Abstract: Christensen and Bower (1996) and Christensen (1997, 2003) discuss disruptive innovation by applying Dosi’s concept of disruptive technological trajectories (Dosi, 1982). In the studies on performance of hard disk drives, Christensen uses and re-uses “a reprinted graph,” in which time and performance are on the horizontal and vertical axes. However, careful examination of different publications shows a varying shape and vertical axis, raising doubts about its reliability. In fact, whether the technological trajectories look disruptive or sustaining depends on the unit on the vertical axis. To present the nature of technological trajectories, it would appear more appropriate to set the vertical axis to volumetric recording density for hard disk drives. Moreover, the technological trajectories of hard disk drives would not be disruptive, if the vertical axis was adjusted to reflect weights of hard disk drives or amounts of their electricity use. It is conceivable that Christensen came to this conclusion that the technological trajectories are disruptive before considering a more appropriate performance measure for them.

Keywords: hard disk drive, disruptive technological trajectory, disruptive innovation, innovator’s dilemma
1. Introduction

Nelson and Winter (1977) used natural trajectories\(^1\) to determine the direction of technological progress. Based on this, Dosi (1982) introduced the concept of technological trajectories. Further, Christensen and Bower (1996) make a distinction between trajectory-sustaining innovation and trajectory-disrupting (or trajectory-disruptive) radical innovation.\(^2\)

Dosi (1982) defines a technological trajectory as the pattern of “normal” problem solving activity, that is of “progress,” on the grounds of a technological paradigm (Dosi, 1982, p.152). These activities represent continuity or incremental innovation (Dosi, 1982, p. 158). For example, the technological change from a 14-inch removable disk pack to a 14-inch Winchester drive has a sustaining impact on an established trajectory of performance improvement (Christensen & Bower, 1996). In Figure 1,\(^3\) this can be seen as the switch from technology A to technology B.

In general, a new technology consecutively replaces an old one. As technology A approaches a given level of maturity, the pace of its performance improvement decreases, causing a switch to technology B. Similarly, there is a switch from technology B to technology C and on to technology D. This is known as a continuous technological trajectory, illustrated by the red line in Figure 1, which is a locus of trajectory-sustaining technological change.

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1 Trajectory is the path of a moving object, such as a bullet or shell, or the track followed by a rocket or missile. The trajectory of a bullet or shell takes the form of a simple parabola, but that of a cruise missile can be fairly complex. Incidentally, Nelson and Winter (1977) refer to trajectories in the plural, whereas the singular form trajectory has been in use since Dosi (1982).

2 Bower and Christensen (1995) also use the term “disruptive technologies,” but fail to explain its connection with preceding studies. Although Bower and Christensen (1995) cited the concept before Christensen and Bower (1996), Christensen and Bower (1996) provided a more detail discussion; therefore, we focus on Christensen and Bower (1996).

3 A diagram similar to Figure 1 appears in Christensen (1997) as Figure 2.5.
2. Disruptive Trajectory

By contrast, Dosi (1982) also suggests an extraordinary breakthrough as a result of radical innovation, a clear technological leap that is discontinuous on the upper side; whereas Christensen and Bower (1996) posit discontinuity on the lower side and that when one technological trajectory ends (e.g., Technology A in Figure 2), a trajectory of inferior technology with lower performance (e.g., Technology B in Figure 2) originates from below. Figure 2 clearly shows a disruptive trajectory for hard disk drives when product performance, measured in terms of storage capacity or disk size, deviated due to technological change, that is, from A (14 inch) to B (8 inch) to C (5.25 inch) to D (3.5 inch).

Under normal circumstances, when there is a technological change from an existing technology to a new one with higher performance, such as the change from disk-pack drives to Winchester drives, the market reacts positively to it. This holds true whether the
technological change is continuous or discontinuous (Dosi, 1982, referred to this type of discontinuity as “upward compatibility”), given that performance of the new technology is higher than the old one; if not, the product would not be marketable. Thus, this type of change should be trajectory sustaining.

