

TABLET-BASED VALUATORS THAT PROVIDE
ONE, TWO, OR THREE DEGREES OF FREEDOM

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ABSTRACT

The ability of the user of a graphics system to interactively control the motions of 3-D objects enhances his or her spatial perception and comprehension of those objects. This paper describes several logical devices based on the tablet, each particularly suited to control some type of interactive manipulation of 2-D and 3-D objects in real time. The "turntable" and the "stirrer" convert rotary motion of the tablet pen or puck into values for one-axis rotational control; the "rack", a two-axis device, is used for scaling control; for three-axis rotational control, the tablet-based three-axis trackball is particularly suited.

Key Words and Phrases: input devices, graphics tablet, interactive graphics, virtual devices, 3-D graphics, real-time graphics, turntable, stirrer, light handle, rack, tablet-based trackball.

CR Categories: 4.41, 6.35, 8.2.

1.0 Introduction

Originally conceived as a device for X,Y position digitizing, tracing, and drawing, the tablet has proven to be a versatile device which can simulate many special purpose interactive devices very effectively and inexpensively. In recent years the tablet has taken on the job of all six interactive virtual devices described in the Status Report of the Graphics Standards Planning Committee [GSPC79]. These include the locator (the traditional use of the tablet), the pick (to select picture elements on the screen), the button (for selecting system defined parameters or functions), the stroke (for providing a series of location values), the keyboard (alphanumerics), and the valuator (to determine a single real or integer value). Tablet-simulated valuator may take a variety of forms, just as there are many types of physical valuator such as joysticks and trackballs. Each of these tablet valuator techniques provides a unique style of interaction that is appropriate to a particular range of interaction requirements.

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This paper describes several tablet-based valuator devices, each particularly suited to some aspect of interactive manipulation of 3-D objects in real time. The turntable and the stirrer, one-axis devices, are useful for rotating objects around an arbitrary axis. The rack is a device for manipulating the scale of an object in two axes. The tablet-based trackball with three orthogonal motion sensors allows a very fluid interactive three-axis rotation. The physical characteristics and applications of each of these devices will be described, along with comments on the style of interaction resulting from their use.

2.0 Definitions and Terminology

A few notes are needed at this point to clarify some of the terminology used in the paper. The term "tablet-based device" will refer to examples of different types of input techniques all implemented on a graphics tablet. These may or may not be analogous to a physical device. In addition, a given physical device, such as a trackball, may be simulated by a class of tablet-based logical devices, each with its own characteristics and each appearing to the user as a distinct device.

The tablet maps the position of either a tablet stylus (pen) or flat button-pad (puck) into an X,Y location. Additional information is available as to whether or not the pen has been depressed on the tablet surface or a puck button has been pushed. The logical devices described in this paper are essentially mappings from the X,Y position into a single value, an ordered pair, or an ordered triple, depending on whether the device is to control one, two, or three axes. The mapping may also use information from previous X,Y readings.

A device may operate in either rate or displacement mode. In the displacement mode, the outputs are used to control the magnitude of the parameter which is being manipulated (angle, scale factor, position). For example, when rotating in displacement mode, the image rotates only if, as a result of tablet pen movement, there is a change in the output value of the tablet. In the rate or velocity mode, the outputs are used to control the

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rate at which an image moves in a manner analogous to the use of a rate controlled joystick. In this way continuous transformations can be set up and left running. Rate control is particularly useful for rotations where a continuous slow rotation is a helpful aid in understanding 3-D structures. Specific interactions for performing rate and displacement transformations are detailed in later sections.

Whether in rate or displacement mode, the tablet can be operated either by sensing the absolute position of the puck (position sensing mode) or by sensing only the motion of the puck (motion sensing mode or mouse mode). Position mode is the familiar use of the tablet; the tablet coordinates are used directly. When in mouse mode, the tablet values are only changed when the puck is moved with a button pushed, hence only relative motion of the puck is significant. This is described in more detail in section 5.

Often a graphic manipulation requires the use of the tablet for several different operations, necessitating some method of switching from one method of interaction to another. The sets of buttons found on most tablet pucks are convenient for signalling to the system that the user wishes to switch from one operation to another, or from one stage of an operation to the next.

