Diffusion

Tensor

Imaging

What’s it for?

DTI can identify directional fibers

like muscle

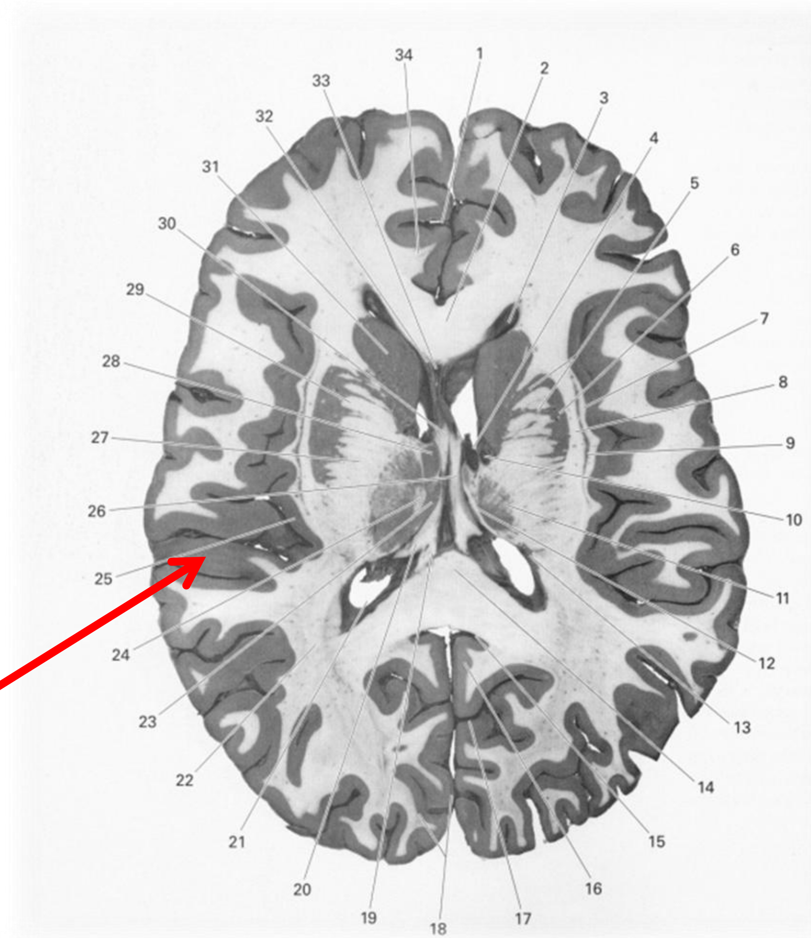
and nerves

We are interested in nerves in the brain

a.k.a.
“axon bundles”
or
“tracts”.

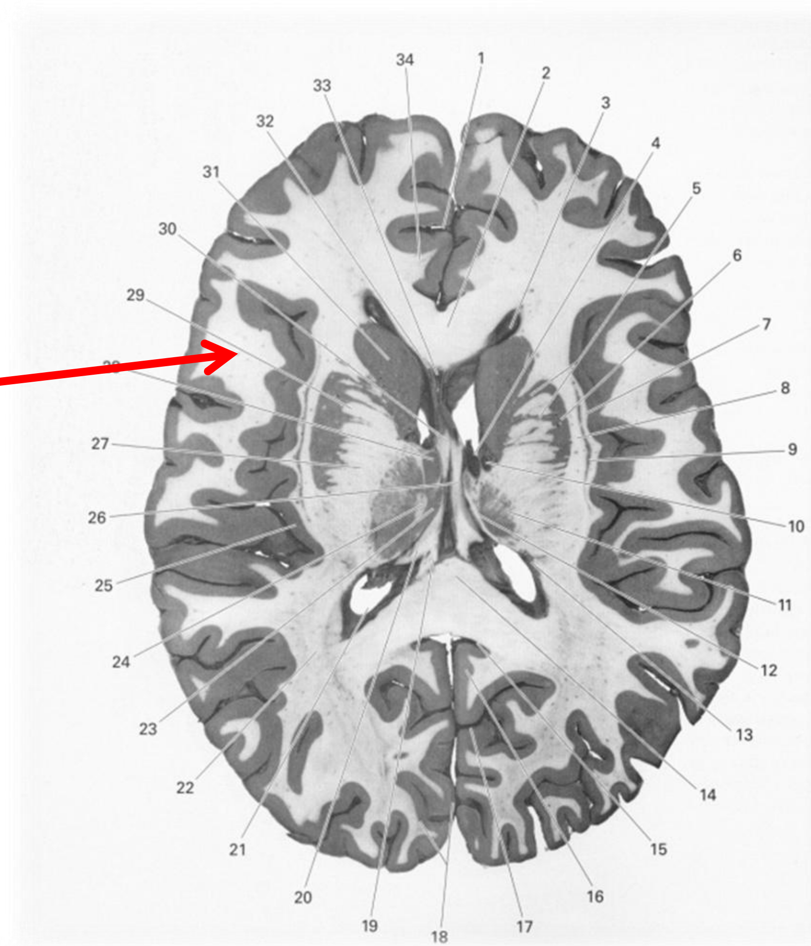
Up 'til now....

people have been pretty good at understanding Grey Matter



But,

not so good at understanding White Matter

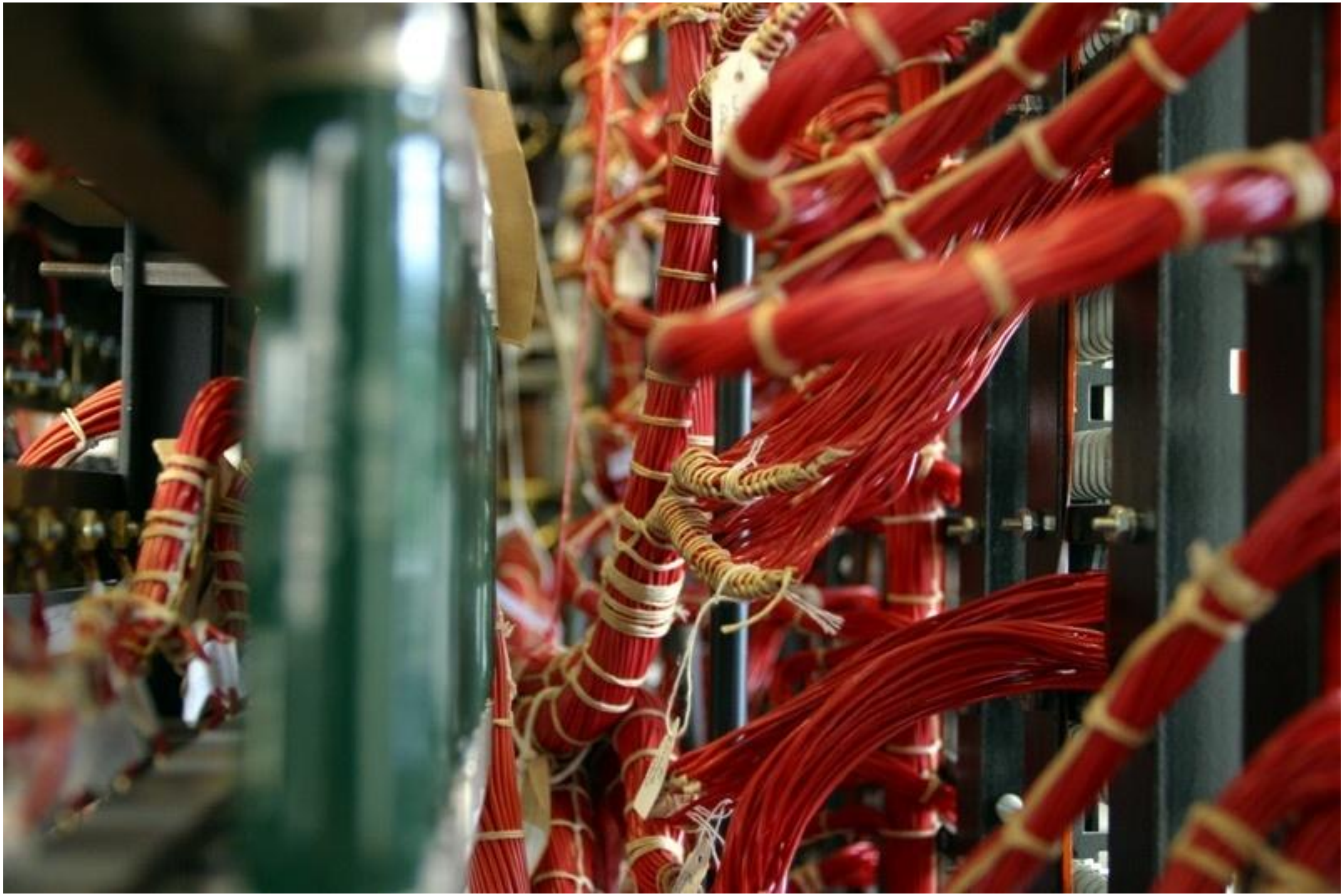


White Matter

is the

brain's

wiring



a.k.a. “tracts”

or “axon bundles”.

DTI shows us

tract location,
and organization

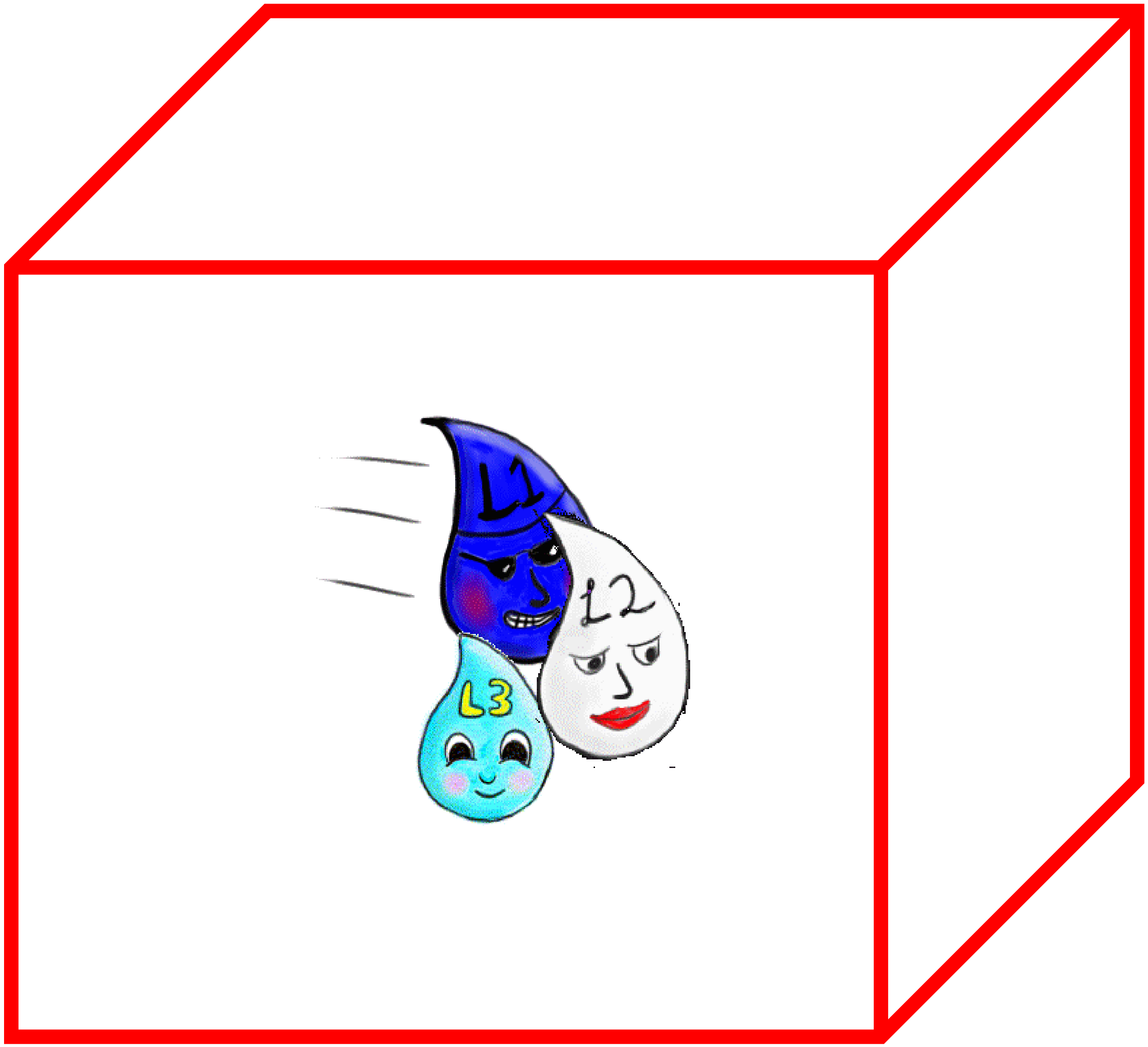
and tract integrity.

How does DTI Work?

Diffusion?

Diffusion is a dispersal of particles.

DTI tracks the dispersal of water molecules in each voxel.


L1
L2
L3

Diffusion can be
free or directional.

Free diffusion

results from

Brownian motion:

random

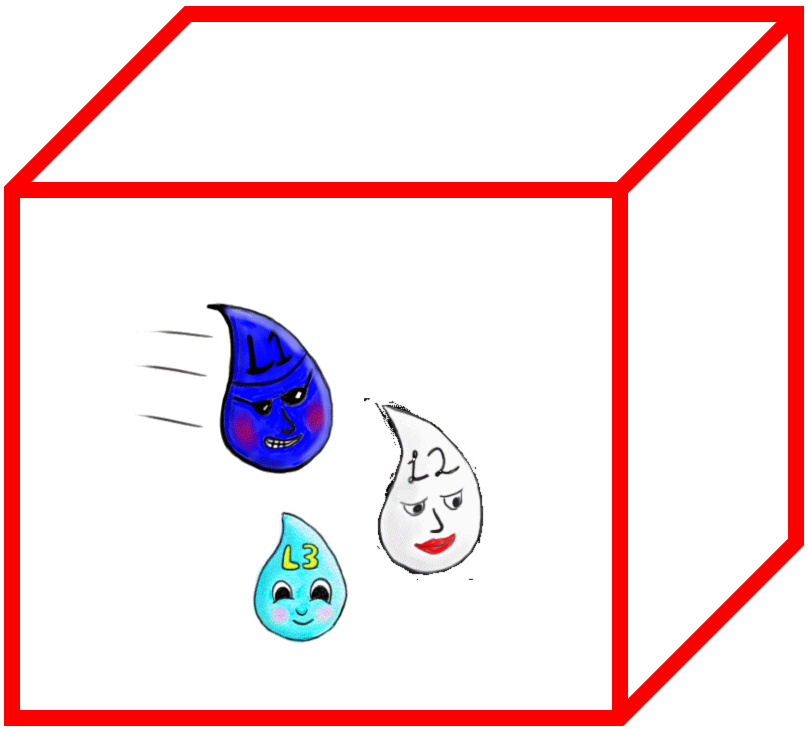
thermal motion

of molecules.

