THE PHYSICS OF BASKETBALL:
AN INTRODUCTION TO SCIENTIFIC THINKING

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Good morning. My name is Jim Faller -- it's easy to remember -- look at the first slide (slide 1). It turns out my name is spelled exactly the same as a famous German toy company — unfortunately I am not related. I come from Boulder, Colorado; and this (slide 2) is the building I work in, the Joint Institute for Laboratory Astrophysics, usually referred to as JILA. Boulder is located at the foot of the Rocky Mountains. The JILA gorilla is seen at the top of the building.

I will begin by telling you a story. There was a famous physicist in the early 1900's by the name of Abraham. You may well know his book, The Classical Theory of Electricity and Magnetism (by Abraham and Becker). Abraham was writing and publishing papers at that time in the field of special relativity as a Professor of Physics at Göttingen. The story goes that the University of Göttingen had a rule that required each professor to give at least one lecture to students each year. When asked by the Chancellor about when he was going to give his lecture to students, Abraham said something to the effect that he didn't have time to give a lecture for students as he was very busy writing papers. Shortly thereafter, Abraham moved to the University of Milan. Several years later some of his former associates from Göttingen saw him at a scientific (mathematical) meeting and asked, "How do you like it in Milan?" He is reported to have answered, "I like it very much. They don't speak German and I don't speak Italian."

Now the problem is that I don't speak Chinese, and I don't know how well you understand English so we, too, may have a communication problem. My intention is to talk very slowly; but my tendency will be, I fear, to go faster than I should.

Now you well might ask, "What has basketball got to do with physics?" The answer is — I believe — it has an enormous amount. How many of you know about basketball? Who doesn't know about basketball? I hope no one will (or did) put up a hand. I thought that you might know about basketball because I know you have the William Jones basketball tournament here; I also noticed in the Chinese newspaper on the plane that you are having the Taiwan International Basketball Tournament this weekend with teams from Japan, Taiwan, and Hong Kong participating.

I would like in the four talks I will be giving at this school to give you some sense of at least one particular way of thinking about science. I don't claim that this way is the only way, or best way, but I hope it will be helpful or at least of interest to some of you. How one thinks about science is a most difficult and important question because if you don't know how to think about a question, or how you should go about doing a real problem, then it seems to me that the only thing you are likely to end up doing in life is solving the problems at the end of some textbook chapter. While that is good to do -- and it gets you an A in the course -- ultimately you will have to know how you take a problem that is "different" from the material in any given chapter and deal with it. Then questions of how you approach a problem, what kind of viewpoints you can adopt, and what methods of synthesis you can use will all bear on whether or not you will be able to solve the problem. In discussing the physics of basketball, I will try to show how one could think about the game of basketball as a physicist, and maybe understand why the game is played the way it is and how it might be played better.

Now, why did I get interested in this topic? Well, basically I got interested because I have two sons who play basketball -- a simple explanation. Each year, the undergraduate physics club at the University of Colorado sponsors a Physics Day; and some years ago (in April of 1980) I gave my first talk on the Physics of Basketball to a Physics Day audience. More recently, an article by Peter J. Brancazio of Brooklyn College, also entitled the "Physics of Basketball" has appeared in an American journal (Am. J. Phys. 49 (4), April 1981, pp. 356-365). This is a very interesting article and in my talk I will show some of the figures and diagrams from it. The next slide (slide 3) I use when I talk on this subject to high school audiences. What I find is that you may have better luck talking about physics if you can somehow make it -- at least superficially -- appear that you are talking about basketball!