In this paper, the terms X, Y, and Z axes will refer to the horizontal screen axis, the vertical screen axis, and an axis normal to the screen, respectively.

3.0 The Turntable

The turntable is a graphic logical input device designed for user control of the two-stage process of rotating an object about a single axis. The turntable facilitates the definition of the centre of rotation and subsequently gives the user direct control of the angle of rotation. Forms of this device have been used in various systems [Tann75], [Ston81].

In practice, the use of the device is analogous to positioning a turntable under the object which is to be rotated, so that the object rests on the surface of the turntable. The turntable can then be rotated, causing the object to rotate about the turntable centre (Figure 1). As mentioned above, activation of the turntable is a two stage operation - positioning the turntable or central axis, and then rotating the object. Corresponding to these steps are two interactive dialogues or procedures, one to establish the axis and the second to control either the angle or the rate of rotation.

The first stage, positioning the axis, is accomplished in one of several ways, depending upon whether the user is picking a preset origin for the rotation (such as the screen centre, the centroid of the object, or a previously tagged point within the object) or is visually selecting an axis which passes through an arbitrary point and is normal to

the viewing plane. If selecting a preset centre of rotation, the user will merely engage in some form of menu selection process and then proceed to stage two. If, however, he wishes to place the centre of rotation at an arbitrary screen location, then a centre of rotation cue must be provided (Figure 2). The centre of rotation cue (the + symbol in Figure 2) is "attached" to the tablet puck so that the user may "drag" it while the appropriate puck button is pushed. When the tracker is appropriately positioned, pushing a second puck button fixes its location.

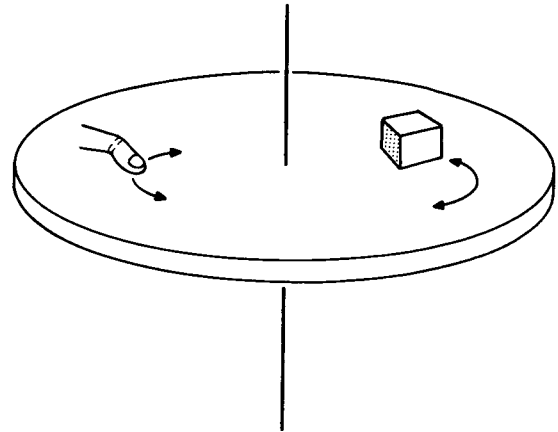


Figure 1 A physical analogue of the turntable device.

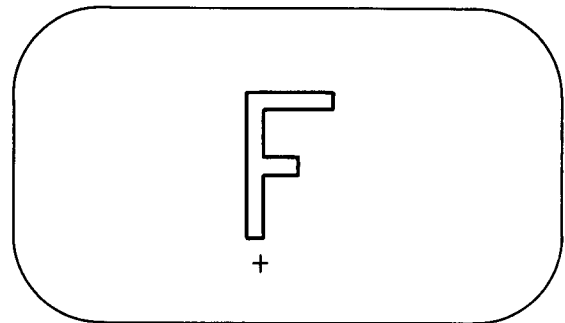


Figure 2 Turntable - Phase 1.
Positioning the centre of rotation cue (+).

In the second stage the user is presented with a pair of vectors (Figure 3) - a fixed horizontal reference vector (BA) which shows the zero degree position, and a rotating vector (BC) which shows the total angular displacement of the object. While the appropriate puck button is depressed, changes in the angular displacement of the tracker position (*) about the centre cue (+) are used to rotate the object. The vector BC is rotated to reflect this change in the angle of rotation of the object. The user then sees the rotation of the selected object as well as a display of the two vectors BA and BC which gives him a direct visual feedback of the angular displacement applied to the object.

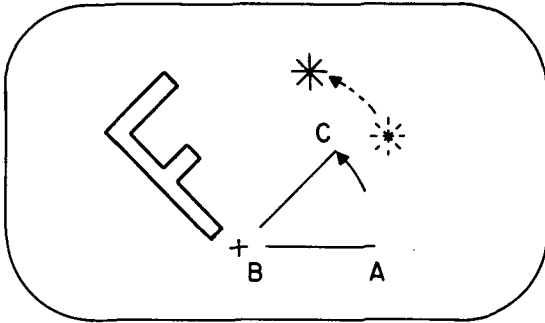


Figure 3 Turntable - Phase 2.
Rotating the object. (*) is the tablet
puck position, CBA is the angle of rotation.