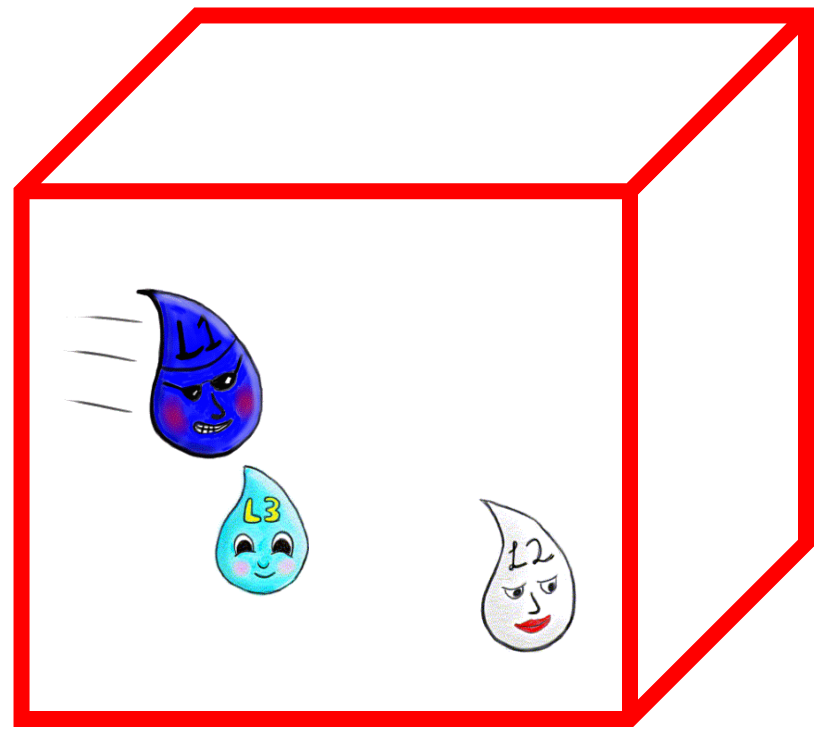
Unrestricted molecules go farther

If they travel farther,
they have higher
Mean Diffusivity.

Low Mean Diffusivity



High Mean Diffusivity



When diffusion is free,

travel is about equal in all directions.

Isotropic

Iso = Equal

Tropic = Motion

Isotropic

What if diffusion's not free?

No, not like that…

What if it's directional?

like this:

Anisotropic

An = Not

NOT isotropic

Anisotropic

NOT spherical

Anisotropic

Good wiring

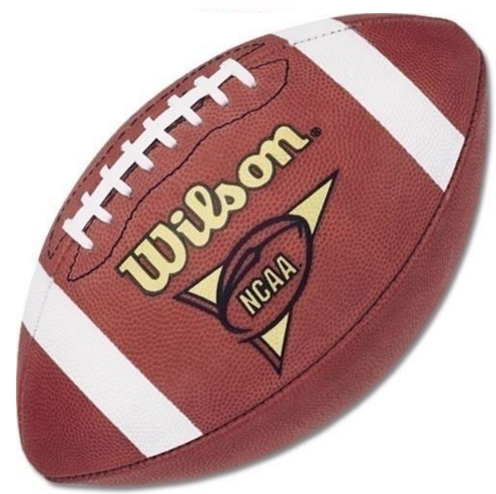
is directional
(has high anisotropy),

because it isn't leaky
or blocked or broken.

Let's Summarize

Diffusion has Shape

Isotropic



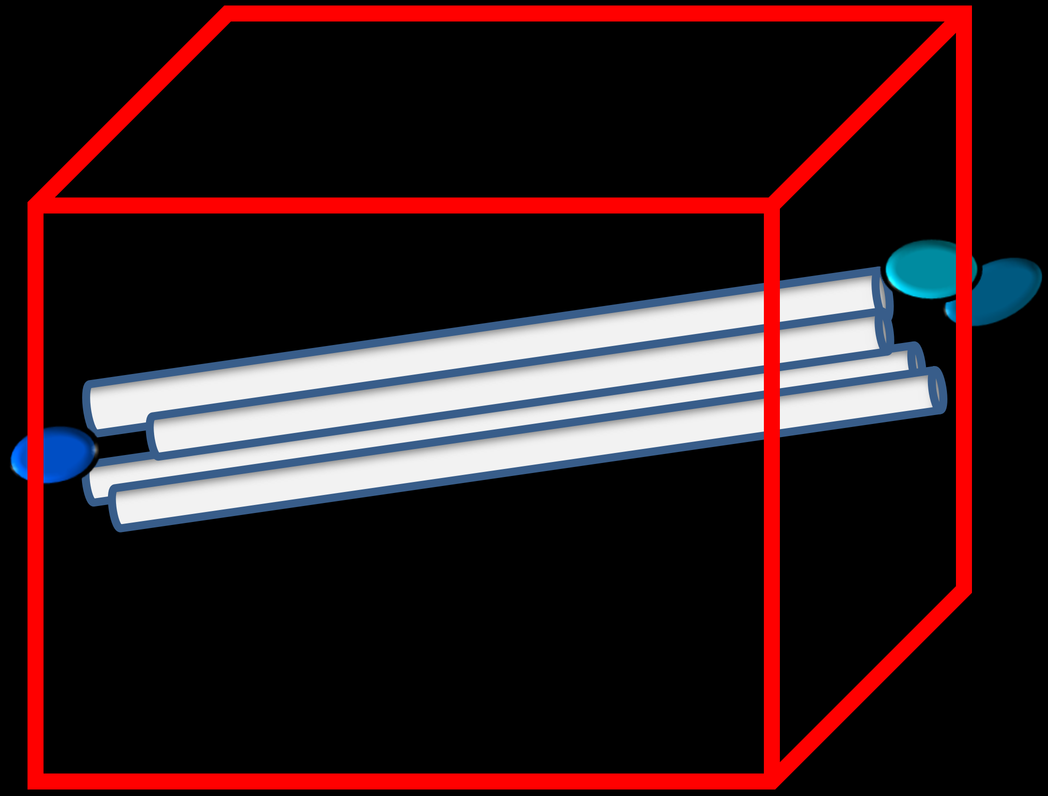
Anisotropic

And Diffusion
has Spread
or
"Mean Diffusivity"

Good Tracts

Low mean diffusivity (little spread)

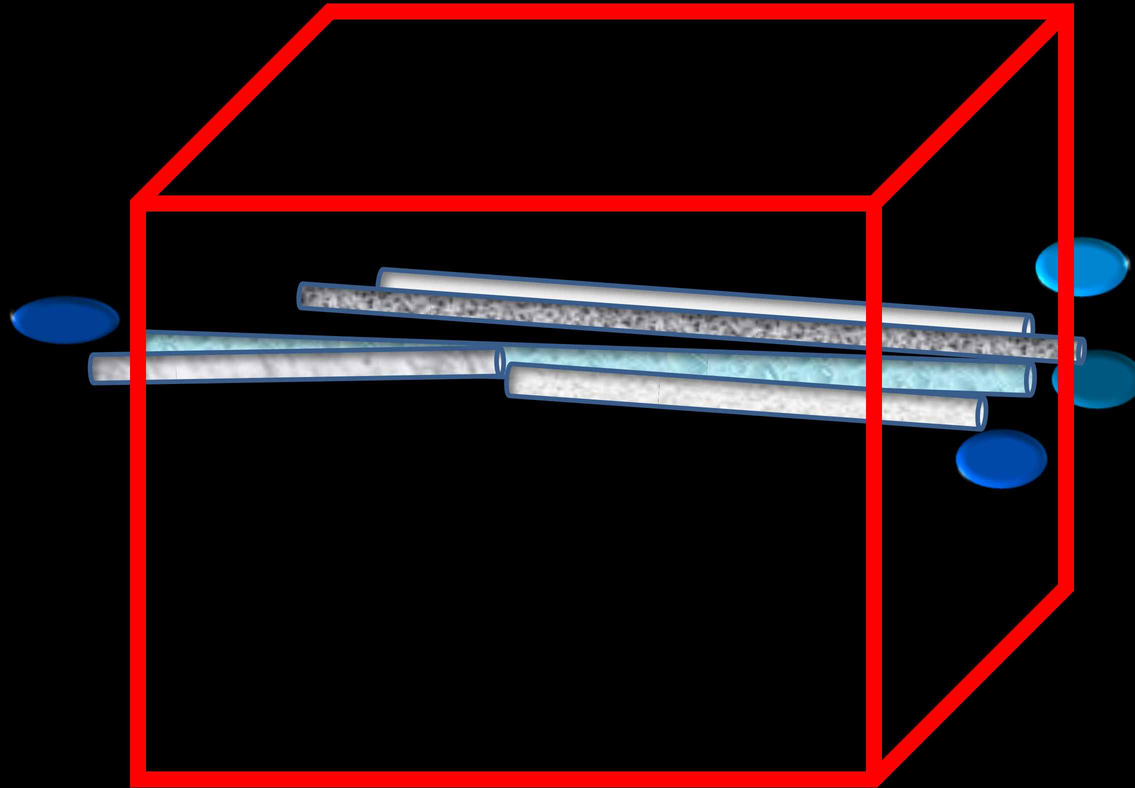
High anisotropy (good directionality)



Bad Tracts

Low Anisotropy
(poor directionality)

High mean diffusivity
(lots of spread)



What does water have to do with transmitting nerve impulses along the axons?

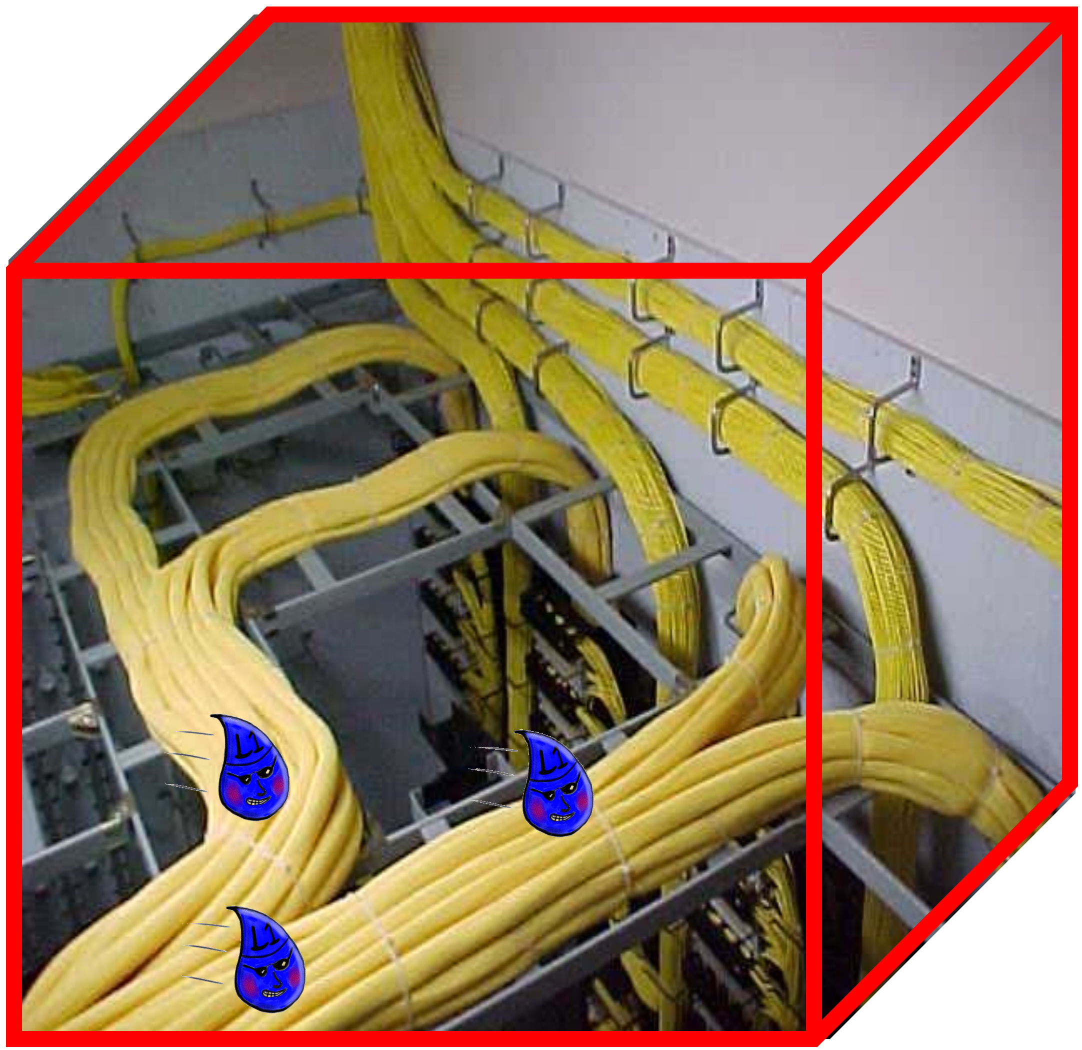
Isn't that all done with electrical and chemical signals?

Correct! Water does NOT transmit signals.

But, lucky for us,

it likes to spread
parallel to the fibers,

…like rain running along a bundle of wires.



