CHAPTER 3—STIMULI

In the studies described here, students responded to the stimuli of computer animations depicting balls rolling on tracks. This chapter provides a detailed description of the stimuli, which is essential for making sense of students' judgments. The chapter can function as a reference for the interpretation of student behaviors described in later chapters.

The chapter begins with a description of the process of inventing distractor motions for the non-realistic animations. This is followed by a description of some technical aspects of generating the two-ball animations. Section 3.2 begins with a set of standard labels for the sections of each track. A set of descriptions for each two-ball animation comprises the bulk of section 3.2. The creation of one-ball animations is described in section 3.3. Section 3.4 is a collection and re-description of unrealistic features found in each animation. The chapter closes with a list of the three different animation orderings, which were intended to alleviate potential ordering effects in administrations of the one-ball and two-ball tasks

One-ball and two-ball animations lend themselves to somewhat different readout strategies. The one-ball animations depict motions of ball B along the valley track, with a static background. The two-ball animations depict essentially the same motions of ball B as their one-ball counterparts, in addition to the (realistic) motion of ball A along the flat track. Students, therefore, were forced to judge the one-ball animations based solely on observations of ball B. In the two-ball animations, students had the additional opportunity to observe the relative motions of balls A and B. As discussed in the literature review, previously reported findings (Trowbridge & McDermott, 1980) indicate that novices may experience difficulty when given the opportunity to infer speed information from observations of relative motion. Both a kinematic and a comparative description are provided for each motion in section 3.2, to highlight the two readout possibilities.

3.1 GENERATING TWO-BALL ANIMATIONS

Before designing computer animations, we asked introductory physics students to complete the strobe diagrams shown in Figure 3.1. Students were told that the ball rolling across track A was shown in each strobe diagram at regular time intervals, and were asked to indicate, with numbered dots, positions for the ball on track B at times corresponding to those shown for the ball on track A (times 3-8 for the flat-valley apparatus, and times 2-8 for the V-valley apparatus). Twenty three students taking a one-semester conceptual physics course and 156 students taking the second semester of an algebra-based physics course completed the diagrams. (These students were not involved in later parts of the study.) Most responses fell into one of four categories. The names for these four categories--similar for the two sets of tracks, and based on features of ball B's motion relative to ball A--have persisted as labels for the distractor motions: (1) slow-lose [sl], (2) fast-slow-lose [fsl], (3) fast-slow-tie [fst] and (4) constant-horizontal-velocity [constvx]. The distractor motions are described in detail in section 3.2.

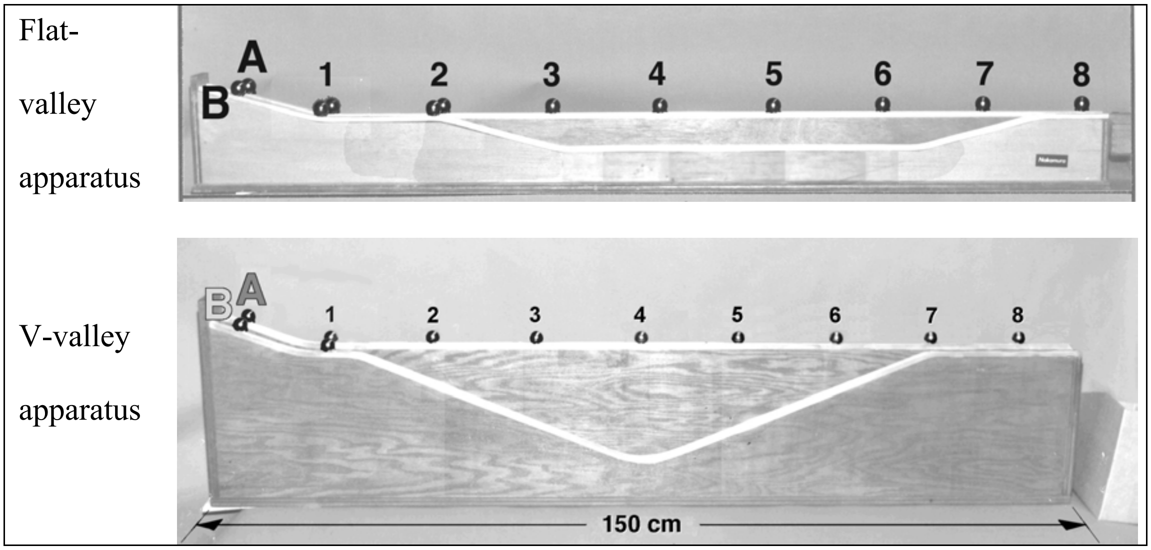

Figure 3.1 Partially completed strobe diagrams.

