Numerical methods in magnetic resonance imaging: the Bloch-Torrey equation

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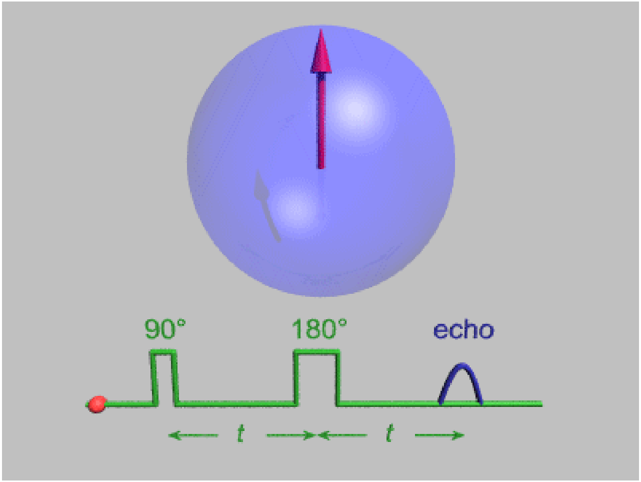
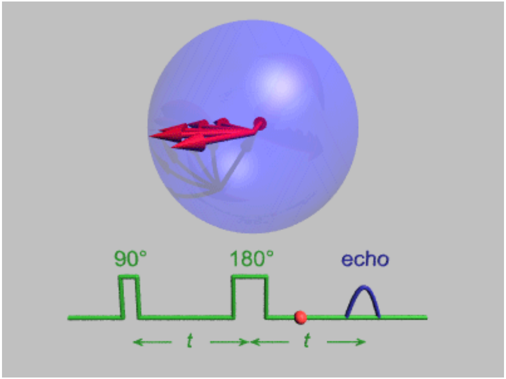
1. Background
   - Magnetic Resonance Visualised
   - The Bloch-Torrey Equation
2. Solving the Bloch-Torrey Equation
   - Operator Splitting Methods
   - Finite Element Methods
   - Time Stepping
3. Results
   - Operator Splitting versus FEM

TODO: uncomment all “pause” statements

1. Animation of a typical “spin echo” MRI sequence



1. Spins (water molecules) do not truly refocus:
    1. Precession rate depends on position
    2. Diffusion plays an important role



Magnetic Resonance Visualised

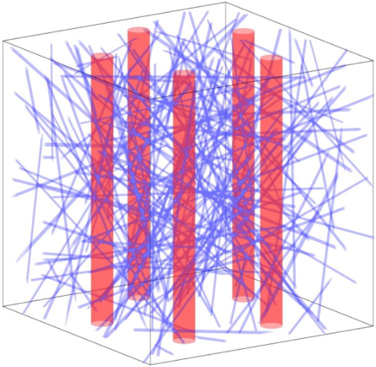


Figure: Simulated imaging voxel

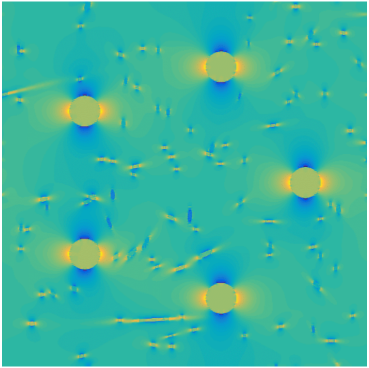


Figure: Cross section of precession rate

The Bloch-Torrey Equation

1. Evolution of the magnetization is modelled by the **Bloch-Torrey equation**

$$\frac{\partial \mathcal{M}}{\partial t} = D\Delta\mathcal{M} - \Gamma\mathcal{M}$$

   where:

$$\mathcal{M} = M_x + i\,M_y$$
$$\Gamma(\mathbf{x}) = R(\mathbf{x}) + i\omega(\mathbf{x})$$

2. IC: $\mathcal{M}(\mathbf{x}, 0) = \mathcal{M}_0(\mathbf{x})$ is given
3. BC: zero Neumann or periodic
4. Note:

$$D = 0 \;\Rightarrow\; \mathcal{M}(\mathbf{x}, t) = \mathcal{M}_0(\mathbf{x})e^{-\Gamma(\mathbf{x})t}$$

1. First, the BT PDE is rewritten in the more suggestive form

$$\frac{\partial \mathcal{M}}{\partial t} = H\mathcal{M}$$

where

$$H = -D\Delta + \Gamma.$$

2. Then, the general solution $\mathcal{M}$ may then be written as

$$\mathcal{M} = e^{-Ht}\mathcal{M}_0$$

where e^{-Ht} is the *evolution operator*

1. Now, the evolution operator may be *split* using the approximation

$$
\begin{aligned}
e^{-Ht} &= e^{D\Delta t - \Gamma t} \\
&\approx e^{-\Gamma t/2} e^{D\Delta t} e^{-\Gamma t/2} + \mathcal{O}(t^3)
\end{aligned}
$$

2. Although e^{-Ht} has no closed form, the split operators do:

$$
\begin{aligned}
e^{-\Gamma t/2}\mathcal{M} &= e^{-\Gamma(\mathbf{x})t/2} \odot \mathcal{M} \\
e^{D\Delta t}\mathcal{M} &= \Phi * \mathcal{M}
\end{aligned}
$$

1. The BT equation can also be solved using FEM
2. First, let $u = M_x$ and $v = M_y$ and write:

$$\begin{cases} \frac{\partial u}{\partial t} = D\Delta u - Ru + \omega v \\ \frac{\partial v}{\partial t} = D\Delta v - Rv - \omega u \end{cases}$$

1. Applying the method of lines:

$$M^h \mathbf{u}_t = -(DK^h + R^h)\mathbf{u} + W^h \mathbf{v}$$
$$M^h \mathbf{v}_t = -(DK^h + R^h)\mathbf{v} - W^h \mathbf{u}$$

where:

$$R^h_{ij} := \int R\,\phi_i\,\phi_j\,\mathrm{d}x$$
$$W^h_{ij} := \int \omega\,\phi_i\,\phi_j\,\mathrm{d}x$$

Time Stepping Methods

$$M^h \mathbf{u}_t = -(DK^h + R^h)\mathbf{u} + W^h \mathbf{v}$$
$$M^h \mathbf{v}_t = -(DK^h + R^h)\mathbf{v} - W^h \mathbf{u}$$

1. Solutions to the Bloch-Torrey equation decay exponentially in time at a rate of roughly $R(\mathbf{x})$
2. For this reason, the strongly A-stable and second order accurate time stepping scheme $\mathrm{TR\text{-}BDF2}$ was used

Operator Splitting versus FEM

1. Comparing the solution of the BT equation with splitting methods versus FEM...
2. **TODO: do this**