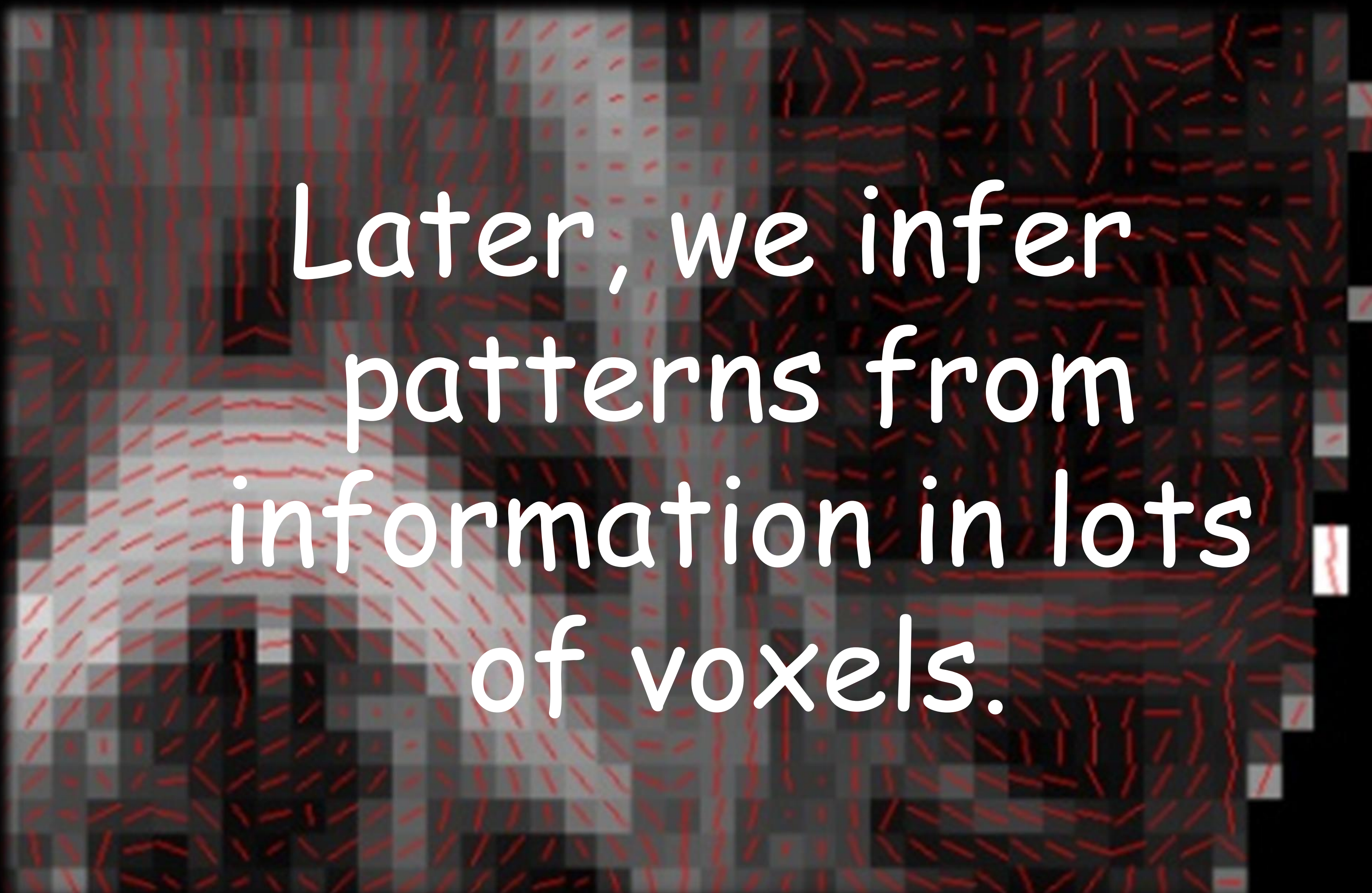
FAQ

So, you track a water molecule along the entire length of a tract?

No, we track net water molecule movement…

of about 8 microns,
(or less)
over ~30 ms

in each voxel
separately.



Later, we infer patterns from information in lots of voxels.

Tensor?

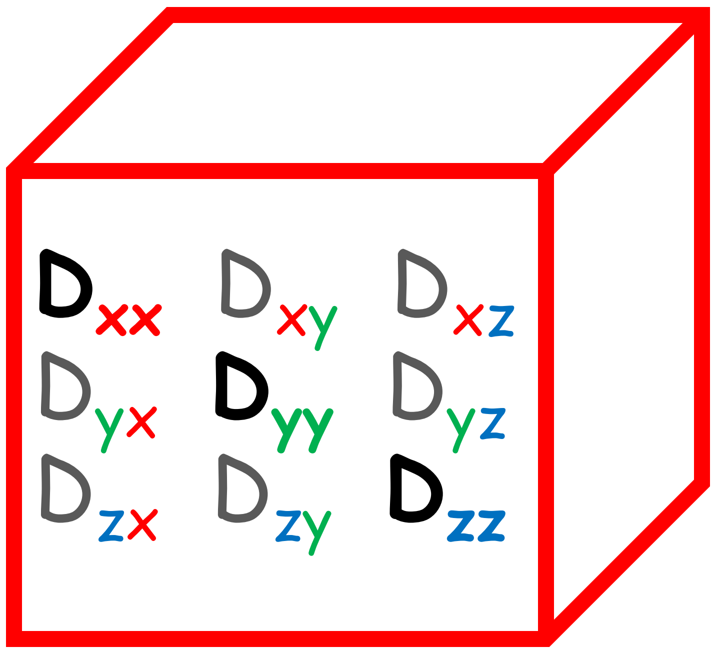
a matrix:

$$\begin{matrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{matrix}$$

representing
shape & direction
of diffusion in each
voxel.

So, there's a matrix
in each DTI voxel.

Each matrix is the tensor for that voxel.



Shape is stored along the main diagonal of the matrix

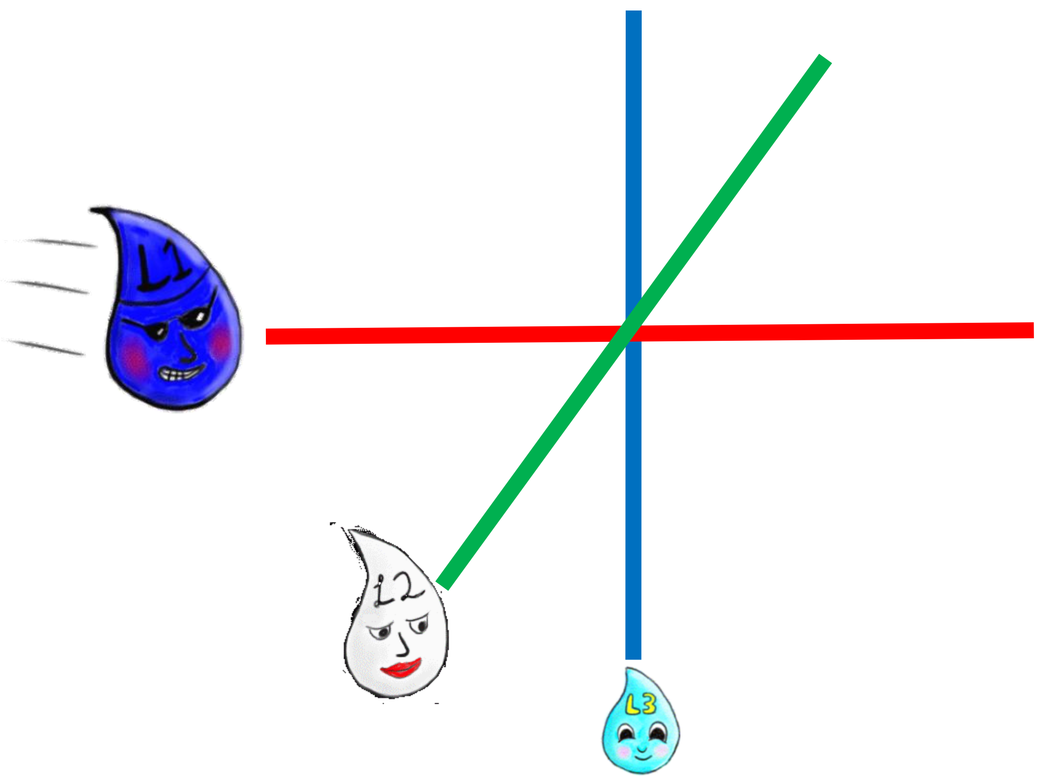
as eigenvalues:

$$\begin{matrix} \boxed{D_{xx}} & D_{xy} & D_{xz} \\ D_{yx} & \boxed{D_{yy}} & D_{yz} \\ D_{zx} & D_{zy} & \boxed{D_{zz}} \end{matrix}$$

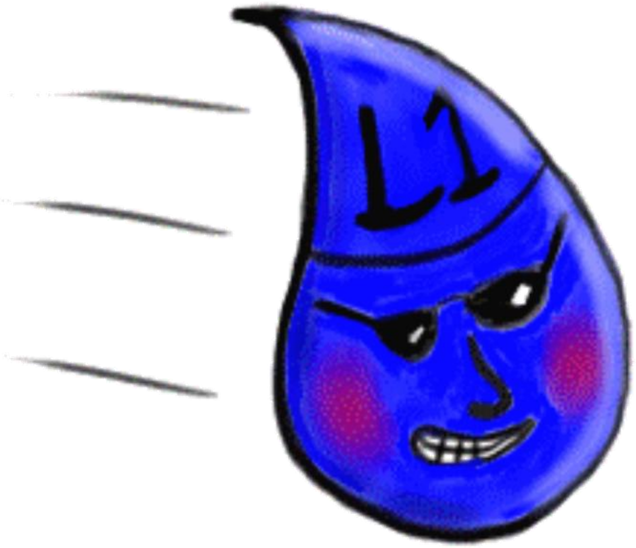
which show the
Length of spread

by the water
molecules

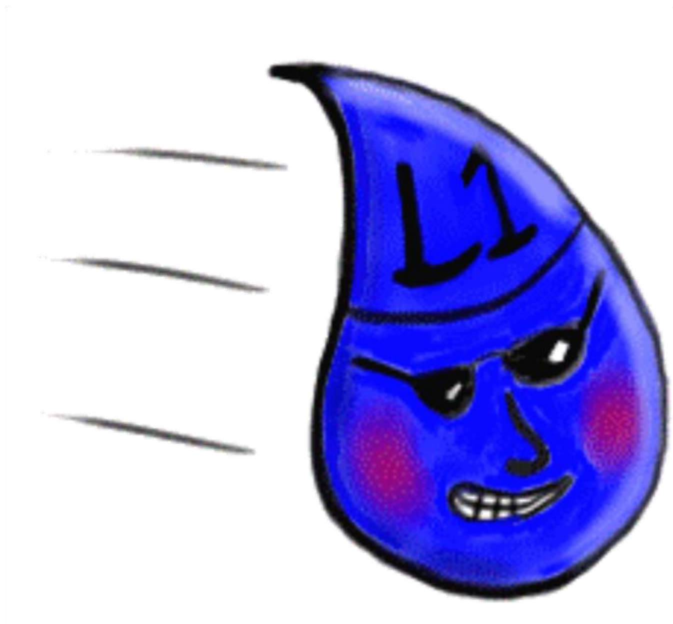
in three orthogonal directions.



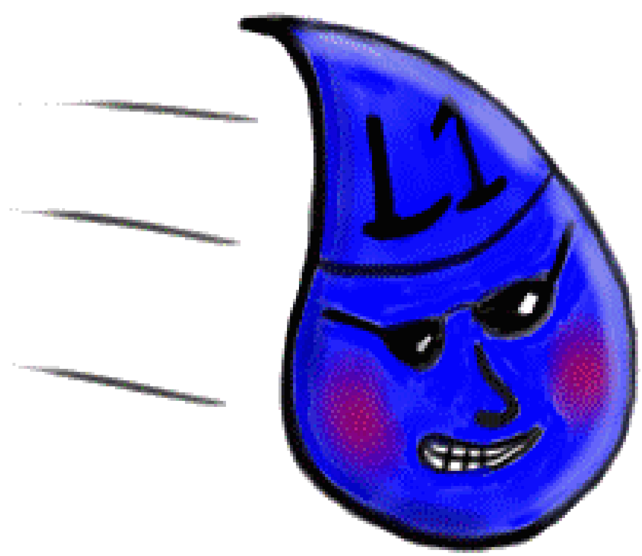
The biggest eigenvalue, L1,



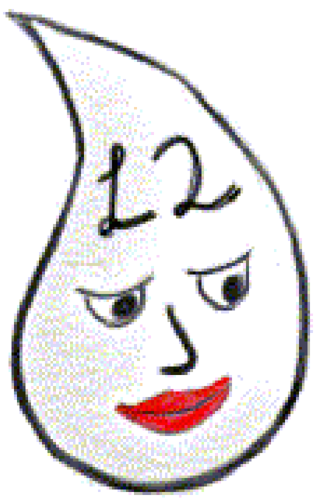
the Longest direction of spread



(the direction of greatest anisotropy).



