A NOTE ON OOMMF TUTORIAL

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Questions:

(1) What the free energy of the boundary conditions; (Typically, micromagnetics; free boundary condition; we can use the periodic boundary condition for the large film. There's no stray field on the boundary.)
(2) Can oommf micromagetics do simulation of antiferromagnetics. (Can model bias layer, to model two lattices.)
(3) Size effect study.
(4) oommf for python: Ubermag
(5) Can oommf be extended to hpc (threads), or for GPU computing (A group in UCSD is go over that project).
(6) What we can do for machine learning. How to learn the stray field, then incorporate into the model of micromagnetics. That's a good point. DeepFFT to learn the stray field.
(7) Can we do concurrent learning based on Exploration-Labeling-Training (ELT) procedure to predict micromagnetics, (even write a library for micromanetics. The Net can be named Deep-Mag. Some reliable data from the oommf simulation for example.)

1. INTRODUCTION

This note is about the oommf tutorial which could be found in `https://www.spintalks.org/tutorials`. The home page of OOMMF (originally developed by Bob McMichael, Michael Donahue and Don Porter) is at `https://math.nist.gov/oommf/oommf.html`. Instructional materials for this tutorial series are being posted at `https://math.nist.gov/oommf/oommf_tutorial/tutorial.html`. A dedicated discussion forum for this tutorial has been set up at `https://nanohub.org/groups/oommf_users/forum/`. The tutorial sessions will be broadcast live at `https://www.twitch.tv/onlinespintronics`.

The whole session contains:

(1) Thur, 21-May-2020: Introduction to Micromagnetics;
(2) Tues, 26-May-2020: OOMMF widgets and pitfalls;
(3) Tues, 2-June-2020: MIF magic,writing an extension, batch processing;
(4) Tues, 9-June-2020: Data analysis,pictures, movies, dispersion curves.

1.1. **Note on Session 1.**

This take place in `OOMMF Tutorial #1: May 20, 2020`.

Topics for part I: Introduction to micromagnetics:

(1) What is the micromagnetics;
(2) How can I use micromagnetics;

(3) Quasi-static simulations;
(4) Micromagnetic dynamics;
(5) Installation demonstrations;

We start with the micromagnetics in a nutshell presented in Figure 1 which is a thin film. The fundamental motion of equation of micromagnetics is given by Landau-Lifshitz-Gilbert (LLG) equation as

$$(1+\alpha^2)\frac{d\boldsymbol{M}}{dt} = \gamma \boldsymbol{H} \times \boldsymbol{M} + \frac{\alpha\gamma}{M_s}\boldsymbol{M} \times \boldsymbol{H} \times \boldsymbol{M}. \tag{1}$$

with time step Δt would be the magnitude of picosecond and t of magnitude of nanosecond.

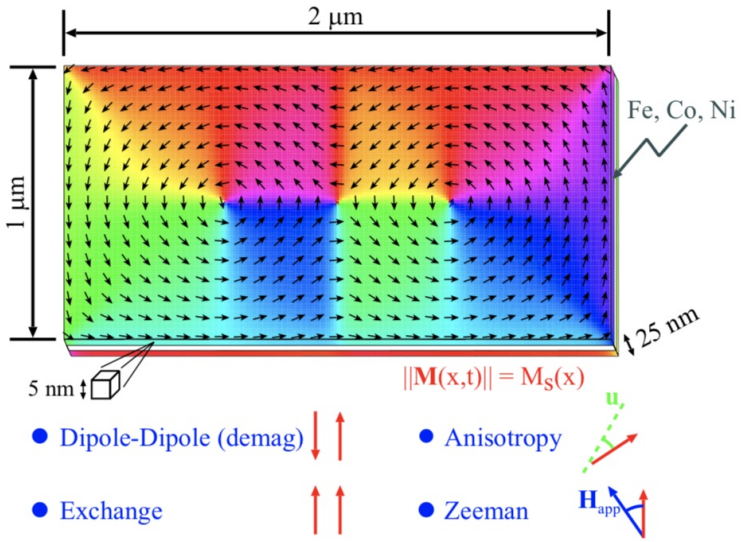


FIGURE 1. Illustration of micromagnetics.

The energy term contains dipole-dipole (demagnetization of stray) interaction, the exchange interaction, the anisotropy interaction and Zeeman energy.

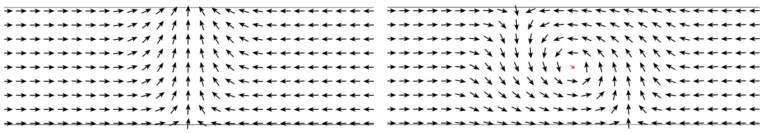
Significance of micromagnetics:

(1) Part design;
(2) Experimental design;
(3) Explaining experimental results;
(4) Understanding unexpected behavior.

