

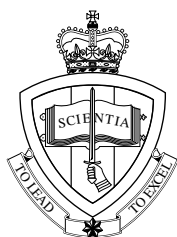
The Graphics Screen and Accuracy

Sharp EL-9650/9900

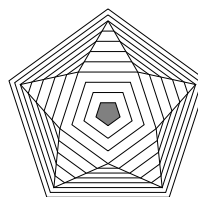
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Contact for more help

Peter McIntyre

School of Physical, Environmental
and Mathematical Sciences
University College (UNSW)
Australian Defence Force Academy
Canberra ACT 2600

Email: p.mcintyre@adfa.edu.au

Phone: (02) 6268 8896

FAX: (02) 6268 8786

At www.unsw.adfa.edu.au/pems/news/high_school/hsc_activities.html

- A variety of graphics-calculator activities for Years 9 and 10 — written as part of the CQTP Program for Sharp, Casio and TI calculators.
- *Using the EL-9650/9900* — an introduction to the basic operations, suitable for Years 8–12.
- *Coordinate Geometry on an EL-9650/9900* — basic commands and a variety of problems, suitable for Years 9 and 10.
- *Population Modelling* — a variety of problems from simple exponential growth to Leslie matrices and difference equations, covering Years 7–12.
- *Sequences and Series on an EL-9650/9900* — basic commands and a variety of problems, suitable for Years 10–12.
- *Matrices on an EL-9650/9900* — suitable for Years 11 and 12.
- *Calculus on an EL-9650/9900* — suitable for Years 11 and 12.
- *Complex Numbers on an EL-9650/9900* — suitable for Years 11 and 12.
- *Programming an EL-9650/9900* — suitable for teachers and keen students.
- *Introduction to Complex Numbers* — complex numbers from the beginning, covering the basic operations, but set in the context of complex numbers as a mathematical structure.

1 The Graphics Screen

Modified from D. Pence, *Calculus Activities for TI Graphic Calculators*, 2nd ed, PWS Publishing, 1994.

Before graphing a function f on a graphics calculator, you must first specify the range of X values to be considered (i.e. restrict the domain to a finitely bounded interval of numbers) and the range of Y values to be allowed. Setting these ranges defines the scales and locates the coordinate axes on the screen. Generally we will use the estimated range of f as the Y range. However, the true range of f may be an unbounded interval, and so it may not be possible to use it for the Y range.

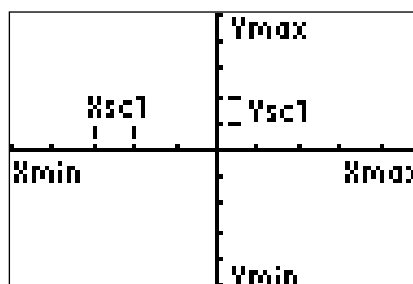
The calculator screen consists of rows and columns of little rectangles, called *pixels*. Compared to a television screen or computer monitor, the pixels on the calculator screen are relatively large. On the EL-9650/9900, the screen consists of a grid 132 pixels across and 64 pixels high.¹ You can just see the individual pixels by turning up the contrast. To do this, press **OPTION** (on the key with $+ - \times \div$ on it) and then hold down the $+$ key. Turn the contrast back down again by pressing **OPTION** and then holding down the $-$ key until you reach the correct setting for you.

Any point (X, Y) on the screen lies in the range

$$X_{\min} \leq X \leq X_{\max}, \quad Y_{\min} \leq Y \leq Y_{\max},$$

where X_{\min} , X_{\max} , Y_{\min} , Y_{\max} are set using WINDOW.

```
Window (Rect)
Xmin=-3.141592654
Xmax=3.141592654
Xscl=1.570796327
Ymin=-1
Ymax=1
Yscl=0.5
```



The first *column* of pixels on the left has the X coordinate X_{\min} , and the 127th *column* of pixels the X coordinate X_{\max} . Similarly, the *rows* of pixels have equally spaced Y values between Y_{\min} and Y_{\max} . There is a similar grid of pixels for any computer-drawn coordinate graph, but on a high-resolution monitor or printer the ‘dots’ or pixels are so small that the eye cannot pick them out.