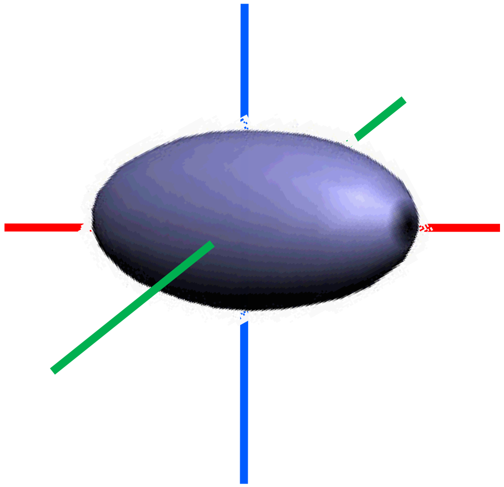
The 2nd biggest eigenvalue, L2



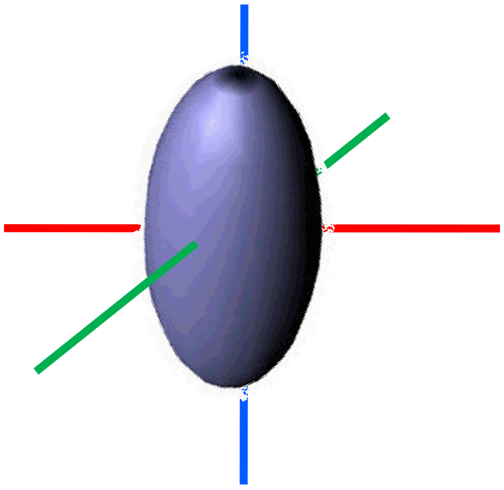
the **second** **L**ongest orthogonal direction of spread

The smallest eigenvalue, L3

the shortest orthogonal Length of spread



L1=2.0
L2=1.0
L3=1.0



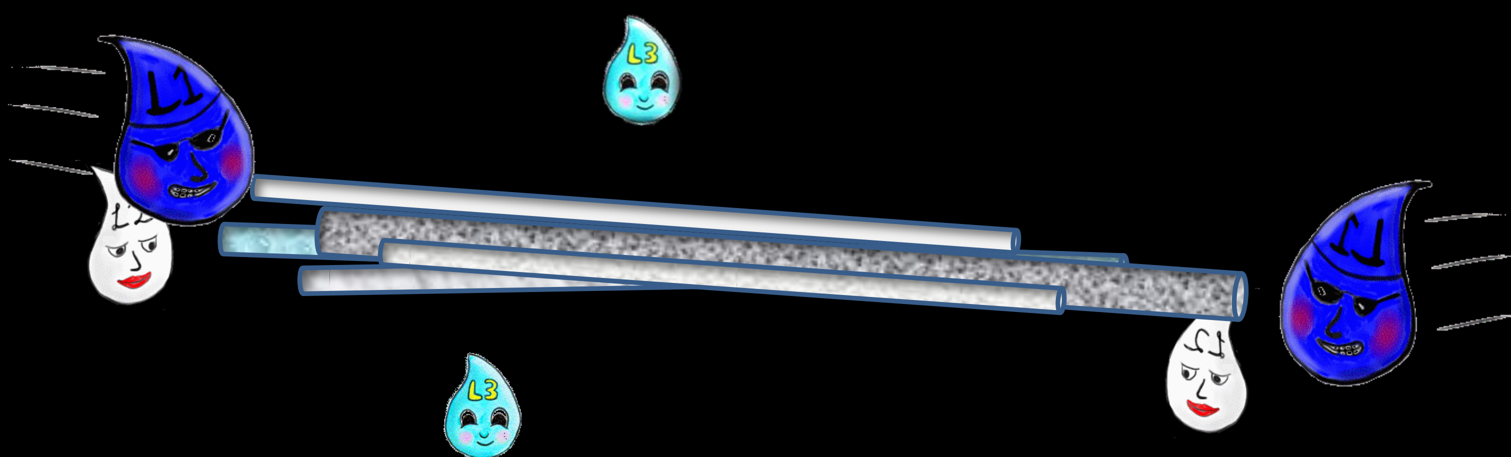
2.0x	0	0
0	1.0y	0
0	0	1.0z

1.0x	0	0
0	1.0y	0
0	0	2.0z

Click to continue

Mean Diffusivity (MD)

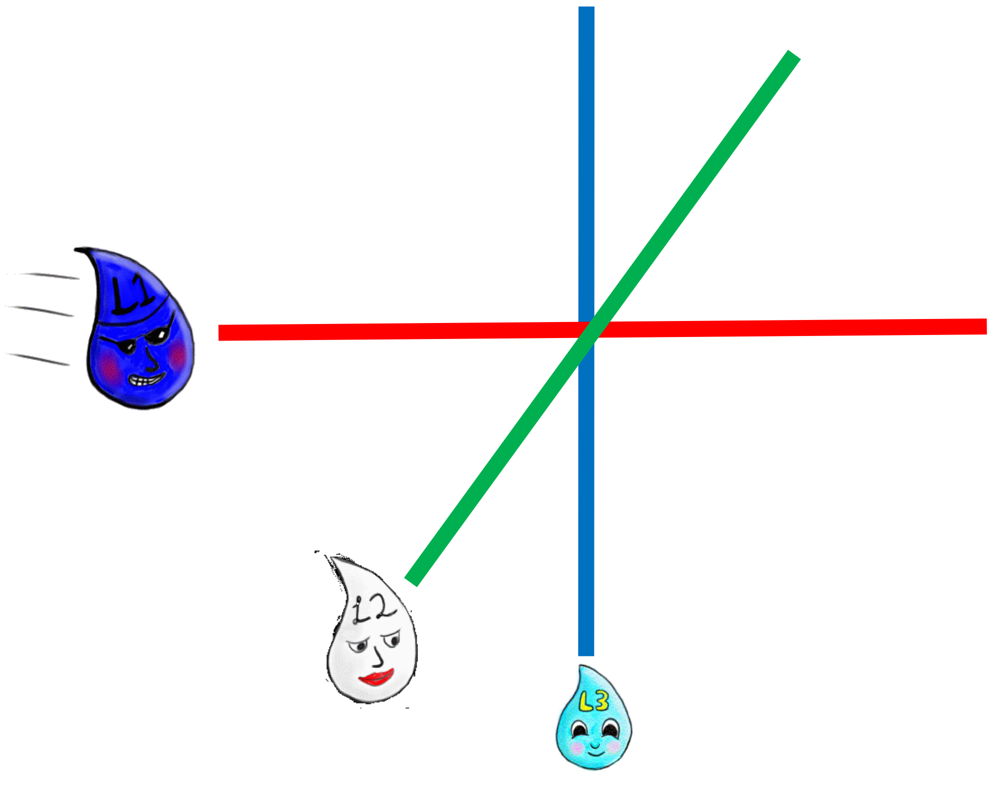
(which we've met before)
is the average of L1, L2 and L3.



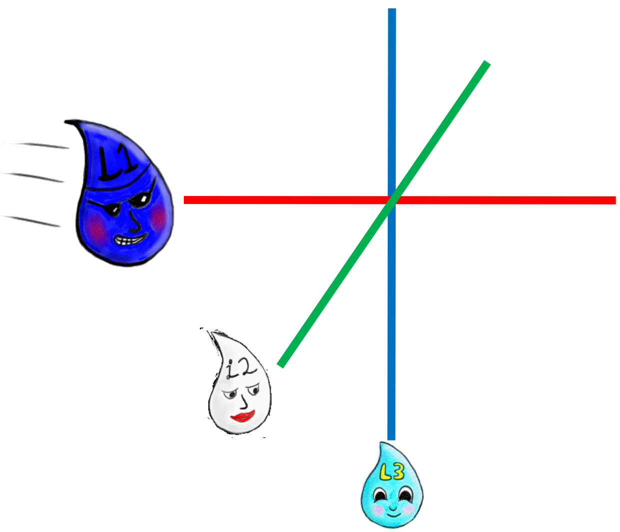
Using eigenvalues,

we can characterize shape in several ways.

If L1, L2 and L3 are equivalent,

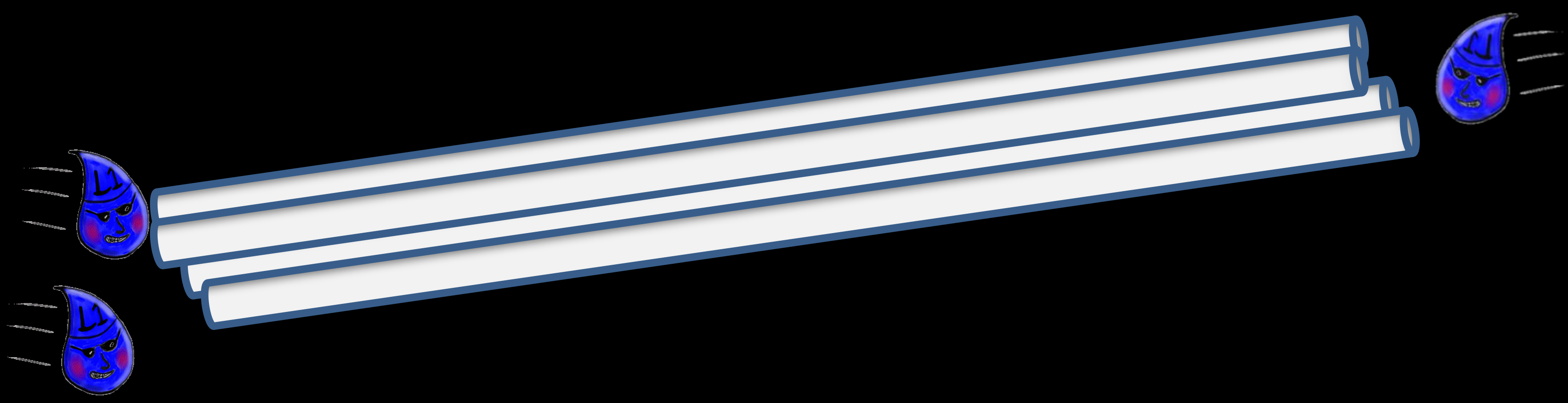


we get isotropic diffusion.



Parallel Diffusivity (PD)

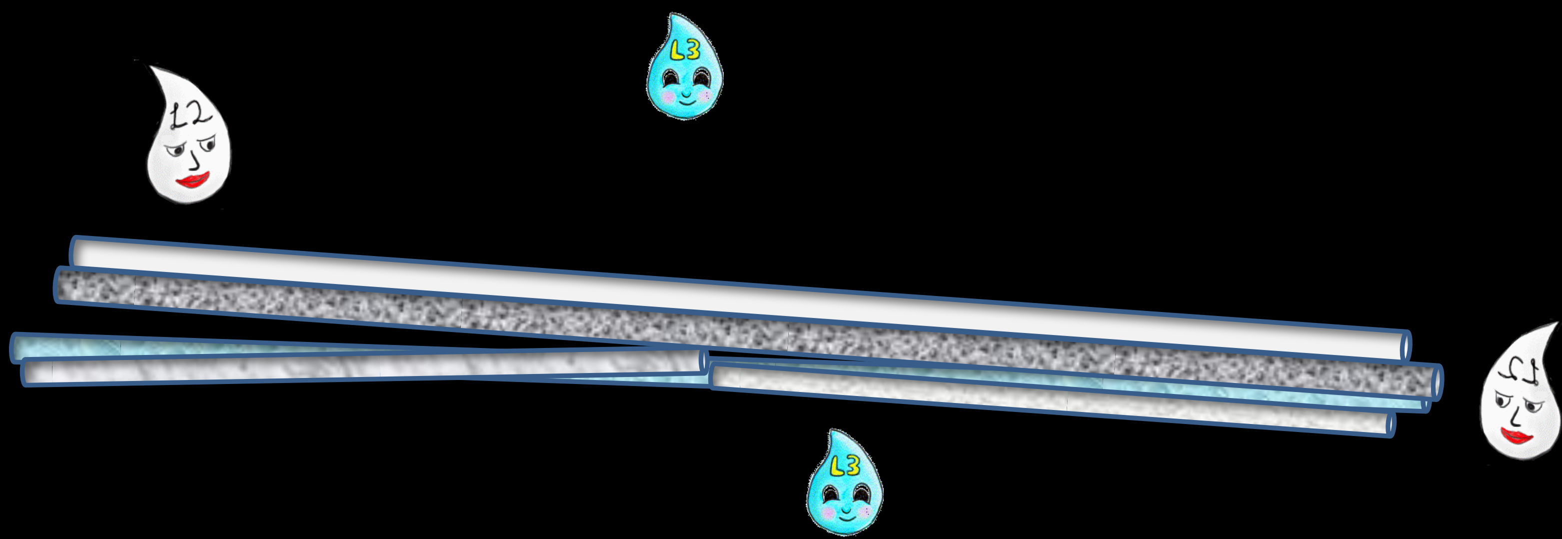
is simply the value of L1



Changes in PD may be related to axonal loss.

Radial Diffusivity (RD)

The average of L2 and L3



Changes in RD may be related to demyleniation

The most common measure is called **Fractional Anisotropy**

$$\mathrm{FA} = \sqrt{\frac{3}{2}\left(\frac{(\lambda_1-\bar{\lambda})^2+(\lambda_2-\bar{\lambda})^2+(\lambda_3-\bar{\lambda})^2}{\lambda_1^2+\lambda_2^2+\lambda_3^2}\right)}$$

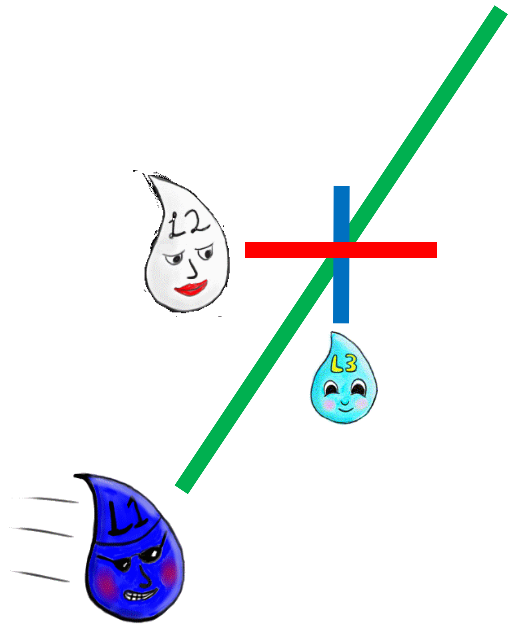
“the extent of anisotropy”.

Good wiring has high FA

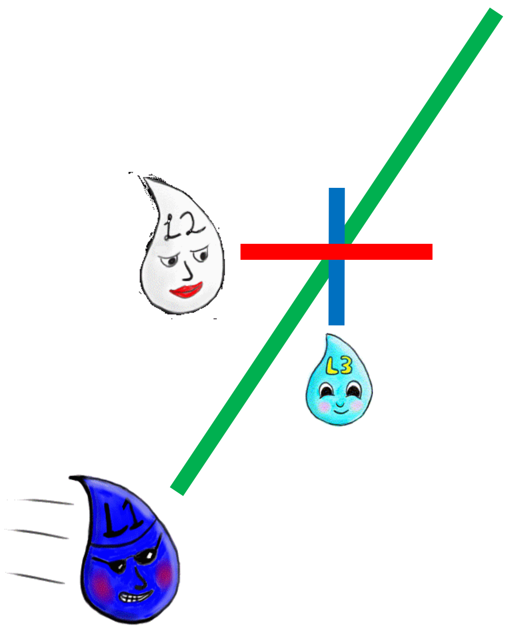
...which shows up bright

FA can be decomposed into 2 “modes”

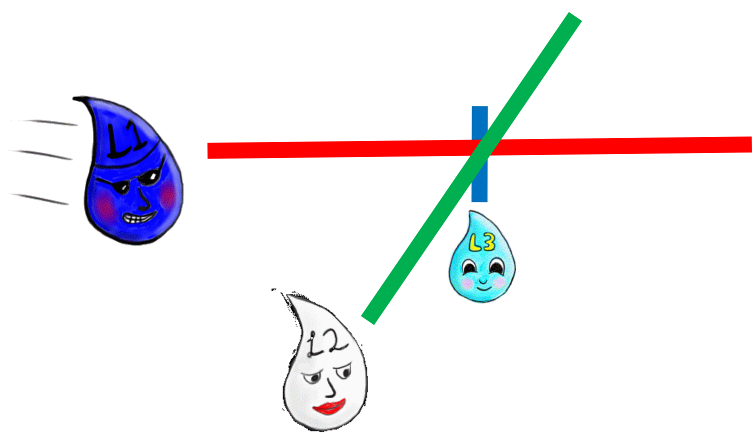
If L1 is big, but L2 & L3 are small:



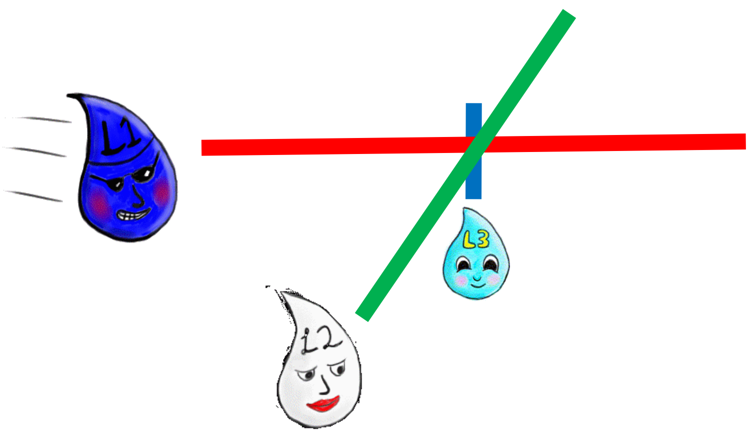
we get linear anisotropy (CL: Linear Case).