However, in the hard disk drive market, toy-like products with inferior performance gain a separate large market and are sold in that market rather than in the existing market. In other words, (1) 14-inch drives (A) were sold in the mainframe computer market (a), (2) the sales of 8-inch drives (B) rapidly increased in the minicomputer market (b), (3) 5.25-inch drives (C) were sold in the desktop market (c), and (4) 3.5-inch drives (D) sold in the portable computer market (d). This has resulted in disruptive technological trajectories and a number of trajectories coexist and retain their form.

Why then did the area within the dotted green line in Figure 2 (the area represented by the red line in Figure 1) not actualize? The reason is that, as shown in Figure 3, performance (dashed red line) rose much more steeply than the required performance level (solid

![Figure 2. Disruptive technological trajectories](image)

Figure 2. Disruptive technological trajectories
As a result, higher-grade disk drives were replaced by lower-grade disk drives:

(a) Mainframe computers: (A) 14 inch → (B) 8 inch  
(b) Minicomputers: (B) 8 inch → (C) 5.25 inch  
(c) Desktops: (C) 5.25 inch → (D) 3.5 inch.

As such, the area within the dotted green line in Figure 2 was never attained. In fact, Christensen and Bower (1996) suggest that a regression analysis showed that the slope of performance (dashed red line) was twice steeper than as steep as that of the required performance level (solid blue line), which means that the former increased more rapidly than the latter, as shown in Figure 3.

3. Mysteries of “Reprinted Trajectory”

Christensen and Bower (1996) present three graphs (Figure 1 left,
Figure 1 right, and Figure 2) showing technological trajectories relating to hard disk drives, which have a powerful impact on the readers. These are noted as reprinted versions of the original Figure 4 top, Figure 4 bottom, and Figure 5 in Christensen (1993). Christensen (1997), a best-seller, also reproduces them as Figures 1.4, 1.5, and 1.7. Since the original diagrams and “reprinted” ones are identical, the reliability and authenticity of reprinted diagrams are normally based on the original publication, Christensen (1993) in this case, and are not called into question when re-used. However, although specified as “reproduced,” these graphs differ visibly from the originals as follows:4

(1) Figure 4 top and bottom in Christensen (1993) show plotted dots and approximate curves. Figure 1 left and right in Christensen and Bower (1996), on the other hand, join the plotted dots to form a zigzag broken line. The same is applied for Figures 1.4 and 1.5 in Christensen (1997).

(2) Figure 4 top in Christensen (1993) shows two trajectories: oxide disks and ferrite heads, and thin-film disk and heads. Judging from the unit on the vertical axis, this graph would appear to indicate linear recording density5 and represents a logarithmic axis with scales from 0.1 to 10. On the other hand, the vertical axis of Figure 1 left in Christensen and Bower (1996) is shown as a logarithmic axis with scales from 1 to 100. The same applies to Figure 1.4 in Christensen (1997). Nonetheless, the relative

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4 In contrast, graphs identical to Figure 4 bottom and Figure 5 in Christensen (1993) appear as Figures 5 and 4 in Christensen and Rosenbloom (1995), which however are not presented as reprints.

5 However, the unit used differs between the graphs. It appears as “areal density (MB/inch)" in Figure 4 top in Christensen (1993), and “areal recording density” in Figure 1 left in Christensen and Bower (1996). Areal density is expressed as number of bits per one square inch. Since it appears as “areal density (millions of bits/square inch)" in Figure 4 bottom in Christensen (1993), it is clear that the unit matches the label. However, the unit MB/inch represents the number of bits per inch and is used to indicate linear recording density. See also footnote 9.
positions of the dots plotted in the three figures by both papers are identical, the result being that the linear recording density has increased tenfold. Thus, at least one of the two graphs must be wrong.

In addition to these differences, there are also cases of partially missing data, added data, and discrepancies. Although these points create a careless impression for a “reprint,” they could be simple errors. On the other hand, the shape of the trajectory of the 14-inch disk drive in Figure 2 in Christensen and Bower (1996) and Figure 5 in Christensen (1993) cannot be dismissed as a simple error. According to footnote 27 (p. 561) and Appendix 2 in Christensen (1993), the solid and dashed lines in Figure 2 (corresponding to the solid and dashed lines in Figure 3 of the present paper) have been defined as follows.