Each pixel has coordinates (the coordinates of the centre of the pixel) that appear at the bottom of the screen as you move the cursor around with the arrow keys. However,

¹The screen used for graphics is actually 127×63 pixels.

each pixel actually represents a region in the plane (i.e. infinitely many points). If a point to be plotted lies somewhere in the region represented by a pixel, the pixel is turned on (darkened). In TRACE mode, the X value at the bottom of the screen is the X coordinate of the pixel, but the Y value is the value of the function at that X value. This is usually different to the Y coordinate of the pixel, but must lie in the range of Y values covered by that pixel.

The X axis will appear on the screen if $Y_{\min} \leq 0 \leq Y_{\max}$. Scale marks are drawn along the axis at a regular spacing X_{scl} , also set in WINDOW. Similarly, the Y axis will appear if $X_{\min} \leq 0 \leq X_{\max}$, with scale marks spaced by Y_{scl} . No scale marks appear if $X_{\text{scl}}/Y_{\text{scl}}$ is set to 0. If $X_{\text{scl}}/Y_{\text{scl}}$ is too small, the scale marks will run together and the axis will look as though there is a parallel line running right next to it. This is often confused with the graph of the function you are trying to plot.

There are several commands in the ZOOM ZOOM menu which provide convenient ways to change the WINDOW settings. These commands also contain an implied GRAPH command.

Default gives WINDOW settings $[-10, 10, 1] \times [-10, 10, 1]$.

Square makes the scales on the X and Y axes the same. For equal scales, $(X_{\max} - X_{\min})$ is $127/63 \approx 2.3$ times $(Y_{\max} - Y_{\min})$. *Square* is useful if the shape of the function you are plotting is important, such as a semi-circle.

It is often useful to have a setting in which the coordinates of adjacent columns and rows differ by 0.1, i.e. the pixel widths and heights are both 0.1. This is achieved by using *Dec*.

There are a number of other default settings for specific types of functions in ZOOM.

2 Function Graphers — Getting the Picture

Modified from T.P. Dick and C.M. Patton, *Student guide to using technology in calculus*, PWS-Kent, Boston, 1992.

A graph provides a powerful interpretational tool by giving us a visual picture of the input–output pairs a function process produces, but it requires much time and effort to prepare graphs by hand. With the availability of computer and calculator graphics technology, we have a much greater opportunity to exploit graphical representations of functions.

Be forewarned: the graphical evidence provided by a machine can be open to perceptual illusions and therefore to misinterpretations. To make intelligent use of graphical tools, it is important to understand their limitations. In other words, getting the most out of graphics technology requires not only knowing how it can be used, but also how it *can't* be used. Let's look at some of the issues you must be concerned with when using graphing technology.

First of all we need to understand how a graph is produced and displayed by a machine. The screen of a calculator or computer is divided into a rectangular grid of small square picture elements called *pixels*. Each pixel has coordinates corresponding to a single point in the plane, but a pixel does not really represent a point. Rather, a pixel represents a small rectangle containing infinitely many points. The specific point given by the coordinates of the pixel may represent the centre or a corner of the pixel, depending on the particular machine or software. If we want the machine to indicate a certain point in the plane, we have to light up or darken the particular pixel containing that point.

The viewing window

Every graphics package on a computer or calculator has a necessarily limited screen. You might think of this screen as a window from which you can view part of the Cartesian plane. By moving this window around the plane, we can focus our attention on various parts of the graph of a function. This window is also a *lens* through which we can obtain both close-up and distant views of the graph by changing scale. Finding the best window locations and scales are navigational skills for finding our way about a function's graph.

Graphical behaviour can be hidden

- by lying beyond the bounds of the viewing window,
- by scale — zooming in obscures global information about the graph; zooming out obscures local information or detail about the graph,
- by numerical limitations — the choice of which pixels to light up or darken is determined by numerical computations, which in turn are subject to the usual round-off, cancellation, underflow and overflow errors that may occur.

Exercise: Graph the function defined by the formula

$$f(x) = \frac{(x^3 - 1)}{(x - 1)},$$

using Y1 and WINDOW parameters $[-6, 5] \times [-2, 10]$. Be careful with brackets.