One full rotation of the tracker around the centre cue, in response to a similar motion of the puck, causes THETA to go through 360 degrees. Normally, THETA directly determines the object rotation. Two simple techniques are available for vernier motion, allowing the user to make fine adjustments. An automatic vernier effect results from varying the distance between the puck position (*) and the centre cue (+); the greater this distance, the more the puck must move to produce a given THETA. Alternatively, a sensitivity button may be used to change the mapping between THETA and the angle of rotation. Thus the object may be made to rotate N times faster or slower than the puck.

In the normal situation above, the user wishes to control the angular orientation of an object on the screen. There are situations - as, for example, those encountered in viewing complex 3-D molecules [Stau78] - where it is desirable to control the rate of rotation of the object so that the object moves continuously at a rate governed by the value of THETA. The automatic vernier effect here is useful, as moving the puck further from the centre of rotation cue, just above or below the zero rotation line, will cause the object to rotate very slowly.

The turntable has been discussed in terms of controlling rotations about the Z axis. The same technique is applicable to producing rotations about the X , Y , or any arbitrary axis. When positioning the centre of rotation cue for a rotation about an axis that lies in a plane parallel to $Z=0$, the system can be set to make a default assumption as to the depth or Z component of the axis, or provide a procedure for depth positioning. For many purposes, setting Z equal to the plane of projection is a natural default. There are a number of distinct interactive procedures for specifying the orientation of an axis in 3-D [Tann81], but these are outside the scope of this paper.

Once the axis has been selected, by whatever means, the rotation is controlled as if it were about the Z axis. The user still moves his pen around the centre of rotation; however, THETA is mapped into a rotation about the chosen axis. As the user moves the tracking cue (*) around the centre cue (+), where both cues remain in the plane

of the screen, the object rotates about the specified axis. Regardless of the orientation of the axis of rotation, the resulting interaction is natural and direct. The turntable improves upon the standard use of the number wheel for rotation by offering the ability to select an axis of rotation, by including a vernier capability, and by providing two forms of visual feedback: a perspective view of the object rotating about a selected axis, and a face-on view of the turntable display which shows the exact angle of rotation.

4.0 The Stirrer

This device, also used primarily for single axis rotation control, converts circular motions of the pen into a series of values that can be used to control the rotation of an object. The user, by making stirring movements with the pen, can move an object around an axis (chosen as in section 3) in the direction of his hand motion (a variation of Newman's light handle [Newm68]). The technique uses the last three puck positions (Figure 4) to calculate a value for PHI, the change of direction at time i . The angle of rotation is then controlled by a function of PHI.

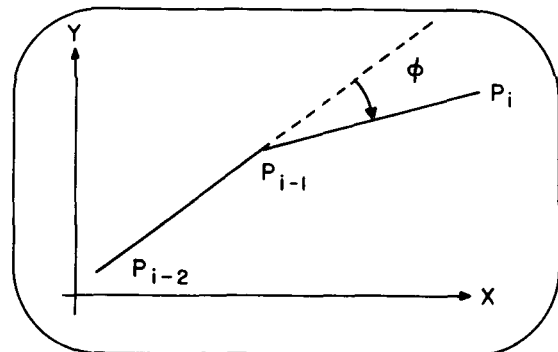


Figure 4 Extraction of curvature from pen motion.

The stirrer is easier to use than the turntable as the user need not be concerned with moving the tracker around a centre point and is free to concentrate on the image he is manipulating. He has only to move the puck in an approximately circular manner to effect the rotation. When the user draws small tight circles, the rotation is quick; gentle curves result in slow object rotation. It does not matter where the tablet puck is on the tablet surface, all that matters is the direction - clockwise or counterclockwise - and the instantaneous curvature as calculated from the last three points. Consequently, the user can keep his eyes on the rotating object and he needs little manual dexterity to control the device. If the user needs to see the current angle of rotation, that value can be included in the status area of the screen or the pictorial display from the turntable method can be invoked (Figure 3).