Two-ball animations, each depicting a motion with features of one of the four categories named above, in addition to an animation depicting realistic motion, were created for each apparatus. Each animation is a Quicktime digital movie. To make each frame of a movie, images of the ball were placed on digitally scanned photos of the tracks, using Photoshop 3.0. The movies were stitched together from the individual image-frames with QuickMovie 1.1, a Macintosh shareware application. The animations are approximately 22-cm wide on the computers used for the student tasks. For each motion, there is an animation that plays at a regular speed of 40 frames per second, and one that plays in slow motion at 20 frames per second. Ball A takes just less than two seconds to reach the end of its track in each of the regular speed animations (77 frames for the flat-valley apparatus, and 69 frames for the V-valley apparatus). Animations are viewed in a web-browser window, with a button to activate each one. Animations can be paused or stepped frame-by-frame. At the time of this writing, the animations can be accessed on the internet at <*http://www.physics.unl.edu/directory/koch/animations/*>.

3.2 ANIMATION DESCRIPTIONS

This section consists of a description of each motion for each apparatus. To standardize descriptions of ball motions, standard names for the sections of each track, shown in Figure 3.2, will often be used. Strobe diagrams, composites of several frames from each two-ball animation with numbers added to indicate increasing time, are shown in Figure 3.3 on page 38 and Figure 3.4 on page 41. Note that all interviews were conducted using the computer animation depictions of the motions represented here as strobe diagrams. In order to get a better understanding of the environment of the student interviews, the reader is urged to view the computer animations, available at <*http://www.physics.unl.edu/directory/koch/animations/*>.