If L1 & L2 are big but L3 is small,



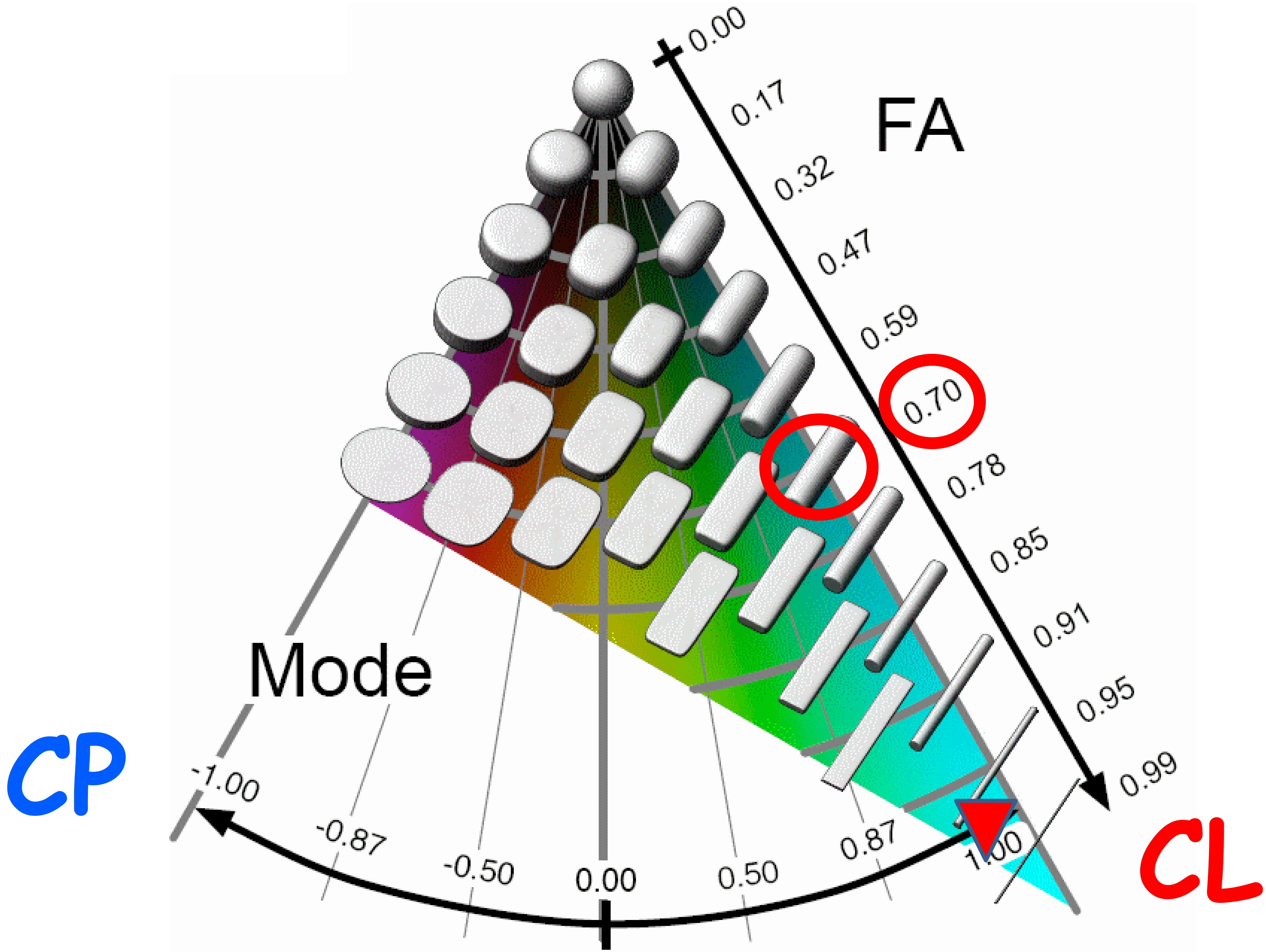
we get planar anisotropy (CP: Planar Case).



CL (linear case) and CP (planar case) are important, because these different “modes”

represent different shapes

of the same
FA value.



FA
0.00
0.17
0.32
0.47
0.59
0.70
0.78
0.85
0.91
0.95
0.99
Mode
CP
CL
-1.00
-0.87
-0.50
0.00
0.50
0.87
1.00

The point is

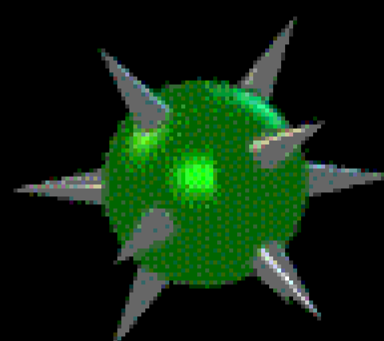
there are several clever ways to measure the shape of diffusion, and each one offers unique information.

Tensors also represent…

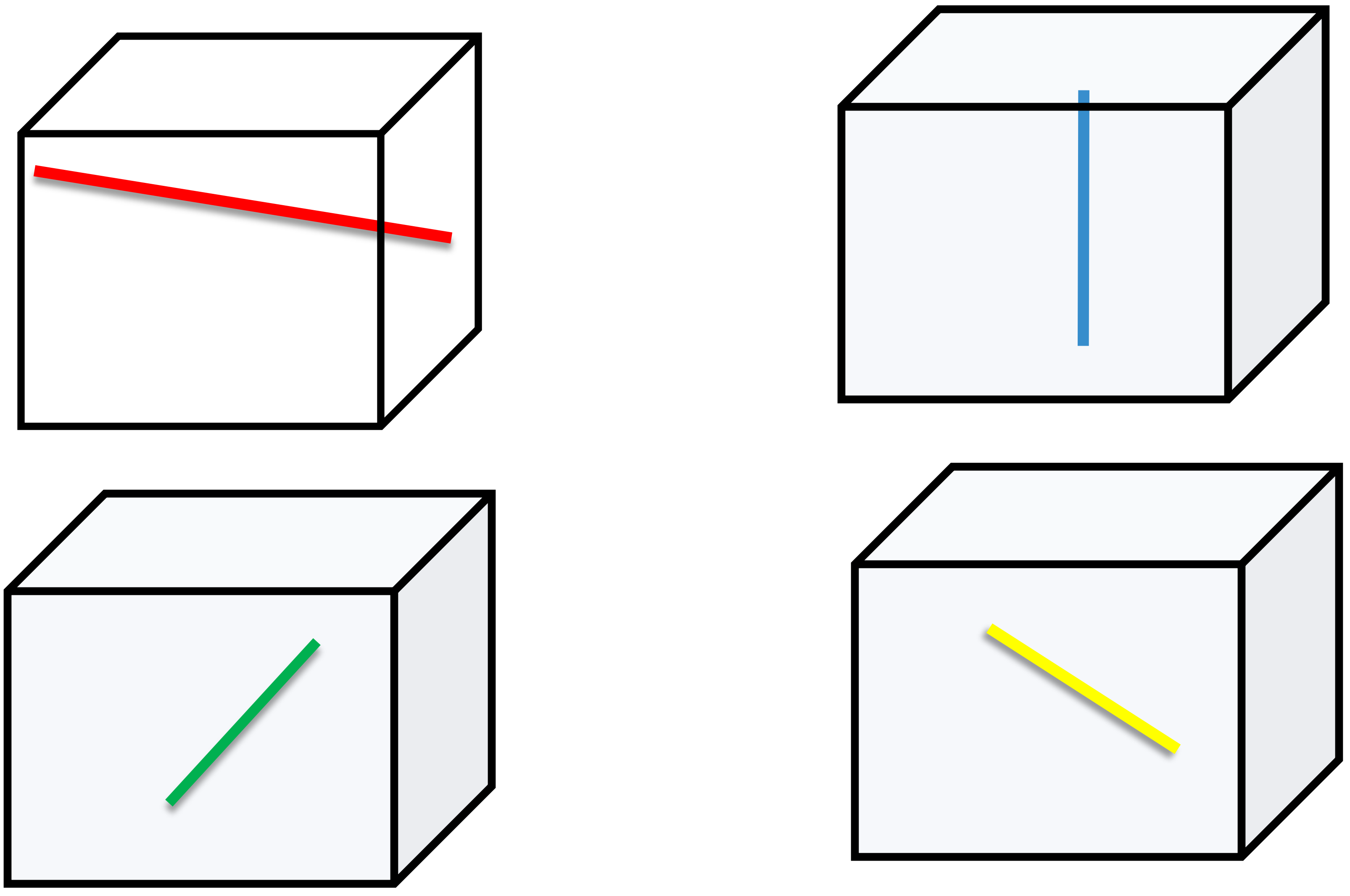
diffusion direction.

To calculate direction

we need to collect data at 6 or more angles



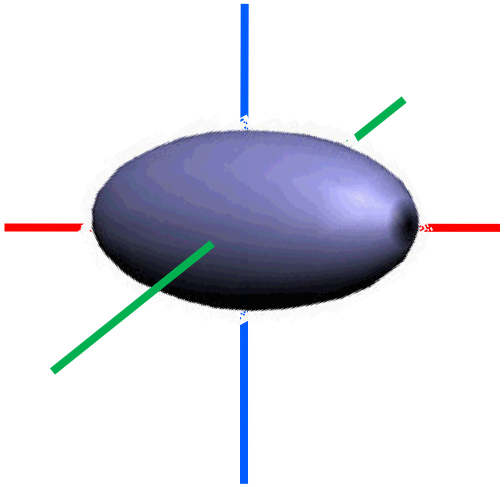
Direction
is stored as
eigenvectors



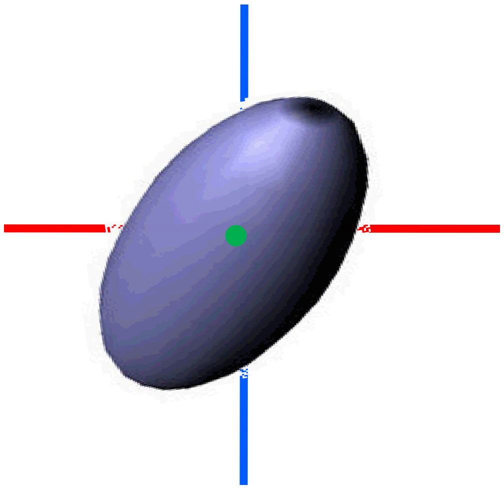
in the off-diagonal parts of the matrix

eigenvectors:

$$\begin{matrix} D_{xx} & D_{xy} & D_{xz} \\ \boxed{D_{yx}} & D_{yy} & D_{yz} \\ \boxed{D_{zx}} & \boxed{D_{zy}} & D_{zz} \end{matrix}$$