5.0 Two-axis Trackball

Various authors have described the use of the tablet as a single number wheel or a pair of number wheels [Newm76], [Thor79]. Briefly, the plane of the tablet is regarded as having two orthogonal axes X and Y, parallel to the borders of the tablet. All pen motion (Figure 5) such as that from $P(i-1)$ to $P(i)$ (where $P(i)$ is the current position of the pen at time (i)) is resolved into components dx and dy . These values can then be used to control a variety of transformations. Figure 6 shows Thornton's use of a two-axis valuator to control rotation about the X and Y axes [Thor79]. This number wheel pair is equivalent to a two-axis trackball or a Stanford Mouse. This is a motion sensing technique that forms a basis for the stretching device (section 6) and is a component of the 3-D trackball (section 7).

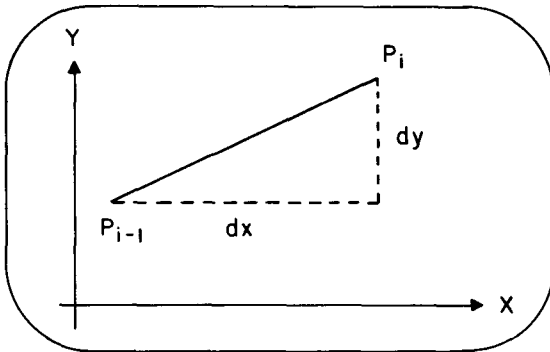


Figure 5 Extracting tablet pen information to control two number wheels.

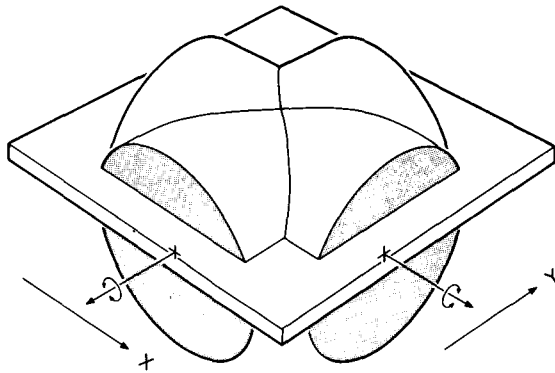


Figure 6 Two number wheels for controlling two-axis rotation.

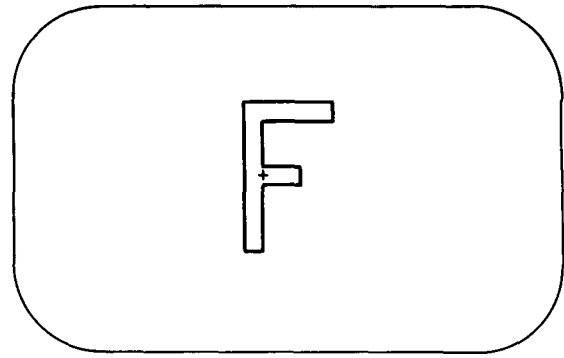


Figure 7 Setting the centre of the scaling operation. The centre of the + symbol will be the scale centre.

6.0 The Rack

The rack, a generalization of a technique used in NEWSWHOLE [Tilb76], [Baec79], is a modification of the two-axis trackball and is designed to facilitate the scaling or stretching of objects. Scaling is a two-step operation. First the centre or origin of the scaling operation must be determined and then the magnitude of the scale factors can be established. To locate the scaling origin, the user, with the tablet in a select mode, picks a point on the screen. Once the user has chosen an origin (+) (Figure 7) he depresses a button on the number pad which fixes it and advances him to the next state. This new state is identified to the user by the appearance of the "identity cue" (.) representing a scale of 1.0 in both X and Y, and the tablet tracker (*). When the tablet tracker is superimposed on the identity cue, an identity scale factor results, and the resulting object is the same as the original.

The transformation process is applied to both X and Y. The X component is determined by
$$XSCALE = (X_{tracker} - X_{origin}) / (X_{identity} - X_{origin})$$
 As the tracker is moved away from the identity cue in an X direction the X scale increases (Figure 8). As the tracker moves back towards the origin, the X scale diminishes to 0 (Figure 9). As the tracker moves past the origin in a negative direction, the result is a negative scale increasing in magnitude (Figure 10). This is equivalent to reflection about the Y axis followed by a scaling by the absolute value of XSCALE. In this technique, the user's hand actions are tightly coupled to the scaling in the two directions. A fluid and easily controllable interaction results. If the scale factor required would force the tracker to run off the screen, then the user has two options: to perform the scaling operation in two or more stages; to perform a menu selection which changes the sensitivity of the scaling operation.

