Image and Volume Registration with AFNI

- Goal: bring images collected with different methods and at different times into alignment
- Facilitates comparison of data on a voxel-by-voxel basis
  - Functional time series data will be less contaminated by artifacts due to subject movement
  - Can compare results across scanning sessions once images are properly registered
- Most (all?) image registration methods now in use do pairwise alignment:
  - Given a base image $J(x)$ and target image $I(x)$, find a geometrical transformation $T[x]$ so that $I(T[x]) \approx J(x)$
  - $T[x]$ will depend on some parameters
    - Goal is to find the parameters that make the transformed $I$ a ‘best fit’ to $J$
  - To register an entire time series, each volume $I_n(x)$ is aligned to $J(x)$ with its own transformation $T_n[x]$, for $n=0, 1, \ldots$
    - Result is time series $I_n(T_n[x])$ for $n=0, 1, \ldots$
    - User must choose base image $J(x)$
Most image registration methods make 3 algorithmic choices:
- How to measure mismatch \( E \) (for error) between \( I(T[x]) \) and \( J(x) \)?
- How to adjust parameters of \( T[x] \) to minimize \( E \)?
- How to interpolate \( I(T[x]) \) to the \( J(x) \) grid?
  ➥ So can compare voxel intensities directly

Existing AFNI programs match images by grayscale (intensity) values
- \( E = \) (weighted) sum of squares differences = \( \sum_x w(x) \cdot (I(T[x]) - J(x))^2 \)
  ➥ Only useful for registering ‘like images’:
    - SPGR\( \leftrightarrow \)SPGR, EPI\( \leftrightarrow \)EPI, but not SPGR\( \leftrightarrow \)EPI
- Parameters in \( T[x] \) are adjusted by “gradient descent”
- Several interpolation methods are available:
  ➥ Default method is Fourier interpolation
  ➥ Polynomials of order 1, 3, 5, 7 (linear, cubic, quintic, and heptic)

Alternative method would be to match features computed from grayscale images:
- Brain outline
- Edges (places where image intensity changes abruptly in 1-2 pixels)
- Such techniques can be used to match SPGR\( \leftrightarrow \)EPI volumes
  ➥ Program 3dAnatNudge can estimate SPGR\( \leftrightarrow \)EPI translations
  ➥ But not rotations or warping
• AFNI program **3dvolreg** is for aligning 3D volumes
  ✦ **T[x]** has 6 parameters:
    ➡ Shifts along x-, y-, and z-axes; Rotations about x-, y-, and z-axes
  ✦ Generically useful for intra- and inter-session alignment
  ✦ Motions that occur within a single TR (2-3 s) cannot be corrected this way, since method assumes a rigid movement of the entire volume
• AFNI program **2dImReg** is for aligning 2D slices
  ✦ **T[x]** has 3 parameters for each slice in volume:
    ➡ Shift along x-, y-axes; Rotation about z-axis
  ✦ Useful for sagittal EPI scans where dominant subject movement is ‘nodding’ motion that may be faster than TR
  ✦ It is possible and sometimes even useful to run **2dImReg** to clean up nodding motion, followed by **3dvolreg** to deal with out-of-slice motion
• Hybrid ‘slice-into-volume’ registration:
  ✦ Put each separate 2D image slice into the target volume with its own 6 movement parameters (3 out-of-plane as well as 3 in-plane)
  ✦ Has been attempted by some AFNI users but the results are not wildly better than volume registration; method often fails on slices near edge of brain
    ➡ More work is needed (i.e., **send money**)
• Intra-session registration:

```
3dvolreg -base 4 -heptic -clipit -zpad 4 \ 
  -prefix fred1_epi_vr \ 
  -dfile fred1_vr_dfile \ 
  fred1_epi+orig
```

- **-base 4** ⇒ Selects sub-brick #4 of dataset fred1_epi+orig as base image $J(x)$
- **-heptic** ⇒ Use 7th order polynomial interpolation (my personal favorite)
- **-clipit** ⇒ Clip off negative voxels to zero
  → Negative voxels are artifacts of high-order interpolation methods
- **-zpad 4** ⇒ Pad each target image, $I(x)$, with layers of zero voxels 4 deep on each face prior to shift/rotation, then strip them off afterwards
  → Zero padding is particularly desirable for **Fourier** interpolation
  → Is also good for polynomial methods, since if there are large rotations, some data may get ‘lost’ when no zero padding is used (due to 4-way shift algorithm used for fast rotation)
- **-prefix fred1_epi_vr** ⇒ Save output dataset into a new dataset with the given prefix name (e.g., fred1_epi_vr+orig)
- **-dfile fred1_vr_dfile** ⇒ Save estimated movement parameters into a 1D (i.e., text) file with the given name
  → Can be plotted with command

```
1dplot -volreg -dx 5 -xlabel Time ‘fred1_vr_dfile[1..6]’
```
Can now register second dataset from same session:

```shell
3dvolreg -base 'fred1_epi+orig[4]' -heptic -clipit -zpad 4 \
   -prefix fred2_epi_vr -dfile fred2_vr_dfile \
   fred2_epi+orig
```

- Note base is from different dataset (**fred1_epi+orig**) than input (**fred2_epi+orig**)
- Aligning all EPI volumes from session to EPI closest in time to SPGR

```shell
1dplot -volreg -dx 5 -xlabel Time 'fred2_vr_dfile[1..6]' gives:
```

- Note motion peaks at time ≈ 160s: subject jerked head up at that time
Examination of time series \texttt{fred2_epi+orig} and \texttt{fred2_epi_vr+orig} shows that head movement up and down happened within about 1 TR interval.