I would begin by pointing out that basketball has an incredible number of clever aspects about it. For example, all good physicists learn that one always modulates; if at all possible one avoids looking for a signal that is at dc (one that doesn't have any time dependence). I would point out to you that in every basketball game the teams change ends at half-time. Long before physicists were modulating, sports teams were changing ends at quarters and/or at half-time. Why? Because the wind tends to blow in some more or less fixed direction, or because a noisy crowd sits behind one particular end. Notice that one changes ends in sporting contests for exactly the same reason that physicists like to modulate signals -- to reduce the 1/f noise terms. I suppose that when the sports people think about it, they don't think about it in quite the same way a physicist would, but nevertheless they have come up with the correct thing to do. Let me mention one or two other examples. Very often in physics you have to deal with questions of pattern recognition. You have to somehow say, "That's just like the E&M problem I remember," although it's now a mechanics question. This same pattern recognition problem comes up in basketball. When you dribble down the court, you have to decide whether you're looking at a zone or a man-to-man defense. (If you don't watch the game very much, I should explain that a zone defense is when no one guards anyone in particular (they all more or less guard the ball), and a man-to-man defense is when everyone guards a particular opponent whether he has the ball or not. Also, in physics one often does a worst-case analysis. Here the crux of a problem is not the idea, but what happens -- as will always be the case -- if everything is not exactly right. That translates (in basketball) to a player coming down the court to shoot a basket. He should be thinking: What if I miss? -- that's the worst-case analysis. The answer is, you don't shoot unless you have at least one of your teammates under your basket to get the rebound. Now most kids don't think about missing, they simply shoot. But they really should ask "What if I miss; what are the chances that my team will succeed in keeping the ball?"

Finally, there is instinct. How do great basketball players learn to play the game? They surely don't get physicists to tell them how. The way they do it is partly as a result of coaching, but mainly by acquired instinct. They play weekends, nights, weekdays -- they play and play and play. And in so doing, they learn (become sensitized to) what works and what doesn't work. I claim that physicists do exactly the same thing. Someone may say, "He has a really good physical 'feel'." What does that mean? It usually means that based on the doing of physics a person has developed very good "instincts." Physicists use a lot of tools, wonderful instruments, etc., but the most important tool that a physicist has is his mind, and this needs to be developed and sensitized.

Let me tell you one more story. There was a very famous magician whose name was Houdini. He was probably the most famous magician who ever lived. Houdini was very interested in discovering whether or not his wife (after she had died) could communicate with him from the after-life. He spent a great deal of time going to seances (where everyone places their hands on a table, ghosts come, voices speak, the table moves up and down, etc.). He wondered whether any of this was real or whether it was all fake. What Houdini did, before he went to these seances, was to sandpaper his legs raw (sore) so he would be accutely sensitized to anything that was happening (for example, under the table) that wasn't quite right. That's what a physicist does -- every time he performs an experiment or solves a problem, while he's not sandpapering his legs, he is sensitizing his mind and/or his fingertips to know how to deal with certain kinds of problems. So you see, a physicist does exactly the same thing that the basketball player does when he plays day-in and day-out -- he learns and benefits from doing.

I believe that there is a great deal of physics that can be applied to basketball, but I would also suggest that there is a greal deal of physics that can be learned from basketball. The next slide (slide 4) is a case in point -- this statement was not written by a physicist but by probably the most famous basketball coach the U.S. has ever produced (John Wooden, who was the head coach at UCLA for a number of years, and whose teams won more NCAA tournaments than any other coach). Yet if you read the quotation without knowing where it came from, it provides a magnificient statement of how one should do or approach experimental physics. You simply should not try the "brute force" approach. If you want to do a particular experiment, you should somehow think about how to do it with finesse, dexterity, and maneuverability -- you could say, if you want, with <u>grace</u>. In other words, you should try to design an experiment that has some elegance about it, which isn't just "brute force." That is how one should do science. In the past, I have used this quote from Mr. Wooden as a clue to how you should build telescopes, how you should design apparatus, etc. It's a great physics quote, in my judgment, and yet it originally applied to basketball.

The next slide (slide 5) introduces a practical case where elegance, maneuverability, and grace came in. Everyone knows who this man is, right? This is Carl Frederick Gauss. That's his telescope and, of course, every German professor had a chair. The story is told that when Gauss was a little boy, his teacher wanted to keep the class occupied for the day (so she could do something else she needed to get done). To keep them busy, she simply told the students that they were to add up all the numbers from one to ninety-nine. However, the story goes, as she walked out of the class confident that they would be occupied for hours, the little Gauss boy raised his hand and told her the sum was 4950. You know that he did not use a "brute force" approach. He did not simply add up 1 plus 2 is 3, plus 3 is 6, plus 4 is 10, plus 5 is 15, etc. What he surely did was to notice that 1 plus 99 is 100, 2 plus 98 is 100, 3 plus 97 is 100 and finally 49 plus 51 is also 100. So he probably multiplied 49×100 and added the leftover 50 to arrive at his answer of 4950. It is obvious that you can arrive at the answer in many ways, but it is also clear that elegance and grace provide a path to the result that is greatly superior to the brute force approach.