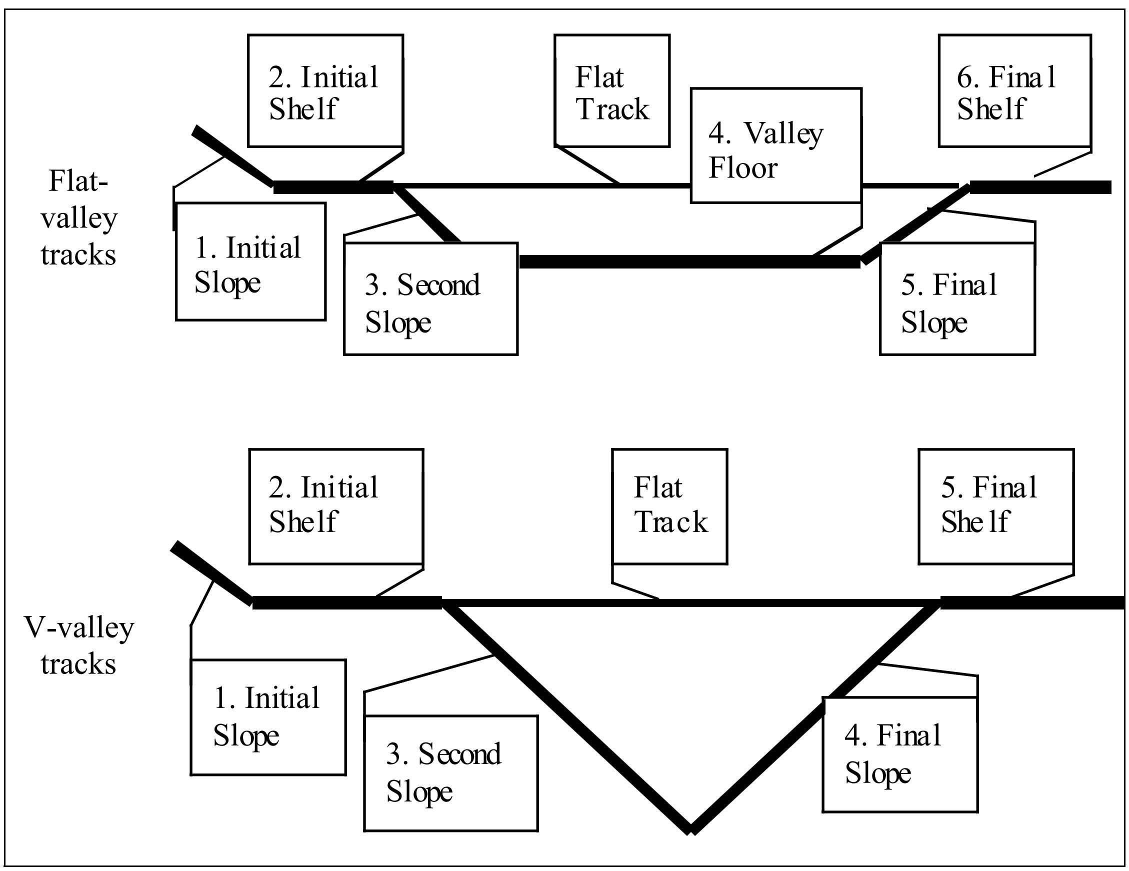

Figure 3.2 Labeled track sections.

Ball A has the same motion in all two-ball animations for each apparatus; only the motion of ball B is varied from one animation to another. In each animation, the two balls begin at rest and accelerate down the initial slope together. Ball A continues at constant speed across the flat track. Ball B continues at constant speed across the initial shelf. After the beginning of the second slope, ball B moves differently in different animations. When a ball reaches the end of its track, the animation stops.

Animation names were based on the characteristics of the corresponding categories of student-generated diagrams, as described above. The names convey a sense of ball B's progress relative to ball A. For example, in the flat-valley "fast-slow-tie" animation ball B moves *faster* than ball A at the beginning of the valley, then becomes *slower* than ball A towards the end of the valley floor, and is finally *tied* with ball A after the end of the final slope. The exception to this naming heuristic is "real", which corresponds to realistic motion of ball B on each set of tracks and is not based on student-generated diagrams.

To reflect the possibility that students may pay attention to the relative motions of balls A and B in the two-ball animations, the features of each animation are described in two complementary ways. The *comparative description* focuses on the position of ball B relative to ball A as they move across the tracks. The *kinematic description* is based solely on the speeds and speed changes of ball B.

1 "slow-lose" [sl]

2 "fast-slow-lose" [fsl]

3 "fast-slow-tie" [fst]

4 "constant v_x" [constvx]

5 "real" [real]