If we have a long strip material with finite thickness, there exist the head-to-head domain wall types, shown in Figure 2 in which the transverse wall appeared in thin film and vortex wall appeared when the the thin film is wider under the stray field.

Question: Which domain wall we can see. The head-to-head phase diagram described here in Figure 3.

An example of pinning by a simple defect.



(A) Transverse wall (B) Vortex wall

FIGURE 2. The domain wall of the long strip material.

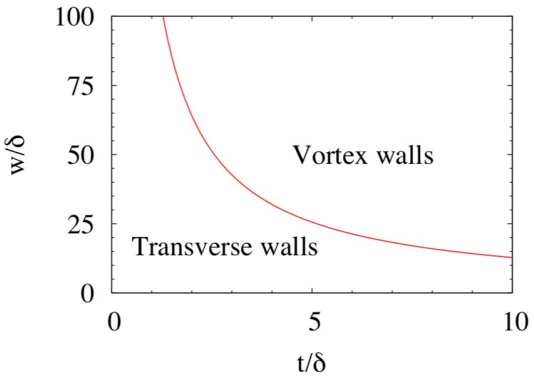


FIGURE 3. Illustration of head-to-head phase diagram, where w denotes the width, t being the thickness of the material.

Here's the energy formalism for Brown's equations:

(2)

$$E_{\text{exchange}} = \int_V \frac{A}{M_s^2}\left(|\nabla M_x|^2 + |\nabla M_y|^2 + |\nabla M_z|^2\right) d^3r$$

$$E_{\text{anisotropy}} = \int_V \frac{K_1}{M_s^2}(\boldsymbol{M}\cdot u)^2 d^3r$$

$$E_{\text{demag}} = \frac{\mu_0}{8\pi}\int_V \boldsymbol{M}(r)\cdot\left[\int_V \nabla\cdot\boldsymbol{M}(r')\frac{r-r'}{|r-r'|^3}d^3r' - \int_S \hat{n}\cdot\boldsymbol{M}(r)\frac{r-r'}{|r-r'|^3}d^2r'\right]d^3r$$

$$E_{\text{Zeeman}} = -\mu_0\int_V \boldsymbol{M}\cdot H_{\text{applied}} d^3r.$$

Remark 1. *The most hard to compute is the demag energy. We use FFT to compute the convolution part.*

The Brown's equation with constraints: $\boldsymbol{M}$ is piecewise smooth and $\|\boldsymbol{M}(r,t)\| = \|\boldsymbol{M}(r)\| = M_s(r)$ or equivalently

$$\|m(r,t)\| = \boldsymbol{M}(r,t)/M_s(r) = \|\boldsymbol{m}\| = 1. \tag{3}$$

As for the exchange lengths: Magnetocrystalline exchange length (for hard materials):

$$\ell_{\text{ex,K}} = \sqrt{\frac{A}{K_u}}, \tag{4}$$

and magnetostatic exchange length (for soft materials):

$$\ell_{\mathrm{ex},M_s} = \sqrt{\frac{2A}{\mu_0 M_s^2}}. \tag{5}$$

As for the quasi static simulation, the hysteresis loop like in Figure 4. The energy

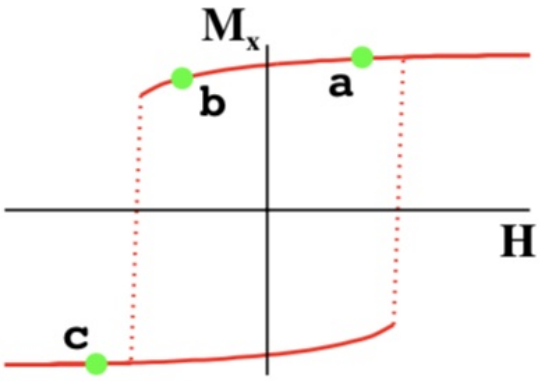


FIGURE 4. Illustration hysteresis loop.

surface for the coercive field are shown in Figure 5. The magnetic configuration for

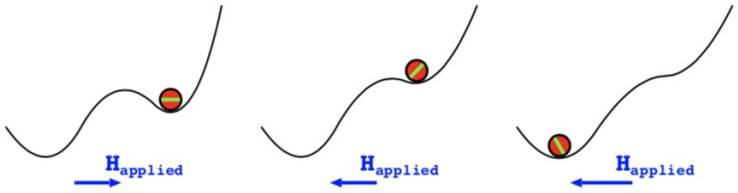


FIGURE 5. Illustration of energy surface.

a, b and c are shown in Figure 6.

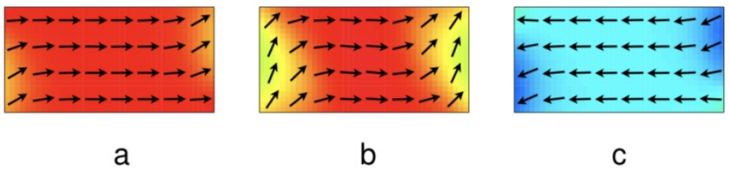


FIGURE 6. Magnetization profile.