(a) the solid lines are regression lines that represent the hard disk capacity of the computers, whose ex-factory prices are medians for each category (mainframes, minicomputers, desktops, and

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6 (1) First, the data (dot) for 1990 on oxide disks and ferrite heads, included in Figure 4 top in Christensen (1993), does not appear in Figure 1 left in Christensen and Bower (1996). However, in Figure 1.4 in Christensen (1997), which includes three trajectories: oxide disks and ferrite heads, thin-film disks and heads, and magneto-resistive heads, the “lost” data for 1990 on oxide disks and ferrite heads has been restored and, further, the trajectory of thin-film disks and heads has been extended by adding data from 1991 to 1995. (2) In addition, two supposedly identical figures that present the same trajectories for Winchester and disk-pack drive—Figure 4 bottom in Christensen (1993) and Figure 1 right in Christensen and Bower (1996)—are, in fact, different. In Christensen and Bower (1996), the data for disk-pack drives through the 1980s changed and the dot of Winchester for 1981 disappeared. In addition, Figure 1.5 in Christensen (1997) has been extended by adding 1984 data to the Winchester trajectory in Figure 1 right in Christensen and Bower (1996). (3) Furthermore, Figure 2 in Christensen and Bower (1996), which Figure 3 in the present paper is based on, contains data for 1974 and 1975, which are excluded from Figure 5 in Christensen (1993). In other words, the trajectory in the former figure has been extended by two dots for 1974 and 1975 from the latter figure. Also, the straight line (joining the dots for 1989 and 1990) representing the required performance level for “E-Notebook PCs,” which appeared in Figure 5 in Christensen (1993), disappears from Figure 2 in Christensen and Bower (1996); nevertheless, it reappears in Figure 1.7 in Christensen (1997). Correspondingly, the 2.5-inch disk drive trajectory has been added.
portable computers) for each year,
(b) the dashed lines represent regression lines of the unweighted arithmetic mean of all disk drives put on the market for each category (14 inch, 8 inch, 5.25 inch, 3.5 inch) for each year.

In other words, the trajectory should be a “straight” regression line. Nonetheless, the trajectory of the 14-inch disk drive is not linear in either Figure 5 in Christensen (1993) or Figure 2 in Christensen and Bower (1996). Instead, its slope is shown as a concave line, whose slope gradually decreases from around 1984. Moreover, in Figure 1.7 of Christensen (1997), which is specified as a reprint of Figure 5 in Christensen (1993), the trajectory of the 14-inch disk drive is terminated at the data for 1984, after which it starts to bend and ease into a gentle slope. It is then cut short and shown as a straight line. This cannot be considered a simple error, but rather there is something intentional about the alteration.

4. Is Technological Trajectory Truly Disruptive?

In fact, the United States even saw the replacement of leading companies in each market segment when such a trajectory disruptive, radical innovation arose. A new technology that the leading company in an existing market treated as “a toy,” (Takahashi, 2005) suddenly gave rise to a new value network and replaced existing technology. Christensen (1997) refers to this as the “innovator’s dilemma.”

Although individual circumstances and reasons are presented in the

7 It can be considered that he followed the term “productivity dilemma” (Abernathy, 1978), which indicates situations wherein a company having made efforts in the past to raise productivity finds it difficult to cope with market changes. Christensen (2003) went on to discuss the connection with product architecture (e.g., Henderson & Clark, 1990; Ulrich, 1995) and put forward that as architecture became modular, the companies that specialized in those modules ousted existing companies. Christensen might have attempted to draw parallels between productivity dilemma and his own concept. However, as Yasumoto and Shiu (2007) and Yoshimoto (2009) indicate, it appears difficult to generalize his model.
second half of Christensen and Bower (1996), this phenomenon is far from being considered a general trend. No actual cases have emerged in Japan, and approaching the issue as a matter of necessity does not feel quite right and seems dubitable. We should be wary of making the connection between disruptive technological trajectory and value network destruction in an oversimplified manner.\(^8\)

