MEMORANDUM

To: FMRI Scientists, Data Analysts, and Their Ilk
From: Robert W. Cox
Subject: Interim Documentation for `FD2`
Date: July 8, 1994

In recent weeks, I have made a number of changes to the `FD` program. The new version, named `FD2`, has been installed on the systems `engineer`, `recoman`, `crimson`, `neurolab`, and `esrxd88`. Here is some documentation for the program, both old and new features. New features are marked with a star*, unless they are obvious (like the whole sections devoted to `FIM` calculations).

In the future, I intend to make the program simpler to use and to modify. As it stands now, some features are obscure and hard to use. As Maxwell Smart used to say, "Sorry about that, Chief."

Comments and feedback are welcome. Send e-mail to `rwcox@post.its.mcw.edu`.

Image Formats

`FD2` accepts $N \times N$ images, for $N = 64$, 128, and 256. Each image file consists of N^2 16-bit (short) integers; in the case of $N = 256$, the data bytes may optionally be preceded by 14336 bytes of Signa header, which will be entirely ignored.

The central data structure of the program is a *time course* of images. All of these images must have the same dimension N. Images read in after the time course is complete (*extra* images—see below) may have any legal value of N. This allows the input of high resolution anatomical reference scans as extra images.*

X11

X11 is the windowing system on Unix™ computers. `FD2` runs as an X11 'client' program, which communicates with a 'server' program, which in turn is what actually displays things on the screen. The proper use of some options in `FD2` requires some knowledge of X11; in particular, the '`-geom`' and '`-fim_colors`' options use X11 geometry and color strings.

To use `FD2` effectively, you must be able to deal with X11 windows—lower and raise them, iconify them, etc. I'm not going to try to explain X11 in this memorandum. The best way to learn it is to try it out, and/or get someone to show you the ropes.

Command Line Options

These are typed on the line with which you invoke `FD2`. An example is

```
FD2 -im1 4 i1.* -extra i1.0001 &
```

Some options conflict with each other; these are noted below. The program attempts to catch such errors in usage.

After the options comes the list of files to be read into the program. In the example above, `i1.*` means to read in all files whose names starts with '`i1.`' and ends in anything. The program can handle a maximum of 1050 files in the time course; there is no explicit limit to *extra* files after the time course.

-d display This option can be used to set the X11 display. This is only needed if **(a)** you are running `FD2` on one computer but displaying the results on another, and **(b)** have not set the Unix `DISPLAY` environment appropriately. If these conditions hold, then **(1)** type `xhost +` on the machine on which you will be displaying, and **(2)** use this option with `display` replaced by `machinename:0.0`.

-geom geometry This option is used to control the initial X11 geometry of the image window. It is very seldom used, since you may resize and move the window to your heart's content after it actually starts up. The correct format for the '`geometry`' string can be found in any book on X11.

-gsize⋆ x y This option is used to change the size of the time series graphing window. The default values of `x` and `y` are both 512. I don't recommend that they be reduced below 200 or above 900. Once the program starts, this window *cannot* be resized.

-nc nlevels This option controls the number of intensity levels (gray scale and color) used to display images. The default is 200, and the legal range is 4...410. Some X11 displays can't handle the default number of intensities, and so you must use something like '`-nc 100`' to make them work. Since the human eye can only distinguish about 250 gray levels under the best of conditions, there usually isn't much need to monkey with this option. (**N.B.**: on `engineer`, the X11 display can't handle 200 levels, so the version compiled there has the default number of levels set to 80.)

-sp degrees This option controls the range of colors displayed when the image is switched to color mode. The smallest legal value is 1, the largest is 360, and the default is 240.

-gam gamma This option is used for gamma correction—a fixup for intensity values that will be displayed. The 'correct' value depends on your monitor. You may try 2.3, or you may simply adjust the intensity using the mouse controls described later.

-num npoints This important option tells `FD2` how many files that it reads in are to be considered part of the time course. Such images may be analyzed via the `FIM` controls described later, and will be graphed in the secondary window. Other images will only be displayed, but will not be graphed or processed through `FIM`. Example:

```
FD2 -num 100 i1.* anatomicalimage
```

Using `-num` requires that you know how many images are in the sequence denoted by `i1.*`. The next option does away with that need.

-extra* This is the *only* option that should appear in the list of image file names (as opposed to being before the list). It means that all files *before* are in the time course, and all files *after* are not. Example:

```
FD2 i1.* -extra anatomicalimage
```

As mentioned earlier, images after `-extra` need not be the same dimensions as the time course images. The options `-num` and `-extra` conflict with each other and may not both be used in any single run of `FD2`. Note that you may read in extra files later using the '`F`' key.