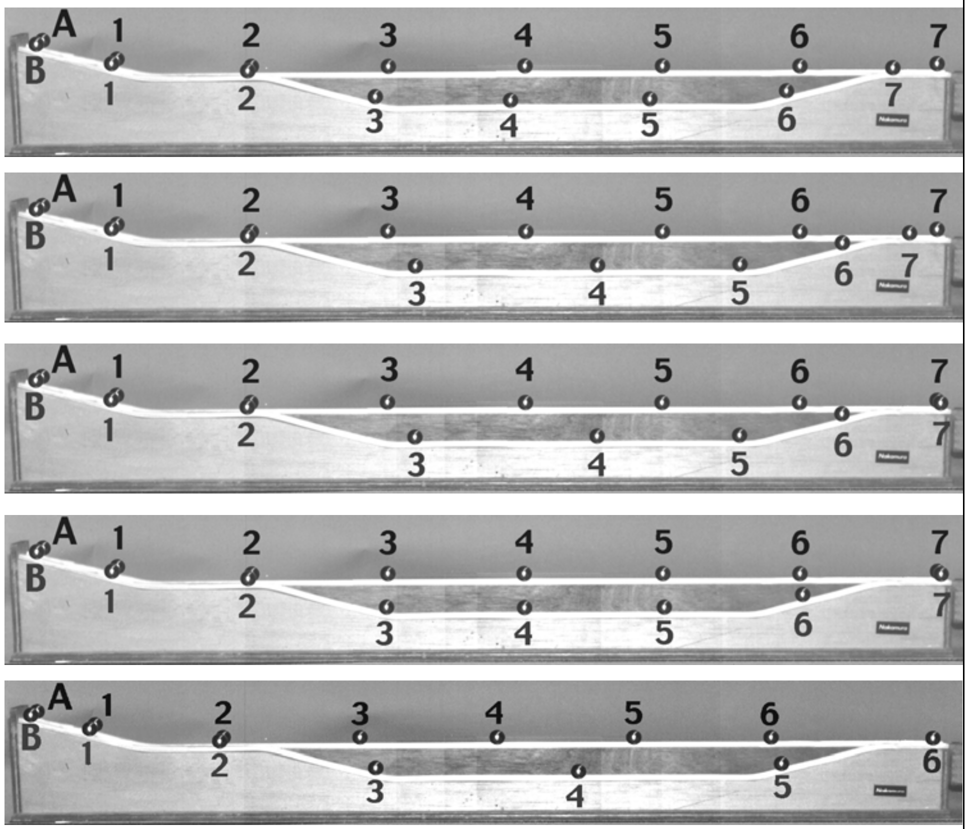

Figure 3.3 Two-ball flat-valley strobe diagrams. Gaps between ball positions correspond to ten frames in the computer animations.

3.2.1 Flat-valley-1 "slow-lose" [sl]

Comparative Description--Ball B falls behind ball A on the second slope. Across the valley floor, the separation between the two balls is constant, but the horizontal separation increases as ball B moves up the final slope. At the end of the tracks, ball A is ahead of ball B and moving slightly faster.

Kinematic Description--Ball B moves with a constant speed down the second slope and across the valley floor. Its speed decreases slightly, with a constant acceleration, as it goes up the final slope, and it moves with a constant speed across the final shelf.

3.2.2 Flat-valley-2 "fast-slow-lose" [fsl]

Comparative Description--As ball B rolls down the second slope into the valley, it speeds up and moves ahead of ball A. Ball B increases its lead across the first part of the valley floor, but slows down so that ball A is catching up as ball B moves towards the end of the valley floor and up the final slope. The two balls are tied at the end of the valley. Ball B moves more slowly than ball A across the final shelf, so that ball A wins the race.

Kinematic Description--The speed of ball B increases, with a constant acceleration, as it rolls down the second slope. The magnitude of this acceleration is matched to that of ball B down the initial slope, but adjusted for the slightly shallower angle so that the motion is realistic until ball B reaches the valley floor. Upon reaching the valley floor, ball B has an acceleration of constant magnitude directed against its motion until the end of the final slope, so that it moves increasingly slowly. Ball B rolls across the final shelf at constant speed.

3.2.3 Flat-valley-3 "fast-slow-tie" [fst]

Ball B moves in the flat-valley [fst] motion exactly as it does in the flat-valley [fsl] motion, until the two balls meet at the end of the final slope.

Comparative Description--After meeting at the end of the final slope, balls A and B finish the race together, moving at the same speed.

Kinematic Description--At the end of the final slope, there is a discontinuity in the speed of ball B; its speed increases abruptly. Ball B continues with its new speed until the end of the track.

3.2.4 Flat-valley-4 "constant v_x" [constvx]

Comparative Description-- During the entire motion, the horizontal positions of ball A and ball B are approximately equal, so that the two balls are continually tied in their race.

*Kinematic Description--*The horizontal component of ball B's velocity is approximately constant after the initial slope.

3.2.5 Flat-valley-5 "real" [real]

Ball B moves in the flat-valley [real] motion exactly as it does in [fsl] and [fst] until it reaches the beginning of the valley floor. It continues to move as a real metal ball does on a real metal track with negligible frictional losses, as described below.

*Comparative Description--*Ball B is ahead of ball A at the beginning of the valley floor, and the horizontal separation increases as ball B crosses the valley and moves up the final slope. As ball B travels across the final shelf, the separation between the two balls remains constant, with ball B ahead by a considerable margin.

*Kinematic Description--*Across the valley floor, the speed of ball B is constant. Moving up the final slope, ball B slows down with a constant acceleration, which is matched to its earlier acceleration as adjusted for the angle of the slope. At the end of the final slope, the speed of ball B has returned to approximately the speed it had before the valley. Ball B moves with constant speed across the final shelf.