The next slide (slide 6) will give you some idea of how basketball was originally played in America. This is an outdoor basketball game played in 1892. You'll notice that originally there was no hole in the bottom of the basket; every time someone made a basket, the game had to stop, someone had to come up and get the ball out before play could start again. It seems terribly obvious to us today that a hole in the bottom of the basket would solve this problem; but it probably took several years before someone came through with this brilliant stroke of genius (to put a hole in the bottom of the basket). The rim of today's basket is 10 feet from the floor. Why 10 feet? The answer is that the auditorium balcony in the YMCA in Springfield, Massachusetts, where the game was invented, was 10 feet high. It was not a case of systematically thinking about it -- what should be the characteristic size and length? -- how high shall we put it? It was simply that the balcony was that high, and that was where the basket got attached. So it is 10 feet.

The next slide (slide 7) introduces the idea of bouncing the ball -- in basketball this is called dribbling. Let's think a moment about dribbling. How should a person dribble? Like this? or this? (demonstration). Think about it. What do you want to maximize when you dribble (or for that matter when you design an experiment)?. You want to maximize your flexibility to make changes and you don't want to get yourself into a hole. When can you do something (change direction) when you're dribbling? The answer is when the ball is in the palm of your hand. Once it is no longer in contact with your fingers, you can change direction but, unfortunately, you won't be able to take the ball with you. Obviously, if you use a high dribble, the ball will spend all of its time going and coming. A low dribble maximizes the time the ball spends in your hand. Furthermore, if you watch a good basketball player, he dribbles quite hard. Why? So as to minimize the amount of time spent going from and coming back to his hand. If you ask a good dribbler why he does it in a particular way, the chances are he won't know why, but he will know that it works. A physicist might not, in practice, be able to dribble as effectively -- but he knows why.

Next I need a volunteer -- preferably someone who has played some basketball. Good. We're going to have what appears to be a test of skill. Extend your fingers out to the front with your arms straight down in front of you. Now when I say "go," try to catch this meter stick that I am holding horizontally just below your palms. (On letting the stick fall, the volunteer was unsuccessful twice in trying to catch it.) Now does anyone understand why he couldn't do it? The answer is hinted at in the next slide (slide 8).

Remember the tower at Pisa from which Galileo is reputed to have dropped different objects and found that they all fell at the same rate? What does that have to do with meter sticks and/or basketball? When the student tried to catch the meter stick, how fast could he fall? As I had him positioned he could only fall in response to "g" -- the same little "g" that works on the meter stick. So, rather than providing a test of skill, what we have just seen performed could, in fact, be better described as a test of the equivalence of gravitational and inertial mass, namely that all things fall at the same rate in a gravitational field (Eötvös experiment). We can give another example. Suppose you had to race a world-class runner. If you could choose the course, would you choose to race on an uphill, horizontal, or downhill course? The answer surely must be the downhill course. Why? Take the limiting case of a "vertical hill." He would fall at "g" and you would fall at "g" (so at least you would tie).

So what has equivalence got to do with basketball? Do you know what a one-handed push shot is? Let's watch what our volunteer does when I throw him the ball and ask that he go through the motions of shooting. There. How many think he did it right? Wrong? Try again. Now pass me the ball. Notice what I do that is different. I catch the ball with my knees bent ready to go up while the student (wrongly) first caught the ball, then flexed his knees (free fall under gravity), and then went up. This cost him over one-tenth of a second, and in a game that would more often than not result in a defensive hand in his face before he got his shot off. The point to remember here is that all basketball players fall at the same rate in a gravitational field; so to quicken your game, do your "falling" before the ball arrives, rather than after.

In the American Journal of Physics article that I mentioned earlier, the author (Brancazio) points out the value of backspin in basketball. Why? He says, "It's clearly a problem in mechanics." It turns out, according to his (one-dimensional) analysis, that a backspinning ball "always experiences a greater decrease in translational energy and in total energy than a forward spinning ball. In addition, the energy losses suffered by a forward-spinning ball are always less than those experienced by a ball with no spin." Brancazio suggests this energy loss associated with the bounce of a backspinning ball is what makes the shot seem to be "softer" and therefore more likely to drop in the basket after it hits the rim.