-im1 num This option means that the first `num` images will be identical—that is, that images 1, 2, ..., `num` − 1 will be replaced with image `num`. The main use of this is to allow the T_1 steady-state to be reached in a sequence of echo-planar images. Example:

```
FD2 -im1 4 i1.* -extra i1.0001
```

In this example, the first 3 images are thrown away and replaced by `i1.0004`. Then, I have used the `-extra` option to put the first EP image off the end of the time course—this shot usually looks the best, and so makes a nice reference to look at.

-fim_colors* This option allows you to control the `FIM` overlay colors and thresholds from the command line. It is described in detail later, along with how you can program the X11 defaults database to make your color selections permanent.

-ideal* **reffile** This option lets you read in a reference time series for `FIM` calculations. The file is in the format that you know and love: one integer number per line, all numbers over 33333 are taken to mean 'ignore this data point in the time course of images'. You may also read a file interactively, via the '`FIM`' key, so this is only useful if you want to start up with `FIM` running.

-pcthresh* **value** This option lets you set a threshold for `FIM` calculations—if none is given, the default is 0.50. This is the threshold for the partial correlation coefficient: all values larger will be accepted, values smaller rejected. **N.B.**: this is not compatible with the `-pcnt` value used in the old `fim` program! The `value` given here must be in the range 0.0–1.0 (not inclusive). Using the '`FIM`' key, you can also change the threshold interactively.

Runtime Options Controlled by the Keyboard

There are a vast number of these, probably because that is the easiest thing to program under X11 (as opposed to buttons and other widgets). Note that these are case sensitive: '`S`' and '`s`' cause totally different actions. In no particular order:

$\boxed{\texttt{q}}$ Quit the program. '`Q`' also works.

$\boxed{\texttt{C}}$ Change image to color.

$\boxed{\texttt{B}}$ Change image back to gray-scale.

$\boxed{\texttt{s}}$ If image is in color, swap the color-scale.

$\boxed{\texttt{1}}$ Move to first image in time course. ⋆Keys `2`–`9` also work to move to the appropriate image. For images past 9, use the `I` key. (Whatever you do, don't press the `0` key!)

$\boxed{\texttt{L}}$⋆ Move to last image in time course.

$\boxed{\texttt{l}}$ Move to last image in program (including extra images).

$\boxed{\texttt{>}}$ Move to next image.

$\boxed{\texttt{<}}$ Move to previous image.

$\boxed{\texttt{I}}$ Type in the image number to move to. The cursor changes to a hand shape, while the program expects you to type in the number, followed by a 'return'.

$\boxed{\texttt{S}}$ Save the current image to a file, whose name will be requested in a dialog box. Note that the `FIM` color overlay, if present, will *not* be saved with the image. Also note that the actual image saved contains the `FD2` scaled values, not the original values that may have been read in from disk. This means that the image saved is mostly useful for display purposes, not for further analysis.

$\boxed{\texttt{+}}$ Scale graph plots up.

$\boxed{\texttt{-}}$ Scale graph plots down.

$\boxed{\texttt{M}}$ Increase number of graphs.

$\boxed{\texttt{m}}$ Decrease number of graphs.

$\boxed{\texttt{N}}$ Type in number of graphs to display (1–25⋆). The cursor changes to a hand shape, while the program expects you to type in the number, followed by a 'return'.

$\boxed{\texttt{G}}$ Increase grid spacing in graphs.

$\boxed{\texttt{g}}$ Decrease grid spacing in graphs.

$\boxed{\texttt{R}}$ Change image frame color.

$\boxed{\texttt{r}}$ Change grid color in graphs.

$\boxed{\texttt{p}}$ Save time series displayed in central (colored) graph to a file—this may later be used as a 'reference' or 'ort' file for `FIM`. The program puts up a dialog box and asks you for the filename. If you are saving a lot of time series, the next option may be more useful. **N.B.**: if you used the `-im1 num` option, the first `num` -1 values in the time series files will be set to 99999, which is a flag to `FIM` that they are not to be used.⋆

$\boxed{\texttt{w}}^{\star}$ Save the time series displayed in the the central (colored) graph to a file. The filename format is '`xxx_yyy.suffix`'. The values of '`xxx`' and '`yyy`' are the grid coordinates of the saved pixel. The suffix (including the period, if you want it) are requested the first time you use '`w`'; later invocations of the '`w`' key use the same suffix.