L1=2.0
L2=1.0
L3=1.0



2.0x	0	0
0	1.0y	0
0	0	1.0z

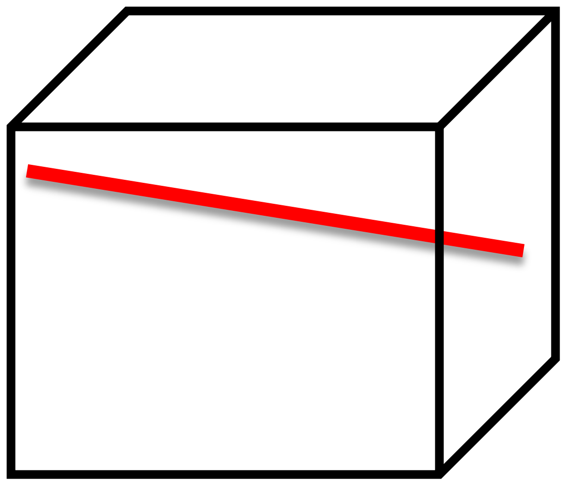
1.5x	-0.5	0
-0.5	1.0y	0
0	0	1.5z

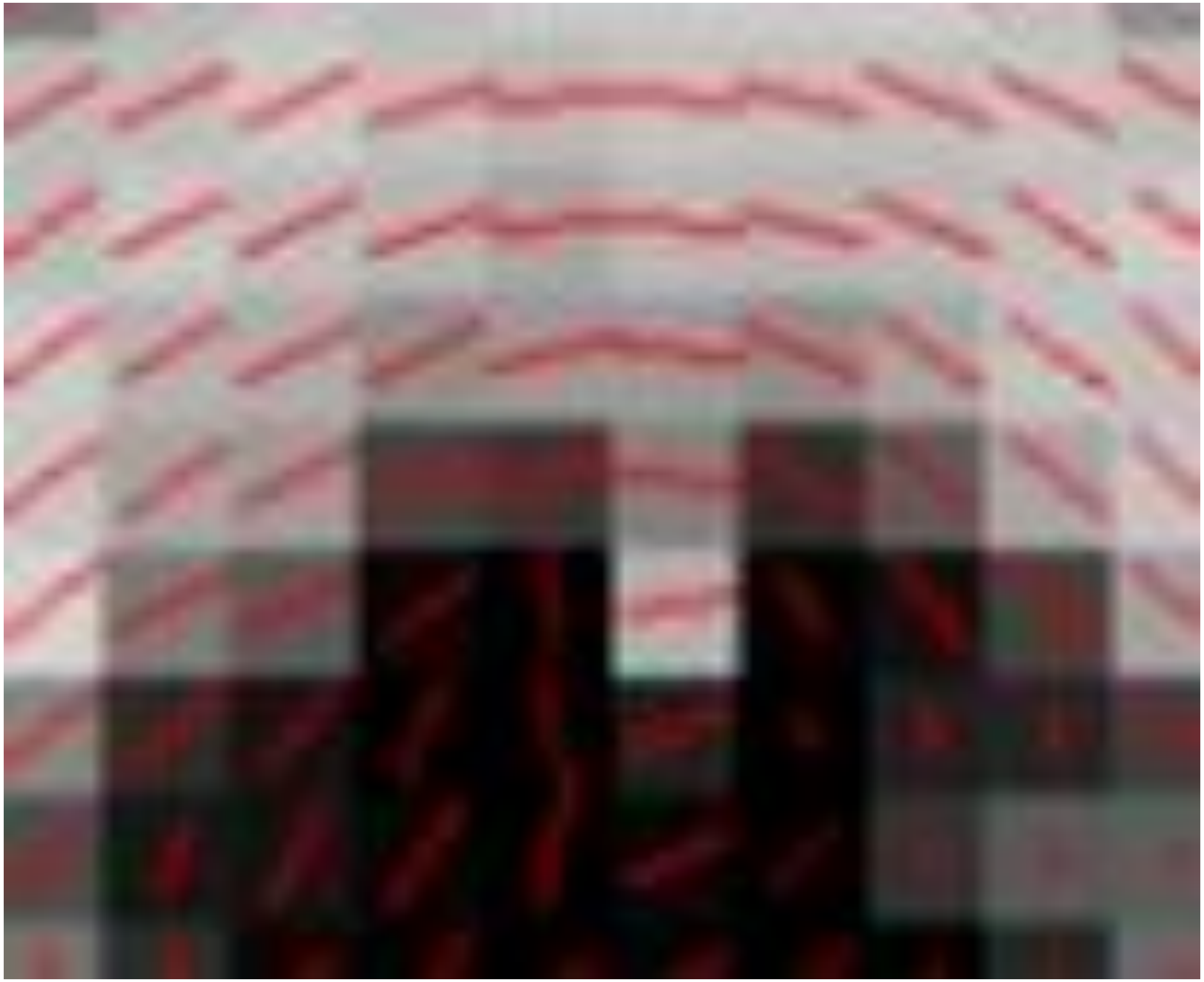
Click to continue

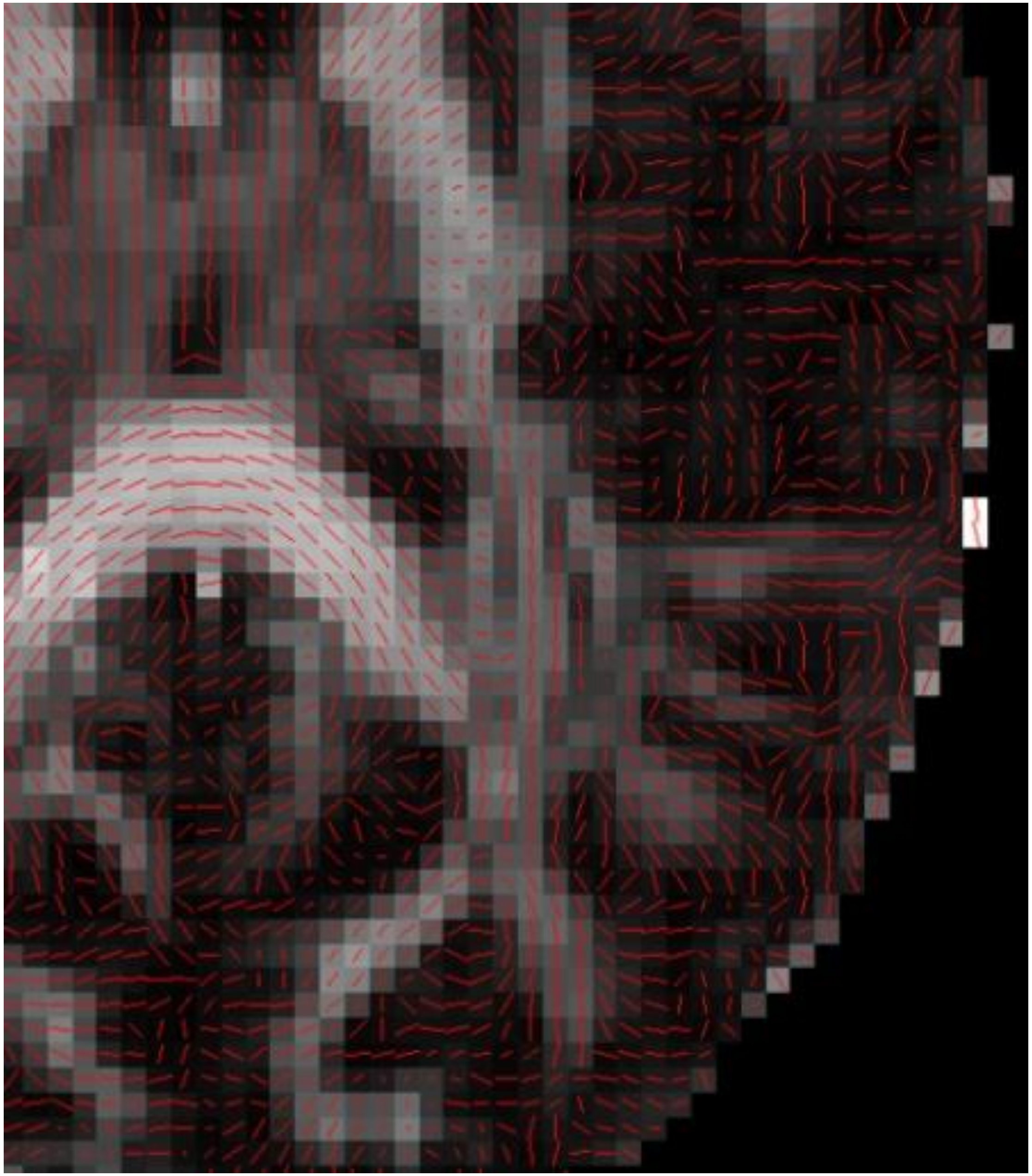
We can look at the Primary Diffusion Direction

(The main Eigenvector: V1)