Another physics type of problem that you have to worry about in basketball is the question of projectile motion -- how do you shoot? At what angle should you release the ball? How fast should you release the ball? The geometry of the problem is seen in the next slide (slide 9). Not surprisingly, an angle of approximately 45° turns out to be the optimum release angle -- a somewhat larger or somewhat smaller angle of release would result in approximately the same range. On the other hand, as is clear if one thinks about it a bit, there is no stationary character in regard to the velocity of release -- a little more speed will always result in the ball going farther. Now there is, what appears to be at first glance, a trivial theorem in basketball which says that the diameter of the hoop must be larger than the diameter of the basketball. The theorem becomes not so trivial, however, as soon as you consider the case of not putting the ball straight through but at an angle. Then that simple theorem becomes something one has to calculate and in fact requires that the entrance angle be greater than 32° or the ball won't go through.

Brancazio, in his AJP paper, goes into rather extensive algebraic detail about basketball shooting and its kinematic optimization. He concludes that the better players, though not formally taught how to shoot, have learned by imitation, trial-and-error, and constant practice, that there is a best shooting angle -- and tend to launch their shots close to that "best angle" as opposed to the "flat shot" which tends to be used by less successful players.

The next slide (slide 10) reminds us of what a basketball court looks like. In physics, one often thinks about characteristic lengths and times. What is the characteristic "length" associated with the game of basketball? Answer: 10 feet, the height of the basket; and this accounts for the fact that you'd like your forwards and centers (the ones who play near the basket) to be characterized by the same length, namely approximately 10 feet tall. On the other hand, under professional rules (the court shown), and this year under some collegiate rules, there is now a three-point line at between 19 and 24 feet from the basket. Successful shots launched from beyond this line count three rather than the usual two points. This provides another characteristic length associated with the game. Does this mean that we should expect players who are 19 to 24 feet tall to dominate the outside shooting game? Fortunately, none are available, and given by default a non-resonance situation, this permits an occasional short man to make it (as a guard) on the team.

Is there a characteristic time associated with the game? The next slide (slide 11) summarizes the shot clock rules associated with the new college basketball rules. However, rather than suggesting 30, 40, or 45 seconds as the characteristic time, I would suggest a more meaningful characteristic time as the time required to move approximately 1 meter (about the farthest one can expect to escape from one's defenseman); using a "rough" human velocity capability of 10 meters/sec results in a characteristic time of about 1/10 sec -- the same order of time lost (as we saw earlier) if one catches the ball and then bends his legs prior to going up for a shot!

In order to solve a particular science problem, one will often try to find a similar case and then say, "I'll just scale the old problem to find the new answer." Sometimes that works, but occasionally it goes wrong. Suppose, for example, you wish to find out how far one can shoot a basketball. You might begin, for example, by reading an article that appeared in the American Journal of Physics entitled, "Maximizing the range of the shot put" (Lichtenberg and Wills, Am. J. Phys. 46(5), May 1978, pp. 546-549). In this article, the authors explain, among other things, the fact that the best angle of release for maximum range is around 42° (not 45°) since the shot is released at a finite (non-zero) height above the ground. At the very end of their article they acknowledge a simple calculation due to Martin G. Olsson which connects the static strength of the putter and the velocity (or range) of the shot. This calculation goes as follows: "If the putter can lift a dumbbell of weight W from his shoulder he will be able to impart an acceleration

$$a = W/m = (W/mg)g$$

to the shot (neglecting the weight of the shot). If his arm has length ℓ the final velocity will be

$$v = [2g\ell(W/mg)]^{1/2}$$

using W = 150 pounds, ℓ = 3 feet, mg = 16 pounds, we find

$$v \simeq 42 \text{ ft/sec."}$$

Lichtenberg and Wills then suggest that since the putter imparts additional velocity from his initial movement in the ring this would probably account for the required 47 feet/sec (the velocity needed to equal the world shot put record of about 73 feet).