$\boxed{\texttt{A}}^{\star}$ Toggles autoscaling of image displays. Normally, images inside the time course are all scaled in intensity together (extra images are scaled individually at all times). When you turn '`A`' on, then time course images will be scaled individually. When you use '`A`' again, they will be scaled (for display) collectively again.

$\boxed{\texttt{F}}^{\star}$ Read an image file into the program. It will be placed at the end of the extra images.

$\boxed{\texttt{K}}^{\star}$ Remove an image from the program. Only extra images may be so killed—time course images are inviolate.

$\boxed{\texttt{H}}^{\star}$ Hide the `FIM` overlay, if present. This is useful when you want to see underneath the colorized regions. Pressing `H` again will cause the `FIM` overlay to reappear.

$\boxed{\texttt{h}}^{\star}$ Hide the graphing area frame in the image window. Pressing `h` again will cause the frame to reappear.

$\boxed{\texttt{O}}^{\star}$ Switch the `FIM` overlay to a checkerboard pattern (instead of the solid fill that is the default).

Mouse Controls

These options are invoked by clicking a mouse button in the image or graph window. The options that involve clicking on a 'key' in the graph window are discussed later.

Image: Button 1 Positions the frame over the chosen pixel, and redraws graph window accordingly.

Image: Button 2 At the right side of the image, this will squeeze the colors (or gray-scales); at the left, it will expand them. At the top and bottom, it changes the color saturation. In the color bar at the right, it will circulate the colors. Button 2 works as long as you press it down, which means that it is very rapid.

Image: Button 3 Does the same as Button 2, but one click at a time. Much better for those of us who are clumsy. Clicking Button 3 in the center of the image will restore the colors to their defaults, which is useful after you have messed them up.

Graph: Button 1 Clicking on a pixel graph will bring that graph to the center. Pressing on the red triangle (at the bottom of all the graphs) and dragging it is a way to move to a desired image in the time course.

Non-`FIM` Keys

Since the use of `FIM` in `FD2` has so many options, it is discussed separately.

`Rot` Button 1 causes a 90° counterclockwise rotation of all images; Button 3 does a clockwise rotation.

`Diff` This allows you to display the difference between a given image and the average of a 'base' image, which is formed as the average of a set you choose. After clicking on '`Diff`', two new keys pop up. Display the first image you want for the base, and click on the '`first image`' key; then display the last image you want for the base, and click the '`last image`' key. After that, any image displayed will have the base image subtracted from it. Click on the '`Norm`' key to go back to normal.

When in '`Diff`' mode, the bottom of the graph window displays the % difference between the image displayed and the base image, in the centered pixel. This is useful if you want to quantify the signal level change between two tasks in an FMRI experiment.

`Avim` Works similarly to '`Diff`', but just displays the average image. Can be used to average out noise. May also be used in `Diff` mode, in which case the displayed image is the difference between two averages.

`FIM`* and Its Pals

Pressing the '`FIM`' key will cause a host of options to become available. The first thing that happens is that three new keys pop up. These keys control the `FIM` options, such as reference time series, correlation coefficient threshold, etc.

No actual `FIM` calculation takes place until you order it. When you click on the '`FIM`' key, its label changes to '`GO!`'. When you click on '`GO!`', then the actual calculations you've set up will be carried out (and the three `FIM` control keys will disappear).

The first `FIM` control key is labeled `set threshold`. By clicking on this, you get a dialog box where you type in the value to be used for the correlation coefficient threshold, a number between 0 and 1.

The second `FIM` control key is labeled `ref/ort file`. It is used to read in a time series file for the reference function, or for an 'ort' function (explained below). Clicking the left button will bring up a dialog box for the reference function filename; clicking the middle button will ask for the 'ort' function filename. These files must be in the usual format for `FIM` (described earlier under the '`-ideal`' command line option).

The third `FIM` control key does many things, partly because I ran out of room to put more keys into the graph window. When `FD2` starts up, this key will be labeled '`PUSH BUTTON 3`'. To cycle between this key's many options, you click the 3rd mouse button when the cursor is in the key's window: this is signified by the '`->`' at the right edge of each key option.

To activate a particular option, you press the 1st or 2nd mouse button. At the time of this writing, the options on this key are:

`ref =pixel` This sets the `FIM` reference function to be the time series displayed in the central graph. Any current reference function is thrown away.