Variations of this technique are available that are essentially constraints to simplify the scaling operation, restricting the scaling to only the X axis or only the Y axis or coupling the two axes for distortionless scaling.

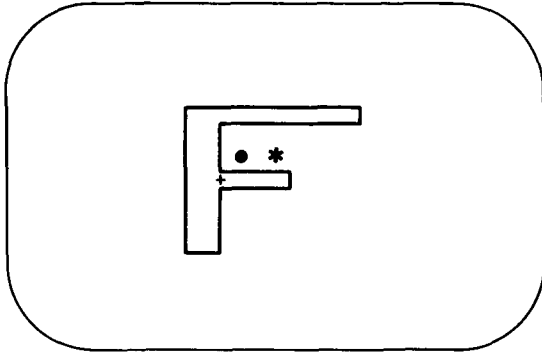


Figure 8 Increasing the X scale factor.

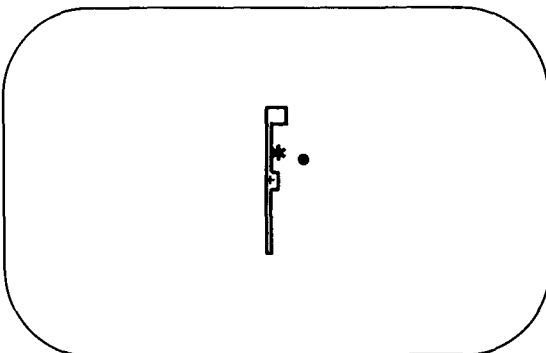


Figure 9 Reducing the X scale factor towards zero.

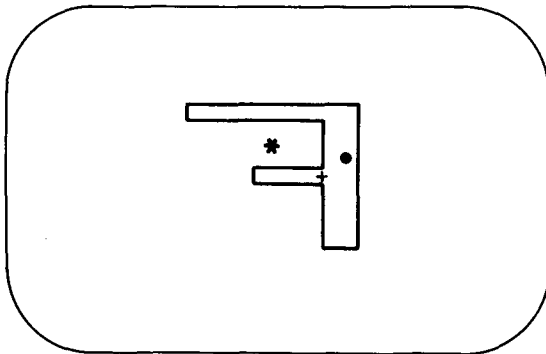


Figure 10 A negative X scale factor.

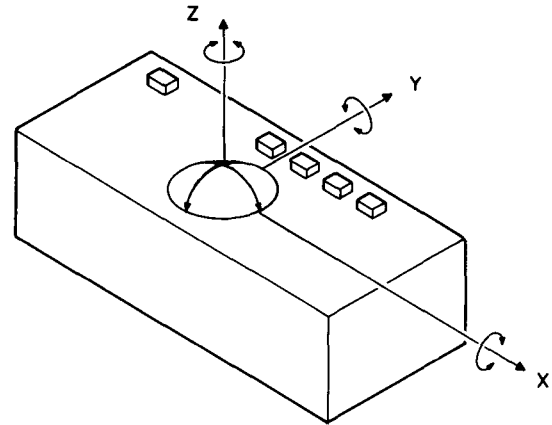


Figure 11 Three-axis trackball.

7.0 The Three-axis Trackball

The tablet-based three-axis trackball emulates a commercially available device - the two-axis trackball - to which has been added a third sensor so that rotation can be detected about each of three orthogonal axes simultaneously. The resulting physical three-axis trackball detects motion about the X axis (rolling the ball up and down), the Y axis (rolling the ball sideways), and the Z axis (twisting the ball clockwise or counterclockwise) (Figure 11).

The full tablet-based three-axis trackball, which is described below, exhibits most of the features of the physical device, but in some ways it is easier to use. The advantage is principally in the improved simultaneous control of the three axes of rotation. It is awkward to combine rotations about Z with rotations about the other axes on the physical device; a rotation about an axis in the XY plane takes one finger to control; a rotation about the Z axis requires that one grip the ball with several fingers in order to twist it. This is because only a small portion of the sphere projects above the surface of the device. The tablet-based device does not have this problem. The puck buttons also favour the tablet-based device over the physical device. Buttons can be added to a trackball chassis, but they are more distant from the user's finger tips and hence take fractionally longer to use.