Now, suppose we use this model to calculate how far you can shoot a basketball. Is it equally applicable in this case? A basketball weighs 1-$1/2$ pounds. (The weight of a shot put is about 16 pounds.) If you use the same equations and apply them to a basketball, you discover that the release velocity is 149 feet/sec. And if you ask how far the ball will go, neglecting air resistance, the calculation says that you ought to be able to shoot a basketball 694 feet — a result that is ridiculous. That is the length of two football fields and a little bit more. What's wrong? In physics, if you are not careful, you can have a perfectly good calculation that is right under its assumptions but which gives a physically ridiculous result. In the case in point, the main difficulty is that you cannot accelerate your arm fast enough to go from bent to fully extended in a time scale of much less than 0.1 sec. For a constant acceleration, this implies a limiting acceleration of $2\ell/t^2$ = 600 feet/sec^2. Whereas if you ask what is the theoretical maximum acceleration given the force applied and the mass of a basketball, it would be closer to 4000 feet/sec^2. The reason that the shot put calculation works is that the shot put is very well impedance-matched to the mechanism, whereas the basketball is much too light; you cannot accelerate your hand fast enough to make it go. A corollary to this observation would be that since a basketball shot is acceleration limited, a two-handed set shot (the kind they used to take) would have a maximum range that is approximately the same as a one-handed shot. Incidently, there are other things one would have to worry about in that the apparatus, namely one's arm, has a mass that is comparable to that of the basketball.

Finally, I should mention that in the U.S. today there is a lot of discussion in the newspapers and magazines concerning "a classroom crack-down on college athletes." In the U.S. one always has as the paradigm the teacher-scholar and the student-athlete. You must not be simply a teacher or a researcher, you must be both. Also in collegiate athletics one would like everyone to be a good student as well as a good athlete. In the future, it is proposed, every college athlete will have to have had and passed courses in mathematics, science, and some English. He will either meet some standard of academic excellence or he won't be allowed to play. A much nicer way, from a physicist's point of view, would be to weight the data (points scored) in much the same way as you would handle data of different quality from an experiment. If one is to take seriously the concept of the student-athlete, then why not score four points if an A student makes a basket, three points if a B student makes one, two points for a C student basket, and one point for a D student's basket. The failing student can play but it doesn't count if he scores. That's certainly how you would handle experimental data if you were a physicist, so why not handle basketball scoring in the same logical way?

In conclusion, I would ask you to believe that basketball is a marvelous mixture of concentration and instinct. And that's what physics is too, a mixture which is developed and learned by playing and thinking about the game. Thank you very much for your kind attention.

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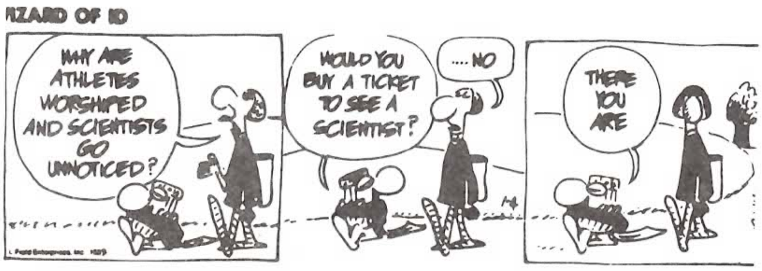

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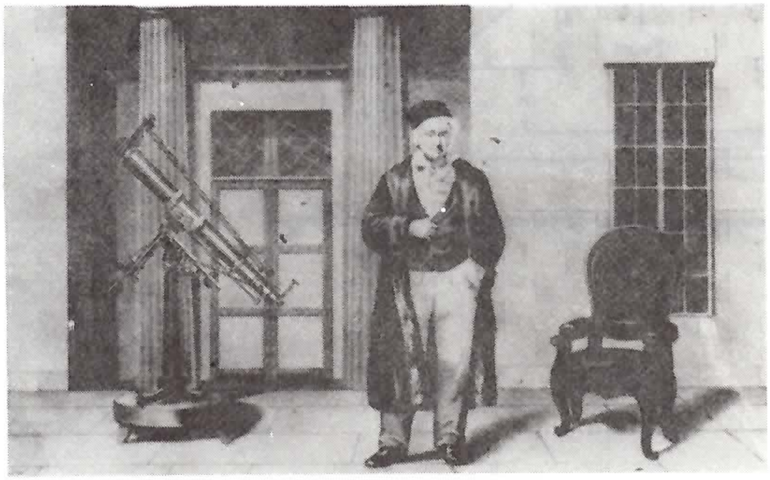
I would be disappointed
if mere physical strength
would ever prove superior
against finesse, dexterity
and maneuverability.
.....*John Wooden*

(4)



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DID YOU HEAR WHAT I WAS TELLING LUCY?
THEY'VE DISCOVERED THAT THE FORCE OF GRAVITATION IS 13% LESS TODAY THAN IT WAS 4½ BILLION YEARS AGO..
BY GOLLY, THEY'RE RIGHT!