`ref+=pixel` This averages the time series in the central graph into the current reference function. (The symbol '`+=`' is from the C programming language.) If there is no current reference function, then it has the same effect as '`ref =pixel`'. With this option, you can create a reference function that is the average of any number of pixels, chosen by alternately bringing the desired pixel to the central graph, then clicking this key.

`smooth ref` This applies a 'median-of-3' filter to the reference time series. The effect is to smooth it out a little.

`thresh -+` This steps the `FIM` correlation coefficient threshold up and down in steps of 0.05. To step down ('`-`'), click the left mouse button; to step up ('`+`'), click the middle button.

`NO FIM` This option turns the `FIM` calculations and display off. To start them up again, you must redefine the reference function. The 'ort' functions and other settings are remembered. If you simply wish to temporarily hide the `FIM` overlay, use the '`H`' keypress, described earlier.

`refplt -+` This option lets you change the number of copies of the reference function that are displayed in the graph windows. As in the '`thresh -+`' option, the left mouse button moves the number down, and the right mouse button moves the number up. The alternatives are: no display, display only in the central graph, display in all graphs.

`save ref` This will bring up a dialog box asking for the name of an output file. The current reference time series will be written to disk under that name. By combining this option with the '`ref+=pixel`' option, you can save averages of pixels that you select interactively.

`polort -+` This sets the number of polynomial 'ort' functions up and down. The default number is 0, which means that only the mean is removed before the correlation coefficient is computed. If you move up to 1, then any linear trend will also be removed. If you move down to -1, then no polynomial 'ort' will be used—this is almost certainly a very bad idea, but the option is there if you want it.

By the way, 'polynomial' here means in time. That is, if the number of polynomial 'orts' is 2, then the functions 1, t, and t^2 will be removed from the data during the calculation of the correlation coefficient.

`ort = ref` This sets an 'ort' function to be the current reference time series. In turn, the current reference time series is invalidated, and you must define the reference function anew. The main application of this option is to create an 'ort' from various pixels (using the '`ref+=pixel`' option). If you have an 'ort' function on disk already, you may read it in directly using the second `FIM` control key, described earlier.

`clear orts` This throws away all 'ort' functions currently defined.

Note that there is no place where the graphs of 'ort' functions are displayed. This is a drawback, since you cannot see what you are removing from the data, so you must simply *know*. When `FIM` is active (that is, when there is a reference function defined), the name of the reference function and the number of 'orts' are displayed in the top center of the graphing window. When that display is red, the current `FIM` overlay is correct; when that display is blue, this means that you must press '`GO!`' to recompute the `FIM` overlay.

`FIM` Outputs

Besides the color overlay, `FIM` also computes two images: the correlation coefficient image, and the `FIM` intensity image. These two images are placed at the end of the extra images. Every time you press '`GO!`' and recompute the `FIM` overlay, a new pair of images will be appended. This is true even if you simply lower the correlation threshold and recompute, and so the two images will be the same as the last computation.

Clearly, a lot of `FIM` correlation and intensity images could build up at the end of the extra image space. You can use the '`K`' key to delete these images as desired. Note that the images are not labeled except as '`correlation_image`' and '`fim_image`', so if you create more than one such pair of images, you must keep track (in your head, or on paper) of which image was created under what circumstances (e.g., threshold, reference function, 'ort' functions, ...).

The correlation image is normalized to the range $[-10000, 10000]$, corresponding to correlation coefficients in the range $[-1.0, 1.0]$. The `FIM` intensity image is similarly normalized to $[-10000, 10000]$, corresponding to the range $[-\alpha_{\max}, \alpha_{\max}]$. Note that for these images, no thresholding has been done (unlike the color overlay). You may use the pixel value display (at the bottom of the graph window) to examine values in these images—simply center the frame over the desired pixel.

The '`H`' keypress control (described earlier) is useful when examining the `FIM` correlation and intensity images, since the color overlay often obscures the very points you most want to look at.

`FIM` Computations

`FIM` computes the partial correlation coefficient of each pixel's time course with the reference function, after removing any 'ort' functions from the time courses. Loosely, you may think of the correlation process as looking for a copy of the reference function in the data. The 'ort' process first looks for a copy of each 'ort' function in the data, and then subtracts that copy out. The usual purpose of such a calculation is to prevent one kind of signal from masking the presence of the reference function.