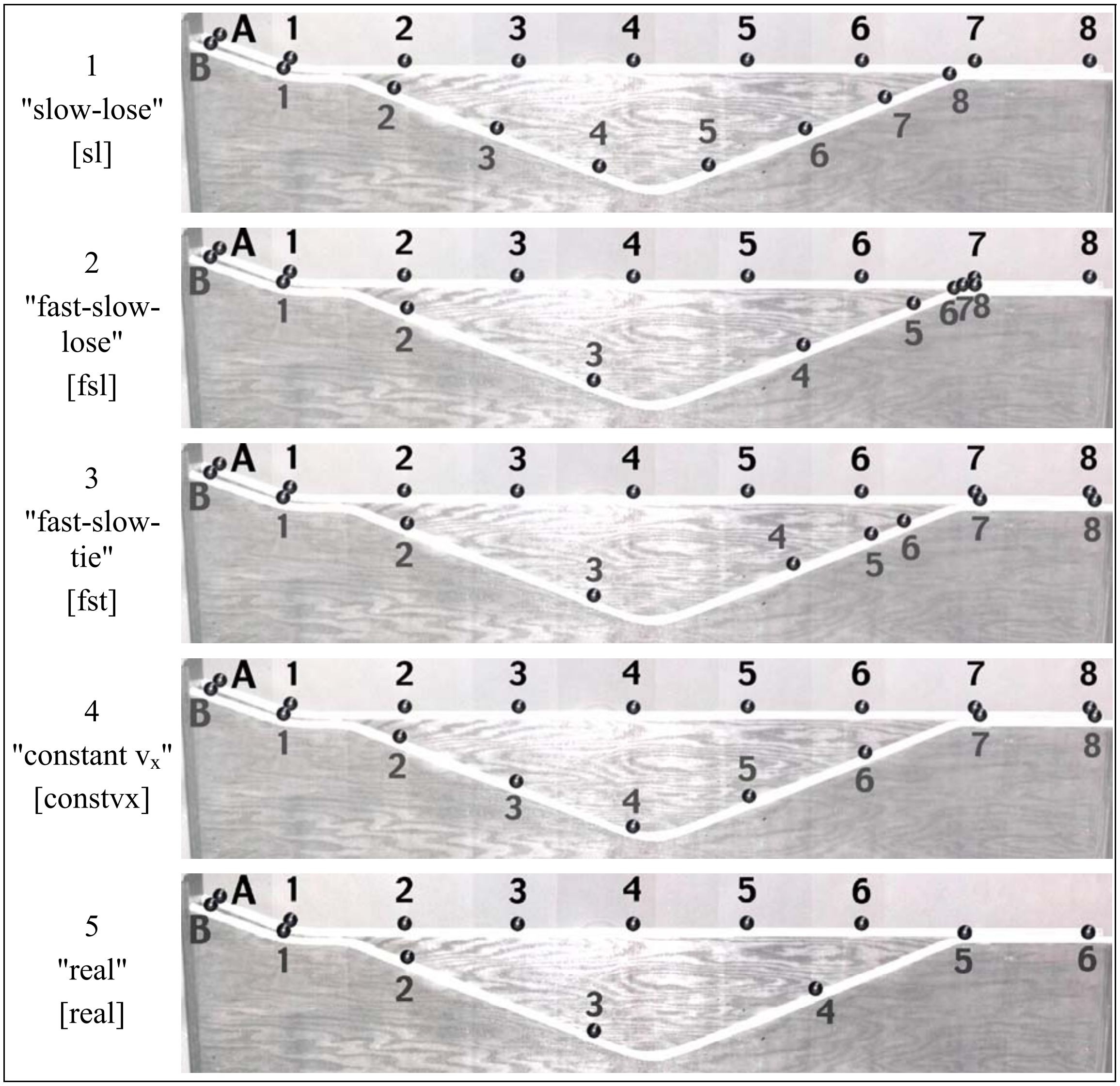

Figure 3.4 Two-ball V-valley strobe diagrams. Gaps between ball positions correspond to eight frames in the computer animations.