Have technological trajectories indeed been disruptive? In fact, a small modification can narrow the gaps between the disruptive trajectories. The unit on the vertical axis in Figure 1 right in Christensen and Bower (1996) or Figure 4 bottom in Christensen (1993), which shows technological trajectories of 14-inch hard disk drives in the switch from disk pack to Winchester drives, is areal recording density\(^9\) per one square inch. In contrast, the vertical axis of Figure 2 or Figure 5 in Christensen (1993), which shows the technological trajectories of 14-inch, 8-inch, 5.25-inch, and 3.5-inch disk drives, represents hard disk capacity. If we change this vertical axis unit to areal recording density, as in Figure 1 right in Christensen and Bower (1996), the gap will be considerably narrower. This is because a circle’s size (square measure) is proportionate to the square of its diameter. If we set the square measure of the 14-inch disk drive to 100, those of the 8-inch, 5.25-inch, and 3.5-inch drives

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\(^{8}\) In the Japanese translation of Christensen (1997), “disruptive” has been translated to mean “destructive.” This may be due to the influence of Schumpeter (1942), Abernathy and Clark (1985), and Tushman and Anderson (1986), leading the translators to assume that disruptive technology trajectories cause destruction of the existing value network. In Japan, it is believed that building a stable interfirm network increases the opportunities for improving competence (Konno, 2003). Perhaps the aim of the translation was to add impact by instilling an image of breaking up the network. As an example of a similar concept known as discontinuous technological change, Shintaku (2005) describes the case of color televisions, in which core electric parts were switched from vacuum tubes to transistors and further to ICs.

\(^{9}\) In both Figure 1 right in Christensen and Bower (1996) and Figure 4 bottom in Christensen (1993), the vertical axis is presented as “areal density (millions of bits/square inch) and can be regarded as representing areal recording density. For hard disk drives, areal recording density is calculated as linear recording density multiplied by track recording density. Track recording density refers to the number of tracks per a given width (e.g., per inch).
would be reduced to 33, 14, and 6, respectively.

Furthermore, taking into account the trend that computers are becoming smaller, if we realistically think of a unit, such as volumetric recording density, rather than areal recording density, the gaps between the trajectories should be reduced even further. That is because, even if we simply take the “capacity (hard disk capacity)/volume of a device” as volumetric recording density, given that the volume of the device is proportionate to the cube of the diameter,\(^{10}\) then by setting the volume of the 14-inch device at 100, those of the 8-inch, 5.25-inch, and 3.5-inch devices would be reduced to 18.7, 5.3, and 1.6, respectively.

In summary, whether a technological trajectory is disruptive or sustaining depends on the unit on the vertical axis. To present technological trajectories, volumetric recording density may well be a more appropriate measure of performance than capacity for the vertical axis in Figure 2. If the vertical axis is adjusted for ratio to weight or ratio to amount of electricity use,\(^{11}\) it is possible that the technological trajectories of the 14-inch, 8-inch, 5.25-inch, and 3.5-inch hard disk drives are not disruptive, but rather sustaining. This is indeed what ought to be taken as an appropriate performance measure for presenting the technological trajectories of hard disk drives. Perhaps Christensen’s initial studies such as Christensen (1993) and Christensen and Bower (1996) have drawn out a conclusion before developing such appropriate performance measures for explaining radical innovation.

\(^{10}\) In fact, it is not as simple as discussed. Hard disk drive devices are generally cuboids. Although the bottom surface is more or less proportionate to the square of the disk’s diameter, the height (thickness) is not necessarily proportionate. The height of the device itself has become progressively standardized, but there are still different standard heights for disks with the same diameter: 3.5-inch disks can be half-height (41.3 mm) or 1-inch height (25.4 mm); 2.5-inch disks can be 3/4 or 3/8 inches thick. Moreover, they can house several disks rather than just one disk.

\(^{11}\) In addition to storage capacity, there is still scope for improving the vertical axis with factors such as access rate and stability.
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