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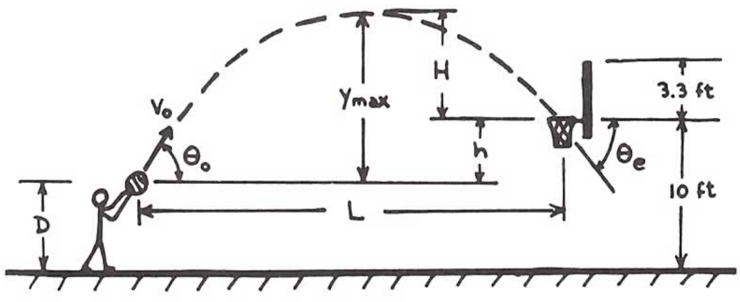
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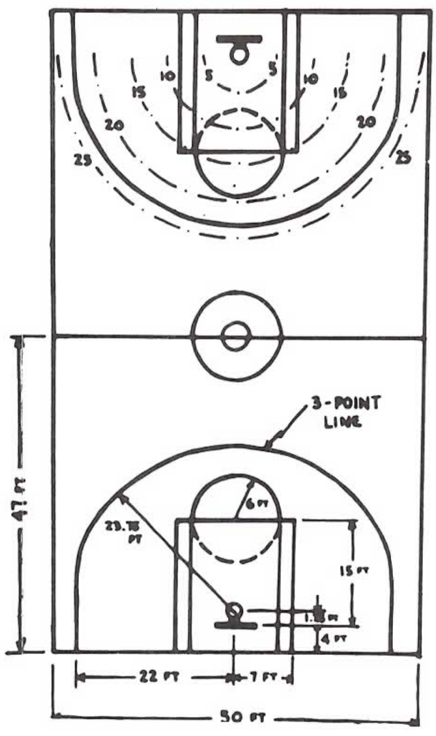
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23.75 FT
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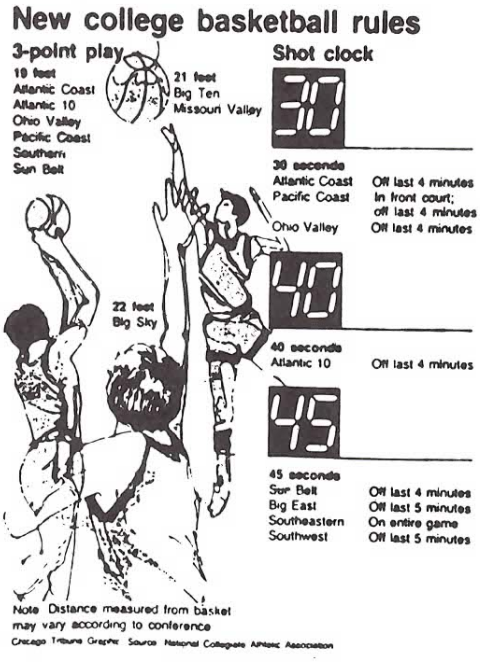
New college basketball rules
3-point play
19 feet
Atlantic Coast
Atlantic 10
Ohio Valley
Pacific Coast
Southern
Sun Belt
21 feet
Big Ten
Missouri Valley
22 feet
Big Sky
Shot clock
30
30 seconds
Atlantic Coast Off last 4 minutes
Pacific Coast In front court; off last 4 minutes
Ohio Valley Off last 4 minutes
40
40 seconds
Atlantic 10 Off last 4 minutes
45
45 seconds
Sun Belt Off last 4 minutes
Big East Off last 5 minutes
Southeastern On entire game
Southwest Off last 5 minutes
Note Distance measured from basket may vary according to conference
Chicago Tribune Graphic Source National Collegiate Athletic Association

(11)