The five V-valley animations are similar to their flat-valley counterparts, with larger speed changes in most cases and more elaborate acceleration schemes for the [fsl] and [fst] animations.

3.2.6 V-valley-1 "slow-lose" [sl]

Comparative Description--As ball B rolls down the second slope into the valley, it falls behind ball A. The horizontal separation increases as ball B rolls up the final slope. Ball A reaches the end of the tracks just as ball B reaches the end of the final slope.

Kinematic Description--Ball B rolls with constant speed down the second slope into the valley. Its speed decreases slightly, with constant acceleration, as it goes up the final slope.

3.2.7 V-valley-2 "fast-slow-lose" [fsl]

Comparative Description--Ball B speeds up and moves ahead of ball A as it moves down the second slope into the valley. As ball B moves up the final slope, the horizontal separation between the balls initially increases; it reaches a maximum when ball B is approximately two-thirds of the way up the slope. After that point, the horizontal separation decreases until the balls meet at the end of the final slope. Ball A then leaves the much slower ball B behind and wins the race to the end of the tracks.

Kinematic Description--The speed of ball B increases, with a constant acceleration, down the second slope into the valley. The magnitude of this acceleration is matched to that of ball B down the initial slope, but adjusted for the steeper angle so that this motion is realistic until the end of the second slope. Rolling up the final slope, ball B has a time-dependant acceleration, opposite its direction of motion, that continues until it reaches the top edge of the valley. The magnitude of the acceleration at the beginning of the slope is much larger than that of the acceleration down the second slope. The magnitude of the acceleration decreases linearly in time to zero at the top of the ramp, so that the two balls are tied just as ball B reaches the end of the valley. At the end of the final slope, ball B has a small velocity directed up the slope. After the end of the final slope, the speed of ball B discontinuously jumps to a value approximately twice as large as its value at the end of the valley. The visual effect is one of ball B momentarily pausing at the end of the hill and suddenly speeding up by a very small amount.

3.2.8 V-valley-3 "fast-slow-tie" [fst]

In the V-valley [fst] motion, ball B accelerates down the second slope exactly as in [fsl]. After reaching the bottom of the slope its motion differs from that in the [fsl] animation, as described below.

Comparative Description--Ball B is ahead of ball A at the bottom of the valley, and moving much more quickly. As ball B rolls up the final slope, the separation between the balls continues to increase until the separation reaches a maximum with ball B approximately half way up the slope. After that point, the horizontal separation decreases until the balls meet at the end of the final slope. The two balls travel together at the same speed across the final shelf, and are still tied at the end of the race.

Kinematic Description--As it rolls up the final slope, ball B has a time-dependant acceleration. This acceleration was designed so that the two balls would reach the top of the valley at the same time and at the same speed. The magnitude of the acceleration at the beginning of the slope is much larger than that of the acceleration down the second slope, and larger than the corresponding acceleration in the [fsl] motion. The acceleration is initially directed against the direction of ball B's motion, but the acceleration has a constant time derivative along the direction of motion. By the time ball B reaches the end of the final slope, the acceleration is along the direction of motion. The effect on ball B's speed is that it slows down to a minimum speed near the top of the ramp, and then speeds up again while still rolling uphill. After the valley, ball B rolls with a constant speed approximately equal to its speed just before entering the valley. The visual effect is that ball B slows down quickly on the final slope and then quickly but smoothly speeds up again, while still rolling uphill.

3.2.9 V-valley-4 "constant v_x" [constvx]

Comparative Description-- During the entire motion, the horizontal positions of ball A and ball B are approximately equal; neither ball is ever ahead of the other.

*Kinematic Description--*The horizontal component of ball B's velocity is approximately constant after the initial slope.

3.2.10 V-valley-5 "real" [real]

In the V-valley [real] motion, ball B accelerates down the second slope exactly as it does in the [fsl] and [fst] animations. Upon reaching the bottom of the second slope slope, it continues as a real metal ball would roll on a real metal track with negligible frictional losses, as described below.

*Comparative Description--*As ball B rolls up the final slope, it is ahead of ball A, and the horizontal separation between the balls increases. As ball B travels across the final shelf, the separation between the two balls is constant, with ball B ahead by a considerable margin.