As implied above, even with a three-axis trackball, the user often performs manipulations by alternating between rolling (XY) and twisting (Z) motions. Consequently there are two distinct ways to simulate a three-axis trackball:

1. provide adjacent buttons on the number pad to allow instant alternations between XY and Z rotations
2. provide full simultaneous control of XYZ axes

The alternation from XY to Z rotation modes is accomplished by pressing either the 'XY' or the 'Z' button on the number pad of the puck. The XY mode is simply the two axis trackball rotation about the X and Y axes as described in section 5. The Z mode uses the stirrer of section 4.

The true simultaneous control of the XYZ axes of rotation is accomplished by combining the two-axis trackball with the stirrer such that the former controls X and Y, while the latter controls Z rotation. In order to provide the resulting device with the 'feel' of the physical device, it is necessary to ensure that relatively straight line motions of the puck produce no Z rotations and that conspicuous attempts to 'stir' the puck produce only Z rotation. In short, the outputs of the two component techniques require modification so that the X and Y rotations are reduced when PHI (Figure 4) is large, and the rotation about Z is made negligible when PHI is small [Tann81]. The result is that regardless of where the user locates the puck, motions in a straight line cause rolling about an axis parallel to the plane of the screen and orthogonal to the direction of motion; motions which are basically circular produce rotations about an axis normal to the screen.

It is also easy to mix these two types of hand motion to produce rotation about all 3 axes at once, because the technique exhibits what Britton *et al* [Brit78] call "kinesthetic correspondence": there is a direct and natural relationship between each of the three distinct hand motions and the corresponding rotations about the three axes.

Several minor advantages accrue to this device:

1. true simultaneity is easier
2. Z motions are easily made continuous
3. the surface of the tablet-based trackball is much larger and hence longer 'finger strokes' result
4. precise location of the manipulating hand is less critical because control motions can be made anywhere on the tablet surface
5. changing logical devices or modes within such a device does not require that the user move his hand, let alone swap gadgets

In practice, the most versatile approach to the tablet-based trackball is to provide (among other possible functions) the following six buttons so that the user can switch instantly into whatever mode is convenient:

- XYZ (full three-axis control)
- XY (two-axis trackball for X and Y)
- Z (stirrer for Z control)
- X (one-axis trackball for X)
- Y (one-axis trackball for Y)
- VELOCITY/DISPLACEMENT (toggle)

The X and Y buttons simulate a trackball in which software has disabled the Z and Y or X sensors. X

axis and Y axis control, when available, is always achieved by means of the same hand motions, regardless of which mode is used; the same is made true for Z. The last button, 'VELOCITY/DISPLACEMENT', switches modes as described in section 2.

8.0 Summary

The ability of the tablet to mimic or emulate physical devices and to provide novel logical devices matched to specific applications renders it the most general purpose and cost effective graphic input device available. In most cases all other physical input devices, excepting the keyboard, can be eliminated. A tablet simulation of a device must perform at least as well as the device it is replacing. This paper describes several techniques that meet this criterion and improve real-time interactive control of 3-D object manipulation, namely: the turntable and the stirrer for one-axis rotation, the two-axis trackball for two-axis rotation, the rack for two-axis scaling, and the three-axis trackball for three-axis rotation. With the tablet, the user need not turn his attention from the task at hand to press buttons, turn knobs, or manipulate a trackball. Consequently, when used to its full capability it is less tiring, causes fewer of the momentary breaks required to search for the appropriate physical device, and provides a less cluttered, less intimidating environment than any equivalent set of input devices. Finally, it should be mentioned that the handling of one device, rather than an array of physical devices, makes easier tasks of programming, debugging, and learning an interactive graphics system.

9.0 Acknowledgements

Many of the techniques in this paper have, in one form or another, been in use for many years at the National Research Council of Canada, and at a number of other locations, for example Xerox PARC and the University of Toronto. We would like to acknowledge the assistance of the members of both of these institutions who helped in the preparation of this paper. Tablet techniques have not been widely published as they are often cumbersome to convey in print. A full understanding is best acquired by live demonstrations, film or video-tape [Baec79], [Newm76], [Wein81], [Ston81].

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