- What is $f(1)$? Check your calculator's reaction to this calculation by evaluating Y1(1) as follows: `VARs` (`A`) `1` (Y1) (`(` `1` `)` `ENTER`.
- Does this problem show up on your graph? Use TRACE to investigate. Explain.
- Now change the X WINDOW to $[-6.3, 6.3]$ and repeat (b). Why the difference?
- Move the cursor using TRACE close to, but not at, $X = 1$ and ZOOM in using `ZOOM` `3`. Do this repeatedly (TRACE close to $X = 1$ then `ZOOM` `3`, about 10 times) until an irregularity appears. ZOOM in several more times. Why do you think this might happen? Look at WINDOW.

The graph of f has a *hole* at $x = 1$, since the function is not defined there. However, a machine plot of this function's graph could have several different appearances near $x = 1$:

- the graph may appear to be continuous if $x = 1$ falls in between the X coordinates of two adjacent pixels (but not close enough to either to have the function value affected noticeably by numerical imprecision);
- there may be a missing pixel if the X coordinate of a pixel is exactly 1;
- there may be a jagged jump or spike if the X coordinate of a pixel is very close, but not equal, to 1, due to numerical imprecision.

You are more likely to observe the visual effects of numerical imprecision at small scalings. Even a continuous function's machine-plotted graph may break apart under repeated zooms because the function cannot be calculated accurately enough.

Exercise: Graph $(2 \cos(x) - 2 + x^2)/x^4$ (Radian mode) using a WINDOW of

- $[-10, 10, 0] \times [-0.1, 0.2, 0]$
- $[-0.001, 0.001, 0] \times [-0.1, 0.2, 0]$.

What do you observe?

This is another example of numerical instability — the calculator cannot calculate $\cos(x)$ accurately enough when its argument is very close to 0.

The dimensions of the viewing window are specified by the WINDOW parameters Xmin, Xmax, Ymin, Ymax, with our notation $[Xmin, Xmax] \times [Ymin, Ymax]$. We also know that the EL-9650/9900 graphing screen is 127 pixels wide by 63 pixels high. (The actual screen is 132×64 , but only 127×63 is used for graphing.) From these numbers we can calculate the dimensions of a pixel.

Example: Suppose we specify WINDOW parameters $[-10, 10] \times [-5, 5]$. Find the dimensions of a pixel.

On the EL-9650/9900, the coordinates of a pixel correspond to the centre of the pixel. The pixels are (effectively) touching, so that each interval between adjacent pixels is equal to the width of a pixel. Since there are 127 pixels across the width of the graphing screen, there will be 126 pixel-width intervals between the centre of the leftmost pixel representing Xmin and the centre of the rightmost pixel (of the 127) representing Xmax. Therefore the *width* of a pixel is

$$\Delta X = \frac{X_{\max} - X_{\min}}{126} = \frac{10 - (-10)}{126} = \frac{20}{126} \approx 0.1587.$$

Similarly, since there are 63 pixels vertically, the *height* of each pixel is

$$\Delta Y = \frac{Y_{\max} - Y_{\min}}{62} = \frac{5 - (-5)}{62} = \frac{10}{62} \approx 0.1613.$$

Exercise: If the viewing window is $[-6.3, 6.3] \times [-3.1, 3.1]$, find the dimensions of each pixel.

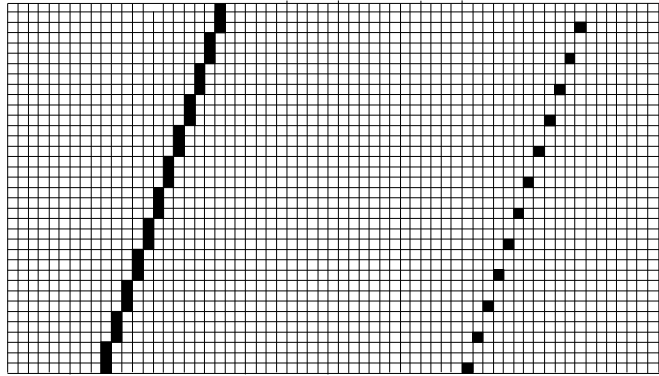
This is often a useful WINDOW to use; it is set automatically by *Dec* in ZOOM ZOOM.