As a line in each voxel

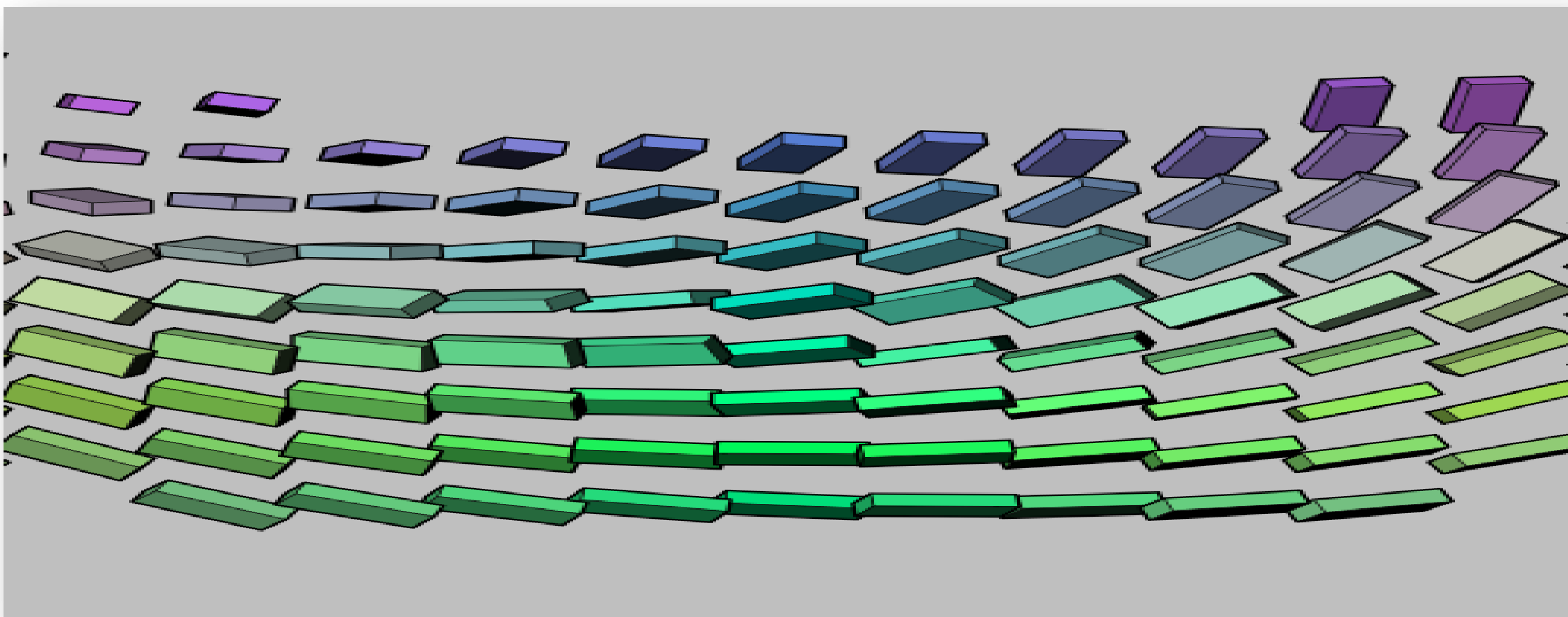




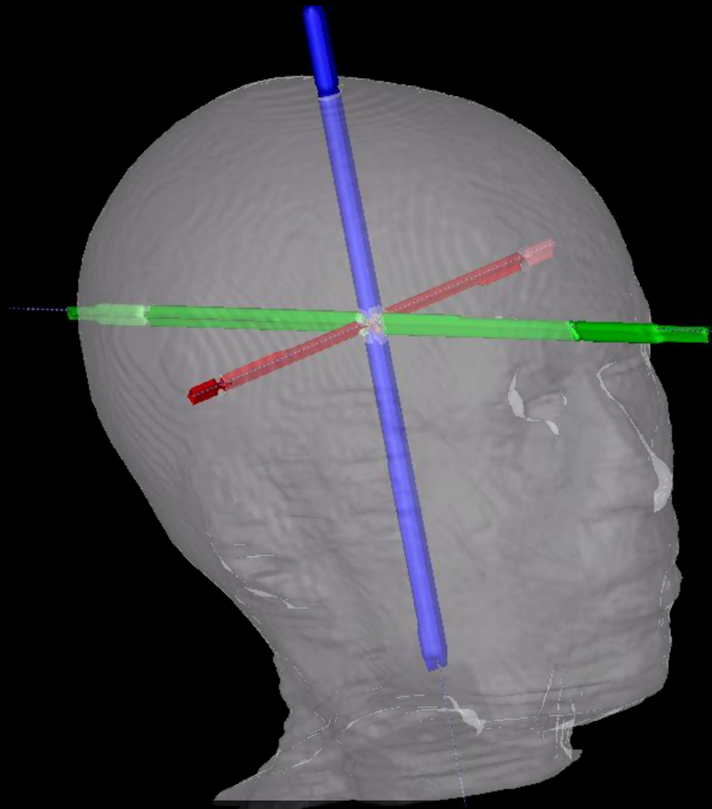


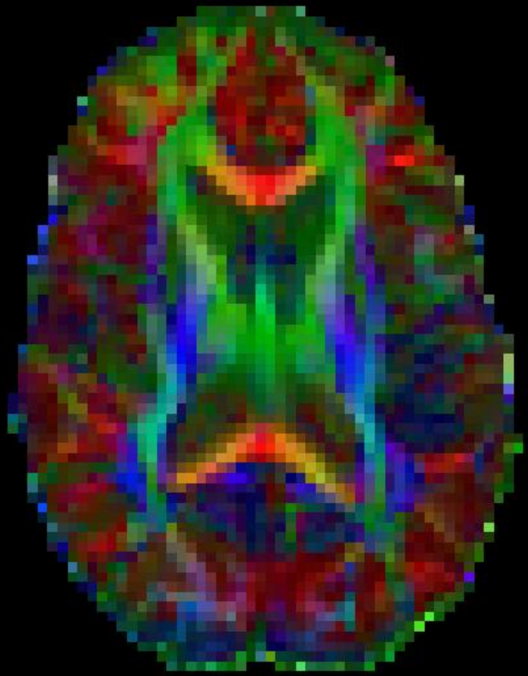
But,

we can represent more information with color

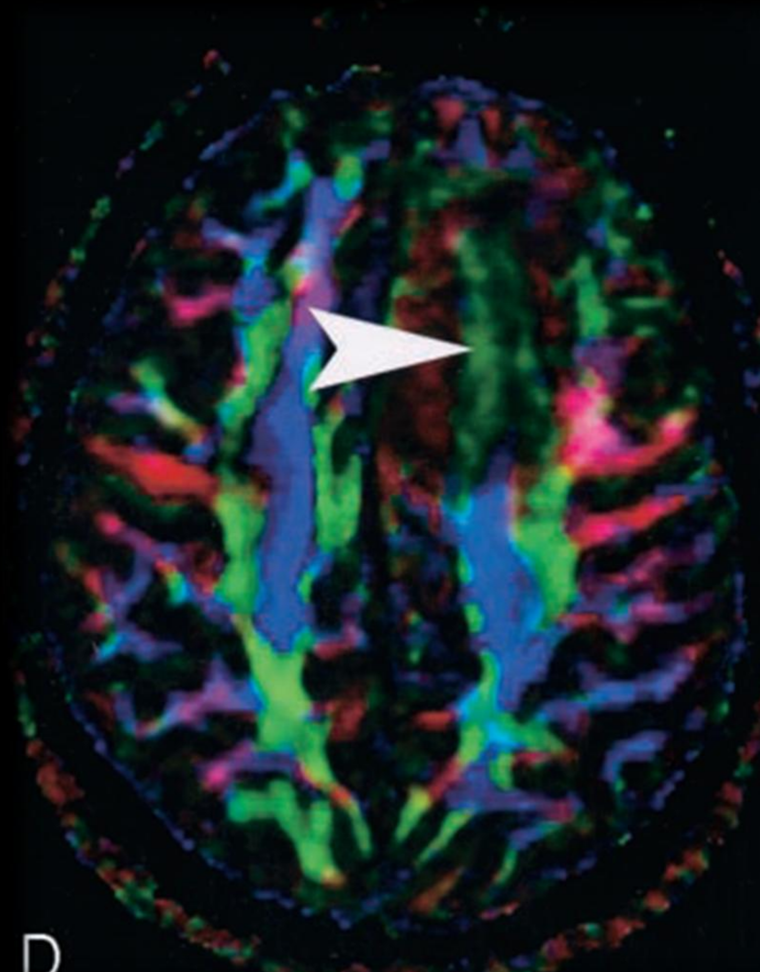


Red=Left-Right
Green=Front-Back
Blue= Top-Bottom



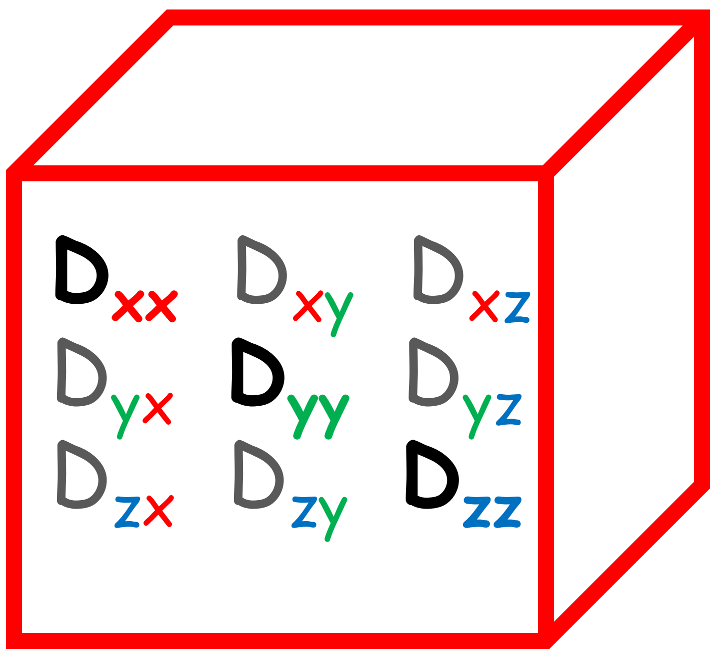


Voxels with poor anisotropy lose brightness

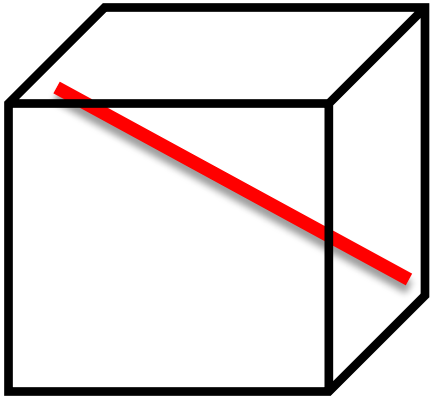


So, the tensor is…

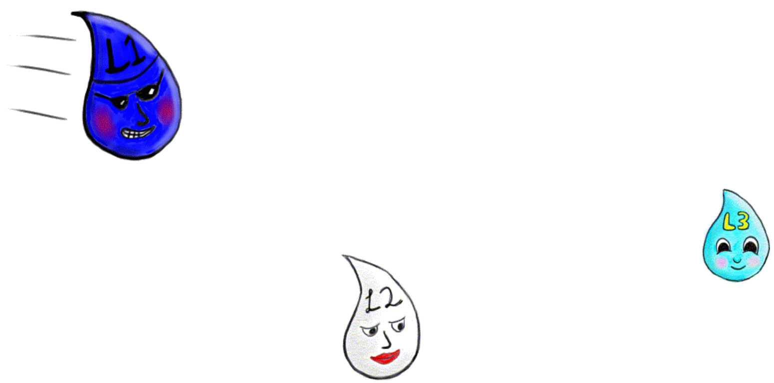
a square of numbers in each voxel



representing the net size, shape and direction



of water molecule movement.



Let's Summarize

Diffusion

Tensor

Imaging

represents water dispersion

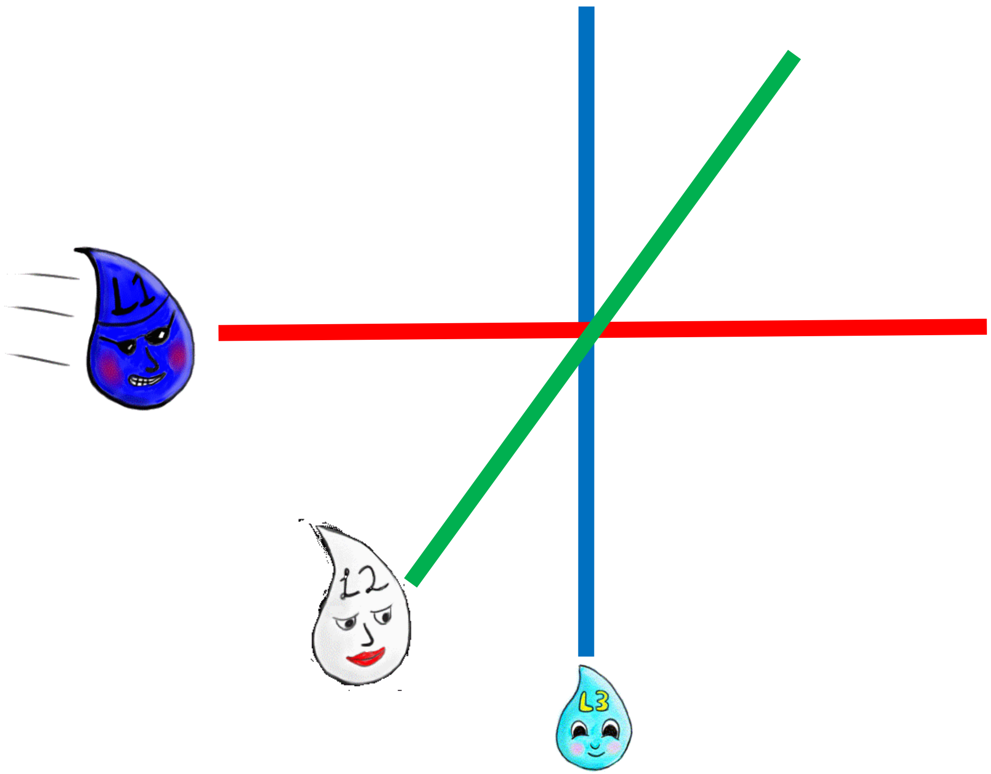
in each voxel,

with a tensor matrix.

It is all about using

Mean Diffusivity

(Distance water travels)



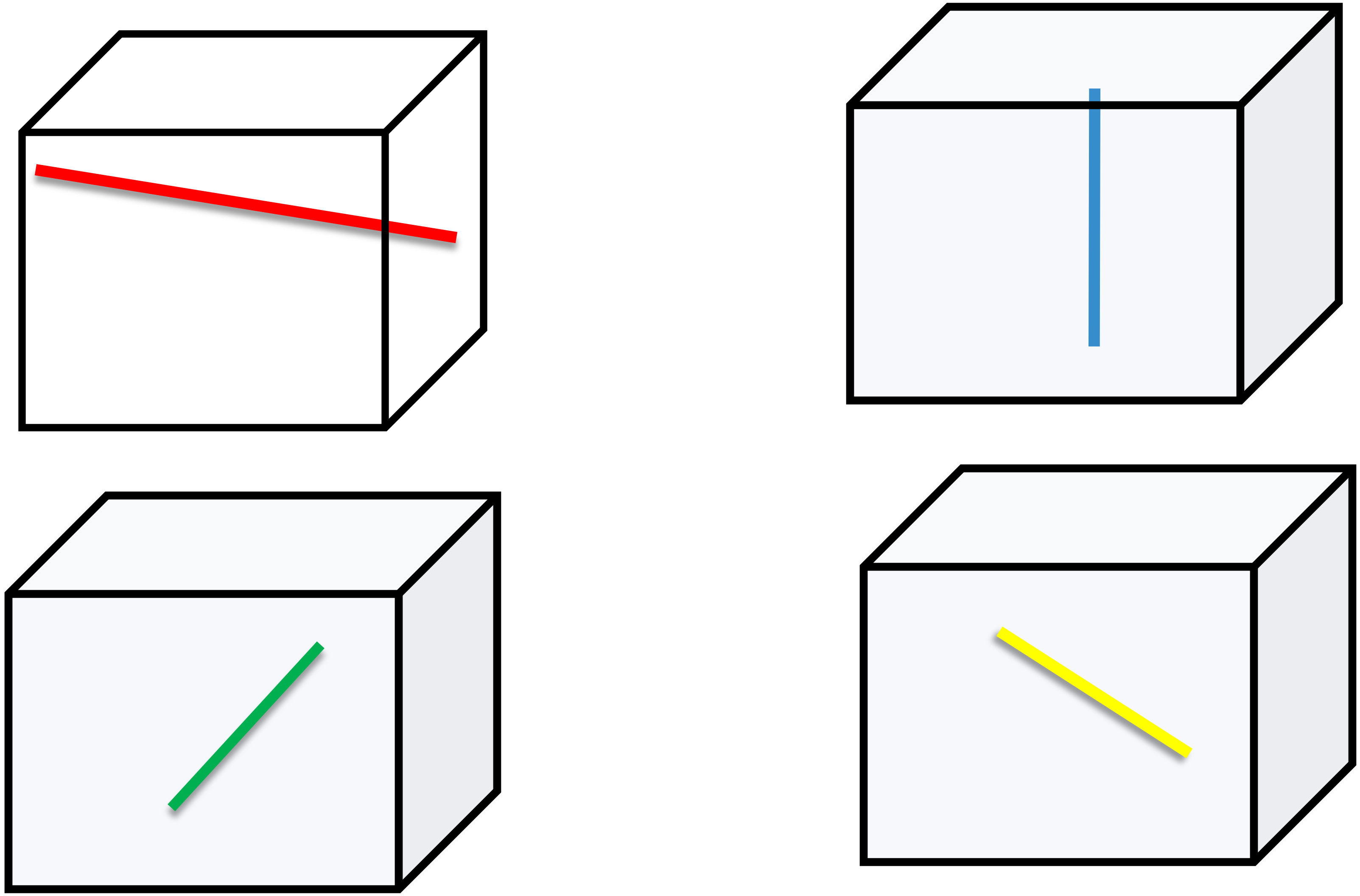
Diffusion Shape

(e.g., PD, RD, FA, CL, CP)

(Parallel Diffusivity, Radial Diffusivity, Fractional Anisotropy, Linear Case, Planar Case)

AND

Diffusion Direction



to determine
location and integrity

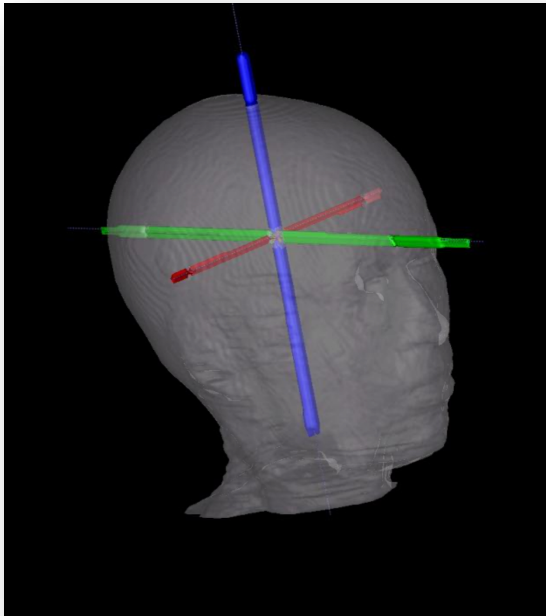
of White Matter Tracts.

Said another way,

DTI measures the motion of water molecules in the brain.

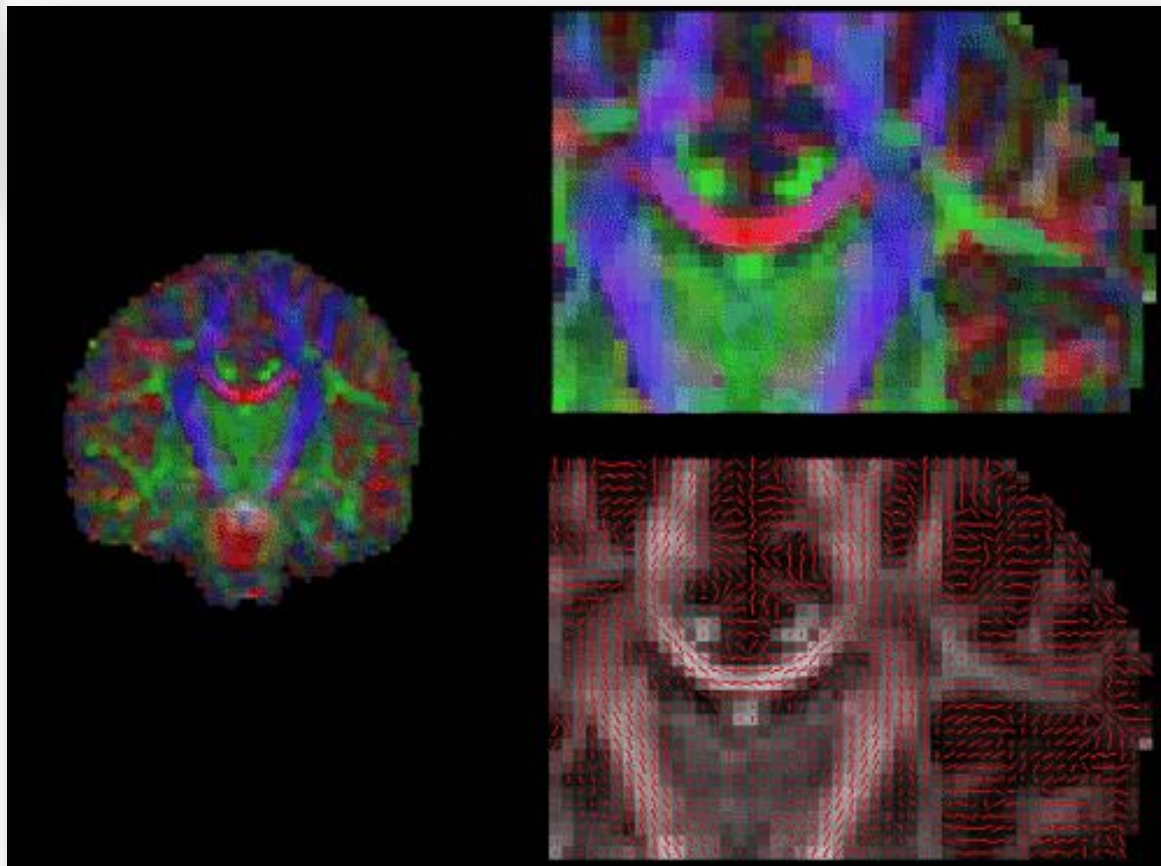
The motion is most anisotropic along good white matter tracts, but begins to fall apart as the tracts degrade.

