. Elevated humidity is expected to increase both the weight and the diameter of a baseball. The authors investigated these effects at RH values of 33%, 56%, and 75%, then used their findings along with models for the drag and lift to calculate trajectories of batted and pitched baseballs. For batted balls, the expectation is that elevated humidity produces two partially compensating effects. An increased diameter results in a larger drag force while an increased weight results in a smaller drag acceleration. Indeed, their net result was an increase of 2 ft in the distance travelled by a fly ball on a typical home run trajectory when the RH is changed from 30% to 50%. Not only is the effect too small to be significant, it even goes in the wrong direction to account for the decrease in offensive statistics. For pitched balls, the same two effects result in slightly less movement on a pitched baseball for a given velocity and spin. However, the authors speculated that the ability of the pitcher to impart spin to the ball might be greatly improved at the higher humidity, giving rise to more movement on the pitch. Indeed, there is anecdotal information suggesting that balls stored at very low RH tend to feel slippery to the pitcher, making it difficult to put spin on the ball.

Meyer and Bohn recognized that a much larger effect on fly ball distances comes from the change in the COR of the ball. This effect had been investigated by Kagan and Atkinson, who measured the COR of an NCAA-approved baseball at 61 mph over the range 0-100% in RH. They found that the COR decreased by 0.054 over that range, from which they estimated a decrease in fly ball distance by about 6 ft between 20% and 50% RH.

It is suspected that the COR increases with increasing temperature, leading to anecdotal reports of equipment managers manipulating the COR of baseballs by using “hotter” balls when their team is batting and “cooler” balls when the opposing team is batting. The only experimental data addressing this issue of which we are aware are those of Drane and Sherwood, who find that the flat-plate COR of a standard NCAA baseball measured at 60 mph increases from 0.524 to 0.548 when the temperature is increased from 25°F to 120°F. To our knowledge, there are no comparable data for a MLB baseball.

The present experiment seeks to improve and extend the work of Kagan and Atkinson with higher precision measurements of the CCOR of official MLB baseballs at more values of the relative humidity. In addition new data are presented on the temperature dependence of the CCOR.

B. Experimental Procedures

Eight groups of official MLB baseballs were given a controlled humidity exposure, after which their weight and CCOR were measured. Four dozen baseballs were placed in a 50% RH conditioning environment for four months. The balls were then divided into eight groups of six baseballs and placed in separate conditioning chambers at relative humidities ranging from 11% to 97% RH and at a fixed temperature of 72°F for six weeks. The humidity was controlled by suspending the balls over saturated salt solutions in sealed containers. Humidity sensors were placed in half of the containers to verify the target humidity level was maintained throughout the study. A control group was left in the initial 50% RH environment for the duration of the study. To determine when the balls had reached saturation, the weight of three baseballs (separate from the primary study) at 33% and 97% RH was continuously monitored. The balls in the 33% RH environment reached saturation in just over a week, while the balls at 97% RH required upwards of three weeks. The average weight for each group is shown in Fig. 7 as a function of the humidity level. The error bars represent the standard deviation for each group. Meyer and Bohn reported a weight gain of 3.4% for MLB baseballs when the humidity was increased from 33% to 75%, in agreement with our measurement of 3.8%.
To study the effect of temperature on the CCOR, the balls were conditioned at 50%RH and 72°F for 4 months, then heated or cooled for 24 hours prior to testing. The CCOR of the balls were then quickly measured before any appreciable temperature change could occur. Since the oven and cooler used for the temperature tests were surrounded by air at 72°F and 50% RH and the temperature excursion was relatively short, the moisture content of the balls was similar to their 50% RH conditioned state.

C. Results and Discussion

The CCOR is presented as a function of humidity level and temperature in Fig. 9. We find that

\[ y = 0.8997x + 4.7248 \]

the slope of the CCOR versus RH for MLB baseballs, \( d(\text{CCOR})/d(\%\text{RH}) = -12.2 \times 10^{-4} \), is considerably larger than the flat-plate COR measured by Kagan and Atkinson\(^{12}\) for NCAA baseballs, \(-5.4 \times 10^{-4}\). The slope of the CCOR versus T, \( d(\text{CCOR})/d(T) = 5 \times 10^{-4}/\text{F} \), is about twice that measured for an NCAA baseball.\(^{20}\)

In view of the large difference between the present measurement of the effect of RH on the CCOR for the MLB baseball and that found by Kagan, it is worthwhile recalculating the effect of the humidor on a long fly ball. If the RH is increased from 30% to 50%, the CCOR decreases by 0.024, or by about 4.5% of its value. We assume a similar decrease occurs at the higher speeds of the ballbat impact. For a typical MLB bat, pitch speed, and bat speed, we estimate a decrease in batted ball speed by about 2.5 mph, corresponding to a decrease in fly ball distance by about 14 ft. Adair estimates that each percent change in fly ball distance changes the probability of hitting a home run by about 7%.\(^9\) Taking 380 ft. as a typical home run distance, a reduction of 14 ft corresponds to a reduction in home run probability by about 25%, a very significant result and one that is not inconsistent with the numbers quoted by Meyer and Bohn.\(^{18}\)

We conclude that it is plausible that the humidor can account for the decrease in offensive statistics at Coors Field since 2002.

A similar analysis can be done for the temperature dependence of the CCOR. Balls stored at 70°F will have a higher CCOR by 0.018 (or 3.3%) than those stored at 35°F. Once again assuming the same fractional change at higher speeds, a reduction of the temperature from 70°F to 35°F would lead to an decrease in fly ball distance by about 10 ft, corresponding to an decrease in home run production by about 19%.

VI. SUMMARY

We have addressed three practical questions at the intersection of baseball and science. We have shown that there is no measurable trampoline effect with a corked bat and that it is very unlikely that a batter can hit a baseball harder by using a corked bat. We have found no evidence that baseballs of today are more or less lively than baseballs used in the late 1970’s. Finally, we have shown that storing baseballs in humidors at 50% relative humidity in Denver can lead to a marked reduction in home run production. A similar effect can be achieved by storing the baseballs at a temperature of 35°F.

Acknowledgments

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The report from the UML study is available at http://go.illinois.edu/physicsofbaseball/UML2000.pdf

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