When graphing a function, the calculator starts with the first (leftmost) column of pixels. It computes the ordered pair $(X, f(X))$ using the X coordinate of that column (Xmin) as the value of X, and darkens the pixel in that column whose Y coordinate is closest to $f(X)$, provided $f(X)$ is within the vertical range of the window, i.e. between Ymin and Ymax. This process is then repeated for each column of pixels from left to right.

Lines may be plotted either connected or dotted. Use DRAW LINE to set Y1 connected (normal line) and Y2 dotted.

For a dotted line, the calculator will darken at most one pixel in each column (so the function graph on screen will pass the vertical line test). For a connected line, the function grapher will darken additional pixels to give the visual perception of an unbroken graph. The figure below shows two calculator graphs of the same line; one is plotted connected, the other dotted.

In either case, note that the calculator graph of a function is simply a finite collection of darkened pixels, whereas the true graph generally consists of infinitely many points.



Exercise: Darken the screen in `OPTION`. Plot $Y1 = 5X$ and $Y2 = 5(X-4)$ using `ZOOM` (A) `5` (default axes). Compare the two lines.

3 Significant Digits and Calculations

When we write down a numeric answer to a problem, we have to make some decision as to how many digits we put in the answer. Firstly we have to decide how accurate our answer is — this will depend on the accuracy of the data we use in our calculations and on whether we introduce any further loss of accuracy by our method of calculation. These considerations are discussed below. Secondly, we have to decide what is a *sensible* number of digits to put in our answer. We wouldn't give the distance to a star to a number of digits that takes us down to millimeters, even if we knew it that accurately.

In specifying the accuracy of an answer, we usually give the number of decimal places (DP) or the number of significant digits (SD) that we think are appropriate. We will use significant digits in this course, because it fits in well with scientific notation for specifying numbers, for example 3.56×10^{-5} .

Examples

1. 0.0036 has 2 SD — leading zeros are not significant. We could also write this number as 3.6×10^{-3} , making the number of significant digits clear.
2. 2 may have one SD or may also be an exact number and so implicitly have an infinite number of SD.
3. 2. has 1 SD.
4. 2.00 has 3 SD — trailing zeros after the decimal point are significant.
5. 240 000 000 has 2 SD — trailing zeros before a decimal point are not significant unless specified as being so. Write as 2.4×10^8 .
6. Be careful with rounding. If your answer is an approximation, you should specify the number of significant digits which are accurate.

$$\pi \approx 3.141592654 \quad (10 \text{ SD})$$

$$\approx 3.14 \quad (3 \text{ SD: rounding down})$$

$$\approx 3.142 \quad (4 \text{ SD: rounding up})$$

$$\approx 3.1416 \quad (5 \text{ SD: rounding down})$$

There are at least three sources of concern about significance of digits in an answer.

- **The accuracy of available data**

You should not expect more significant digits in any answer than there are in the least accurate input to the calculation. *Calculation steps never add significant digits, though your calculator will happily add digits!*

Example: A population of 240 000 000 grows by 2% per year for 3 years. What's the population after 3 years?

Numerically, the answer is $240\,000\,000 \times (1.02)^3 = 254\,689\,920$. However, the original number had only 2SD (2 and 4) and possibly 3 — we don't really know about the first 0. The best answer to the question is “about 250 000 000”, or possibly “about 255 000 000” if we thought the first 0 was significant. The answer 254 689 920 is definitely wrong.

- **The finite precision of your calculating device**

Subtraction of nearly equal numbers can be a real significance killer

Example: If we subtract two numbers that only differ in the tenth digit, the answer has only one significant digit.

Adding or subtracting numbers that are very different in magnitude can also lead to inaccuracy

Exercise: We all know that $A + B - A = B$.

Store 10^6 in memory A.²

Store $\sqrt{2} \times 10^{-5}$ (correct – sign?) in B.

Evaluate $A + B - A$.

Repeat³ with $A = 10^7, 10^8, 10^9$. Explain.

- **Loss of significance due to the way we manipulate numbers**

Don't discard digits in an intermediate result. The only time you should round off is at the end of a calculation. Preferably use your calculator to do the calculation all in one go — it keeps 14 digits.

²

Exp	6	STO	ALPHA	A	ENTER
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³Remember the

ENTRY

 key.