- Assumption of rigid motion of 3D volumes is not good for this case
- Can do 2D slice-wise registration with command

\begin{verbatim}
2dImReg -input fred2_epi+orig \ 
    -basefile fred1_epi+orig \ 
    -base 4 -prefix fred2_epi_2Dreg
\end{verbatim}

- Graphs of a single voxel time series near the edge of the brain:
  - Top = slice-wise alignment
  - Middle = volume-wise adjustment
  - Bottom = no alignment
- For this example, \texttt{2dImReg} appears to produce better results. This is because most of the motion is ‘head nodding’ and the acquisition is sagittal
- You should also use AFNI to scroll through the images (using the Index control) during the period of pronounced movement, on all 3 datasets
• Intra-subject, inter-session registration (for multi-day studies on same subject)
  ✷ Longitudinal or learning studies; re-use of cortical surface models
  ✷ Transformation between sessions is calculated by registering high-resolution anatomicals from each session

- **to3d** defines relationship between EPI and SPGR in each session
- **3dvolreg** computes relationship between sessions
- So can transform EPI from session 2 to orientation of session 1

✦ Issues in inter-session registration:
  ➦ Subject’s head will be positioned differently (in orientation and location)
    ✷ xyz-coordinates and anatomy don’t correspond
  ➦ Anatomical coverage of EPI slices will differ between sessions
  ➦ Geometrical relation between EPI and SPGR differs between session
  ➦ Slice thickness may vary between sessions (try not to do this, OK?)
• Anatomical coverage differs

✧ At acquisition

✧ After rotation to same orientation, then clipping to day 2 xyz-grid

- Same voxels aren’t same tissue
- Because EPI grids differed in xyz — need to shift Day 2 upwards
Another problem: rotation occurs around center of individual datasets.

EPI & SPGR before rotation

Good: Rotate EPI & SPGR about SPGR center

Bad: Rotate EPI & SPGR about individual centers

need to shift left
Solutions to these problems:

- Add appropriate shift to E2 on top of rotation
  - Allow for xyz shifts between days (E1-E2), and center shifts between EPI and SPGR (E1-S1 and E2-S2)
- Pad EPI datasets with extra slices of zeros so that aligned datasets can fully contain all data from all sessions
- Zero padding of a dataset can be done in `to3d` (at dataset creation time), or later using `3dzeropad`
- `3dvolreg` and `3drotate` can zero pad to make the output match a “grid parent” dataset in size and location
Recipe for intra-subject S2-to-S1 transformation:

1. Compute S2-to-S1 transformation:
   ```
   3dvolreg -twopass -clipit -zpad 4 -base S1+orig \n   -prefix S2reg S2+orig
   ```
   - Rotation/shift parameters are saved in \texttt{S2reg+orig.HEAD}

2. If not done before (e.g., in \texttt{to3d}), zero pad E1 datasets:
   ```
   3dZeropad -z 4 -prefix E1pad E1+orig
   ```

3. Register E1 datasets within the session:
   ```
   3dvolreg -clipit -base 'E1pad+orig[4]' -prefix E1reg \n   E1pad+orig
   ```

4. Register E2 datasets within the session, at the same time executing larger rotation/shift to session 1 coordinates that were saved in \texttt{S2reg+orig.HEAD}:
   ```
   3dvolreg -clipit -base 'E2+orig[4]' \n   -rotparent S2reg+orig \n   -gridparent E1reg+orig \n   -prefix E2reg E2reg+orig
   ```
   - \texttt{-rotparent} tells where the inter-session transformation comes from
   - \texttt{-gridparent} defines the output grid location/size of new dataset
   - Output dataset will be shifted and zero padded as needed to lie on top of \texttt{E1reg+orig}
Recipe above does not address problem of having different slice thickness (EPI and/or SPGR) in different sessions

- Best solution: pay attention when you are scanning, and always use the same slice thickness for the same type of image
- OK solution: use 3dZregrid to linearly interpolate datasets to a new slice thickness

Recipe above does not address issues of slice-dependent time offsets stored in data header from to3d (e.g., ‘alt+z’)

- After interpolation to a rotated grid, voxel values can no longer be said to come from a particular time offset, since data from different slices will have been combined
- Before doing this spatial interpolation, it makes sense to time-shift dataset to a common temporal origin
- Time shifting can be done with program 3dTshift
  - Or by using the -tshift option in 3dvolreg, which first does the time shift to a common temporal origin, then does the 3D spatial registration

Further reading at the AFNI web site

- File README.registration (plain text) has more detailed instructions and explanations about usage of 3dvolreg
- File regnotes.pdf has some background information on issues and methods used in FMRI registration packages