Mathematically, the `FIM` calculations may be summarized by the following equations:

$$\rho = \frac{\langle \mathbf{Pr}, \mathbf{Px} \rangle}{|\mathbf{Pr}|\,|\mathbf{Px}|} = \text{partial correlation coefficient}$$

$$\mathbf{x} = \text{data time series (as a vector)}$$

$$
\begin{aligned}
\mathbf{r} &= \text{reference time series (what we `expect' to see)} \\
\mathbf{P} &= \text{projection matrix that removes undesired components of signal} \\
&= \mathbf{I} - \mathbf{S}\left[\mathbf{S}^T\mathbf{S}\right]^{-1}\mathbf{S}^T \\
\mathbf{S} &= \text{matrix formed from `ort' time series (including polynomials)} \\
\alpha &= \frac{\langle \mathbf{Pr}, \mathbf{Px} \rangle}{|\mathbf{Pr}|^2} \\
&= \text{unnormalized } \texttt{FIM} \text{ intensity, used to choose overlay colors}
\end{aligned}
$$

The actual calculations are done in a recursive way, using the same routines as the real-time FMRI program `efd`.

`FIM` Overlay Colors and Thresholds

The overlay colors and thresholds can be altered by the user, but not interactively. The `-fim_colors` command line option can be used to experiment with various color settings, but normally you will want to set your color choices permanently. This is done using the X11 'defaults database', which is defined by a file `.Xdefaults` in your home directory on the machine where the display is.

From 1 to 9 colors may be used to display `FIM` intensities of pixels whose correlation coefficients are above threshold. The `FIM` intensity is defined as the value of the dot product of the reference vector with the (orthogonalized) time series in each pixel. Suppose that the largest such intensity is called 1.0. For each color level you choose, you must specify three items:

threshold **positive color** **negative color**

The threshold is a number between 0 and 1, and determines the `FIM` intensity levels at which the associated colors will be displayed. The colors are to be specified as strings compatible with the X11 color system. You have several possibilities in the format of your color specifications:

- Color names, such as `yellow`, `cyan`, ... The file `/usr/lib/X11/rgb.txt` contains the list of predefined color names. Or see a book on X11.
- RGB values, specified as hexadecimal strings: `#ff9911` gives a sort of orangey color, for example.
- RGB values, specified as floating points levels between 0 and 1: `RGBi:0.0/0.8/1.0` is cyan-ey, for example.
- The various CIE systems. See a book on X11 to explain these.

Number the levels you choose from 1 to L, where $1 \leq L \leq 9$. Level 1 must be the highest threshold, level 2 the next highest, etc. Call the threshold value at level ℓ `fim_thr_`ℓ, the positive color `fim_pos_`ℓ, and `fim_neg_`ℓ, for ℓ from 1 to L. Then on the command line, you can specify the colors by the option:

```
-fim_colors L fim_thr_1 fim_pos_1 fim_neg_1
              fim_thr_2 fim_pos_2 fim_neg_2 ...
              fim_thr_L fim_pos_L fim_neg_L
```

The values that I use correspond to:

```
-fim_colors 3 0.66 yellow cyan 0.33 orange dodgerblue 0.05 red blue
```

For intensities from 0.66 to 1.0, yellow is used; from 0.33 to 0.66, orange is used, and from 0.05 to 0.33, red is used. From -0.66 to -1.0, cyan is used; from -0.33 to -0.66, dodgerblue is used, and from -0.05 to -0.33, blue is used.

Note that after the '`-fim_colors`', $3L+1$ values must follow in the order given: number of levels L, threshold, color, color, threshold, color, color, ... All the colors must be interpretable by X11, or they will be set to the default colors, which you almost certainly will not like.

Obviously, this technique is a pain in some portion of the anatomy. Once you like the colors you have, you can fix the colors and thresholds by editing the `.Xdefaults` file in your home directory. Here are the lines to put in for the example above:

```
FD*fim_colors:   3
FD*fim_thr_1:    0.66
FD*fim_pos_1:    yellow
FD*fim_neg_1:    cyan
FD*fim_thr_2:    0.33
FD*fim_pos_2:    orange
FD*fim_neg_2:    dodgerblue
FD*fim_thr_3:    0.05
FD*fim_pos_3:    red
FD*fim_neg_3:    blue
```

The *next* time you login, the changes to `.Xdefaults` will take effect. To force them to take effect just after you edit the file, you must give the command '`xrdb -merge .Xdefaults`'.

An alternative to using `.Xdefaults` is to create an alias, as in

```
alias fd 'FD2 -fim_colors 2 0.5 hotpink limegreen 0.1 magenta seagreen'
```

Then you may type '`fd`' to start the program with the choice of colors given above. To store an alias, you need to edit your `.cshrc` file.