Kinematic Description--Moving up the final slope, ball B slows down with a constant acceleration, which is matched to its earlier acceleration and adjusted for the angle of the slope. When it leaves the valley, the speed of ball B has returned to approximately the speed it had before the valley. Its speed is constant across the final shelf.

3.3 ONE-BALL ANIMATIONS

A one-ball animation (showing only ball B) was created for each motion by removing ball A from each frame-image of the two-ball animations and compiling new Quicktime movies. Because each two-ball animation ends when the first ball reaches the end of its track, and ball A reaches the end of its track before ball B in the [sl] and [fsl] motions, a number of entirely new frames had to be created so that ball B could make it to the end of its track in the one-ball versions of these animations. (See Figure 3.5 for strobe diagrams of these four one-ball animations.) For each of these four animations except the one-ball V-valley [fsl] animation, the ball continues with constant speed to the end of the track.

In the V-valley [fsl] animations, the speed of ball B at the end of the final slope is extremely slow. In order for the animation to finish in a reasonable period of time, the ball's speed is discontinuously increased to approximately four times its speed at the end of the final slope, and the ball then accelerates so that its speed at the end of the track is approximately twice again as great--nearly nine times its speed at the end of the final slope. (Note that this is still less than half the ball's speed on the initial shelf.) The visual effect is that the ball slows down so much near the end of the final slope that it nearly pauses, abruptly speeds up at the beginning of the final shelf, and then accelerates slightly across the final shelf. Ball spacings from time 8 to time 13 of the one-ball V-valley [fsl] strobe diagram in Figure 3.5 clearly indicate these unrealistic speed changes.

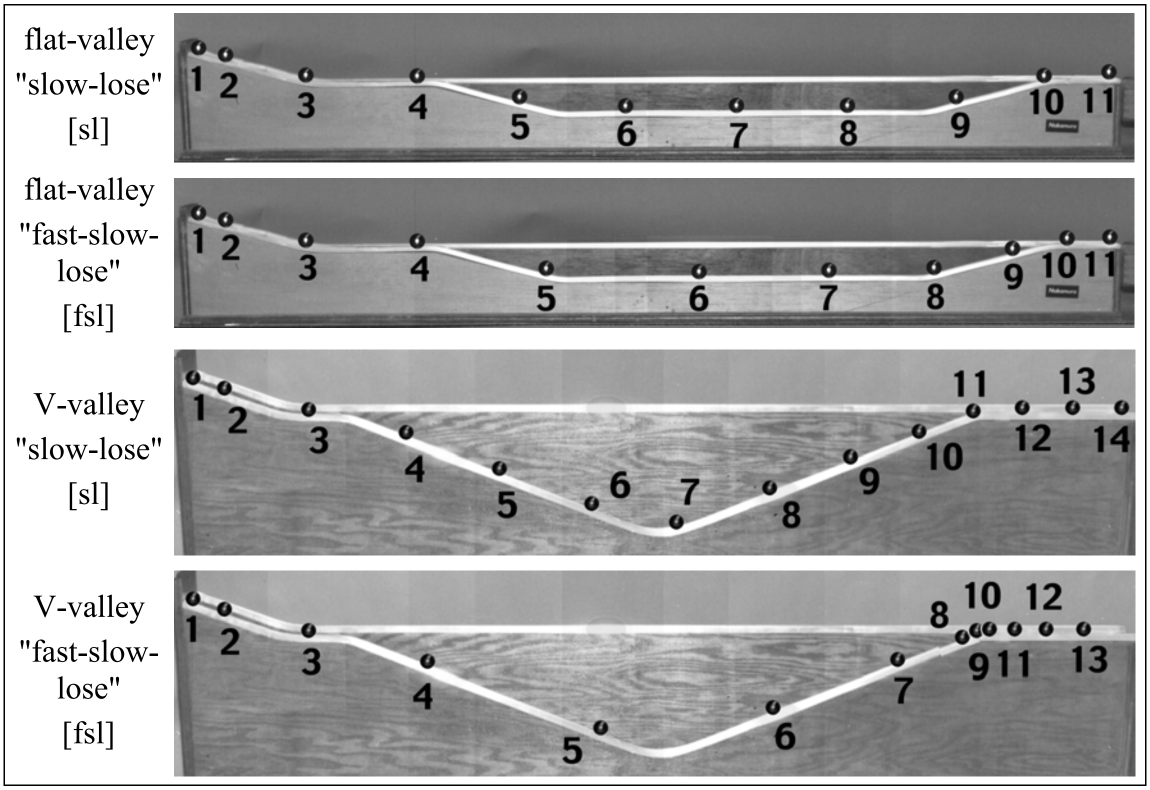

Figure 3.5 Strobe diagrams for one-ball animations with added frames.