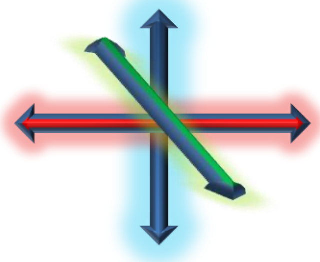
There is less discernable anisotropy in grey matter than white matter, and still less in CSF.



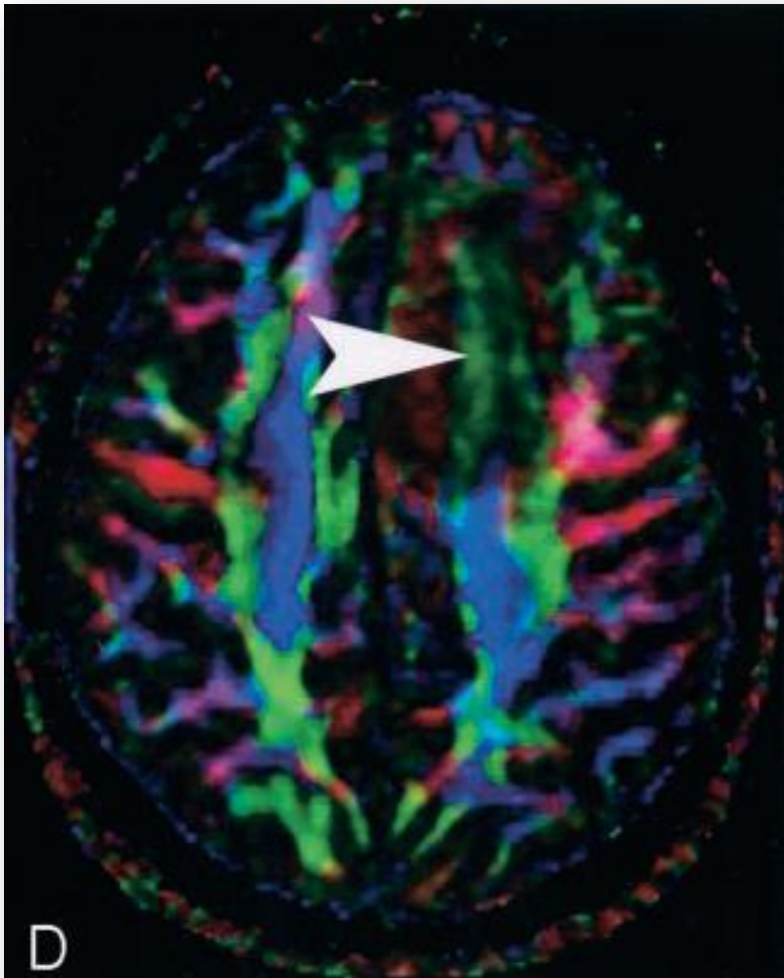
DTI (Diffusion Tensor Imaging),
"Mean Diffusivity",
Fractional Anisotropy (FA),
Tensor Matrix,
V1 (Primary Diffusion Direction)

Diffusion,
Isotropic,
Anisotropic,
Eigenvalue,
Eigenvector,
Voxel,
Intensity

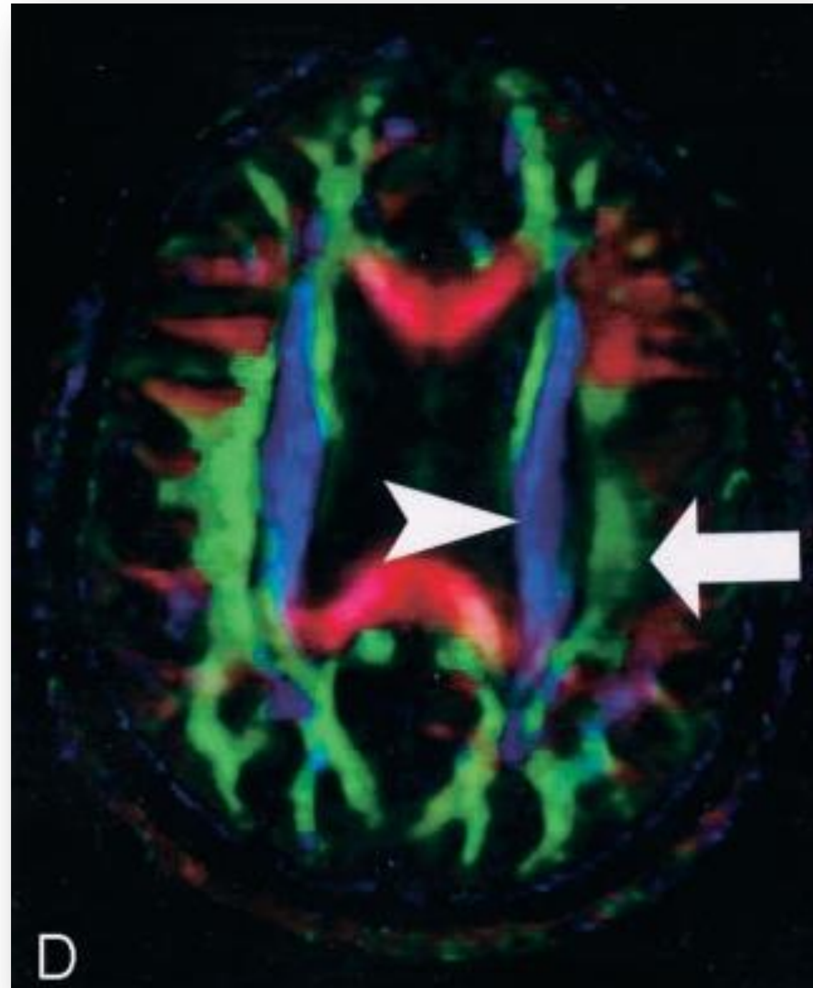




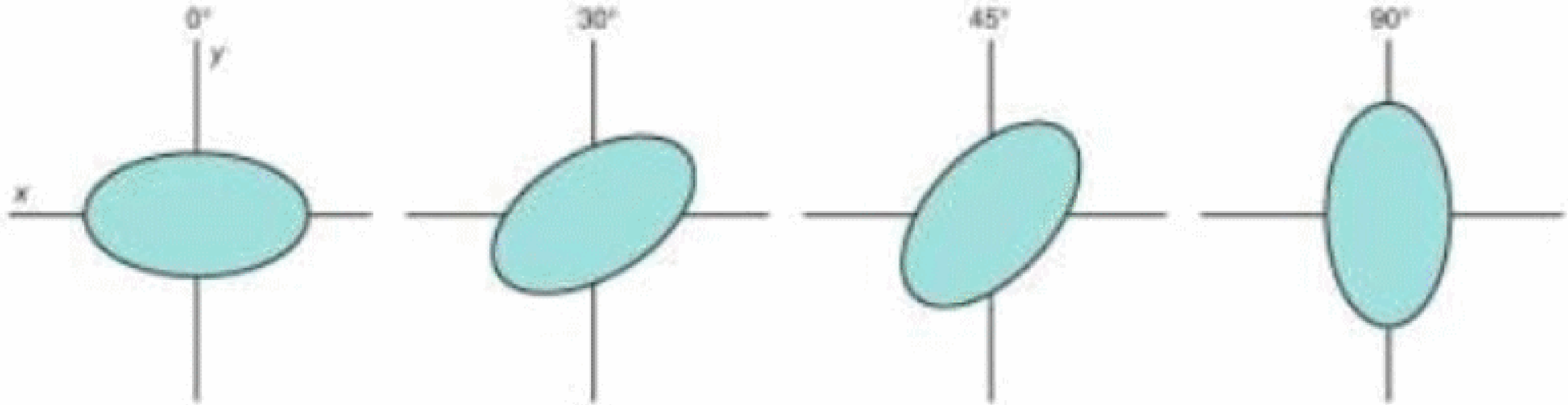
Infiltrating astrocytoma



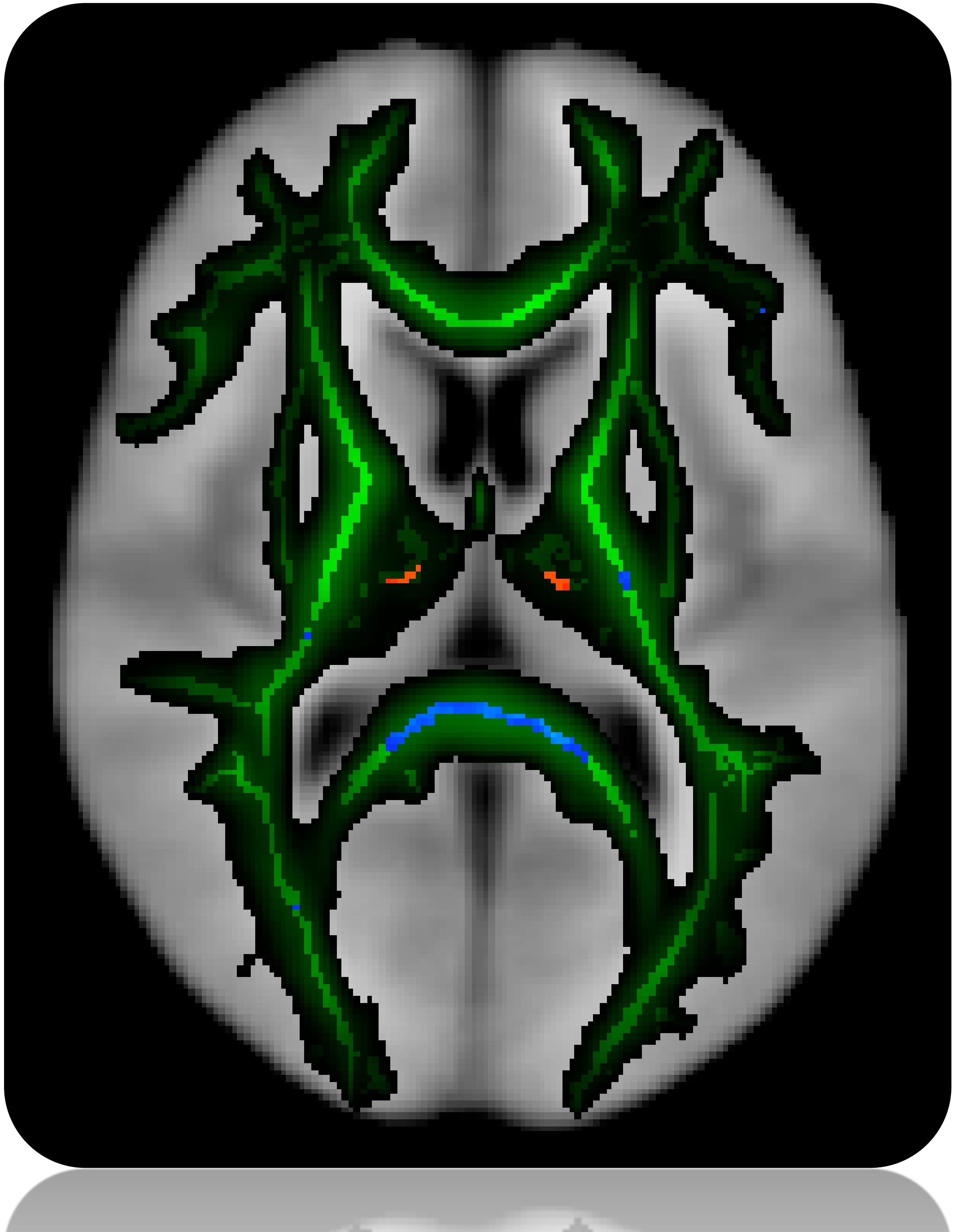
Edema



D_{xx}	D_{xy}	D_{xz}
D_{yx}	D_{yy}	D_{yz}
D_{zx}	D_{zy}	D_{zz}



	0°	30°	45°	90°
D	$\begin{bmatrix} 2.0 & 0 & 0 \\ 0 & 1.0 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}$	$\begin{bmatrix} 1.75 & -0.43 & 0 \\ -0.43 & 1.25 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}$	$\begin{bmatrix} 1.5 & -0.5 & 0 \\ -0.5 & 1.5 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}$	$\begin{bmatrix} 1.0 & 0 & 0 \\ 0 & 2.0 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}$
λ_1	2.0	2.0	2.0	2.0
λ_2	1.0	1.0	1.0	1.0
λ_3	0.5	0.5	0.5	0.5
v_1	[1, 0, 0]	[0.87, 0.5, 0]	[0.71, 0.71, 0]	[0, 1, 0]
v_2	[0, 1, 0]	[-0.5, 0.87, 0]	[-0.71, 0.71, 0]	[1, 0, 0]
v_3	[0, 0, 1]	[0, 0, 1]	[0, 0, 1]	[0, 0, 1]
ADC_x	2.0	1.75	1.5	1.0
ADC_y	1.0	1.25	1.5	2.0
ADC_z	0.5	0.5	0.5	0.5
Trace	3.5	3.5	3.5	3.5



Waiting at the Window

there are my two drops of rain
Waiting on the window-pane.

I am waiting here to see
Which the winning one will be.

Both of them have different names.
One is John and one is James.

All the best and all the worst
Comes from which of them is first.

James has just begun to ooze.
He's the one I want to loose.

John is waiting to begin.
He's the one I want to win.

James is going slowly on.
Something sort of sticks to John.

John is moving off at last.
James is going pretty fast.

John is rushing down the pane.
James is going slow again.

James has met a sort of smear.
John is getting very near.

Is he going fast enough?
(James has found a piece of fluff.)

John has hurried quickly by.
(James is talking to a fly.)

John is there, and John has won!
Look! I told you! Here's the sun!