3.4 UNREALISTIC SPEED CHANGES

Table 3.1 and Table 3.2 list the unrealistic speed changes in each animation to summarize some of the information presented above and to facilitate comparison of the motions in different animations.

Motion	**Unrealistic speed changes**
flat-valley [sl]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope.
flat-valley [fsl]	• Rolling across valley floor--speed decreases. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope and second slope.
flat-valley [fst]	• Rolling across valley floor--speed decreases. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope and second slope. • At beginning of final shelf--speed increases suddenly.
flat-valley [constvx]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--speed is approximately constant.
flat-valley [real]	• No unrealistic speed changes.

Table 3.1 Unrealistic speed changes in flat-valley animations.

Motion	Unrealistic speed changes
V-valley [sl]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope.
V-valley [fsl]	• Rolling up final slope--magnitude of acceleration is initially too large compared to accelerations on initial slope and second slope. • Rolling up final slope--magnitude of acceleration gradually decreases to zero by the end of the slope. • At beginning of final shelf--speed increases suddenly. • (One-ball animation only) Rolling across final shelf--constant acceleration causes gradual speed increase.
V-valley [fst]	• Rolling up final slope--magnitude of acceleration is initially too large compared to accelerations on initial slope and second slope. • Rolling up final slope--acceleration changes sign, so that the ball's speed increases as it approaches the end of the final slope.
V-valley [constvx]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--speed is approximately constant.
V-valley [real]	• No unrealistic speed changes.

Table 3.2 Unrealistic speed changes in V-valley animations.

Some distractor animations share features with motion that would be encountered in an environment with considerable non-conservative rolling friction (as if, for example, the tracks were covered in felt). The [fsl] and [fst] animations for the flat-valley apparatus are somewhat similar to motion in such an environment--the ball speeds up as it rolls down the second slope, but then begins to slow down as it rolls across the valley floor. The V-valley [fsl] animations are also somewhat similar to motion in an environment with high rolling friction--the ball speeds up as it rolls down the second slope, and then slows down in an exaggerated way as it rolls up the final slope, so that it has nearly stopped by the end of the final slope. The speed of ball B increases discontinuously at the beginning of the final shelf in the V-valley [fsl] animations and the flat-valley [fst] animations, which would be, of course, unrealistic even in the presence of non-conservative rolling friction.

3.5 ANIMATION ORDERINGS

In order to alleviate potential ordering effects (for example, students might be inclined to identify the first or the last animation as realistic), three different orderings were created for the one-ball and two-ball animations, as shown in Table 3.3 and Table 3.4. The number in the "Button number" corresponds to the labels seen in the web browser window for each animation. Orderings were kept the same for particular students so that, for example, students experiencing Ordering A for the one-ball flat-valley animations also experienced Ordering A for the one-ball V-valley animations and for both sets of two-ball animations. Students were never exposed to the heuristic names (i.e. [sl] or [fsl]) of the different motions.

Button number	Ordering A	Ordering B	Ordering C
1	[constvx]	[sl]	[fst]
2	[fst]	[fsl]	[real]
3	[real]	[constvx]	[sl]
4	[sl]	[fst]	[fsl]
5	[fsl]	[real]	[constvx]

Table 3.3 One-ball animation orderings.

Button number	Ordering A	Ordering B	Ordering C
1	[sl]	[constvx]	[real]
2	[fsl]	[fst]	[constvx]
3	[fst]	[real]	[fst]
4	[constvx]	[sl]	[fsl]
5	[real]	[fsl]	[sl]

Table 3.4 Two-ball animation orderings.