If we focus on the magnetization dynamics which described by the LLG equation

$$\frac{d\boldsymbol{M}}{dt} = \frac{|\gamma_0|}{1+\alpha^2}\boldsymbol{H}_{\mathrm{eff}} \times \boldsymbol{M} + \frac{\alpha|\gamma_0|}{(1+\alpha^2)M_s}\boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} \times \boldsymbol{M}, \tag{6}$$

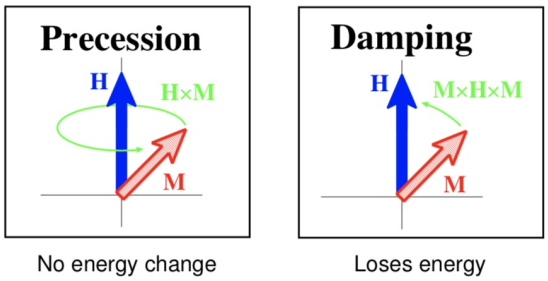


FIGURE 7. Illustration of LLG equation.

where $\boldsymbol{H}_{\text{eff}} = -\frac{1}{\mu_0}\frac{\delta E_{\text{total}}}{\delta \boldsymbol{M}}$ and γ_0 denotes gyromagnetic ratio and α being the damping coefficient. The first term would be the precession term and the second one is the damping term, which described in Figure 7.

Example 1 (Magnetization dynamics)**.** *If we initialize the magnetization and apply the external field as described in Figure 8. Then we evolve the dynamics in Figure 9.*

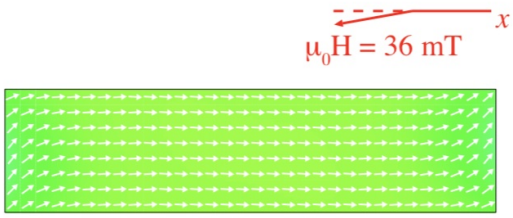


FIGURE 8. Magnetization configuration at initial time.

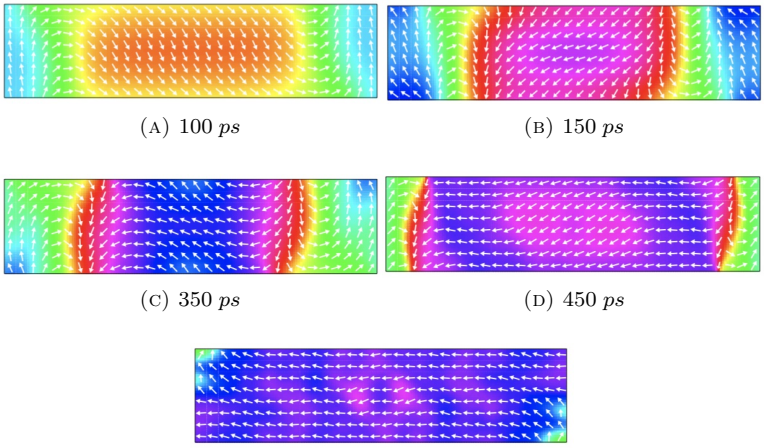
If we consider the long strip of thin film simulation. We set the head-to-head domain wall and the external field as in Figure 10. The dynamics are shown in Figure 11.

What about energy: Zeeman energy transfer to other energy.

Now moving to the demos of installation demonstrations:

(1) nanoHuB: `https://nanohub.org`, we have to login. When login, we can goto the dashboard. We got ot `MyTools`. Seek OOMMF: Object Oriented Micromagnetic Framework and launch tool. Click the `Oxsii` button (which is the solver), the other one `mmDisp` for output. Then go to `file`, load problem, double click `example`, go to `oxs` solver, the `.mif` extension is micromagnetic input format. Take `yoyo.mif` as an example. OOMMF can work in parallel by `Threads`. Push `Ok`.

Launch other widgets, like `mmDisp` which display the vector field. Select `Magnetization` to display. Push `Send` button. Play the option for mmdisp: `Arrow` using Red-Black-Blue and `Pixel` using Red-Green-Blue-Red with quantity `xy-angle`. We then apply that setup. Go to options, then close the `Control Bar`. As for Oxsii part, `Relax` first, basically do one stage, click `Run` to keep going, change stage to every 10 to accelerate. Click `pause`



(A) 100 *ps* (B) 150 *ps*

(C) 350 *ps* (D) 450 *ps*

(E) 750 *ps*

FIGURE 9. The magnetization dynamics.

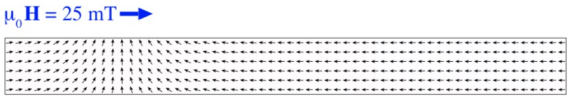
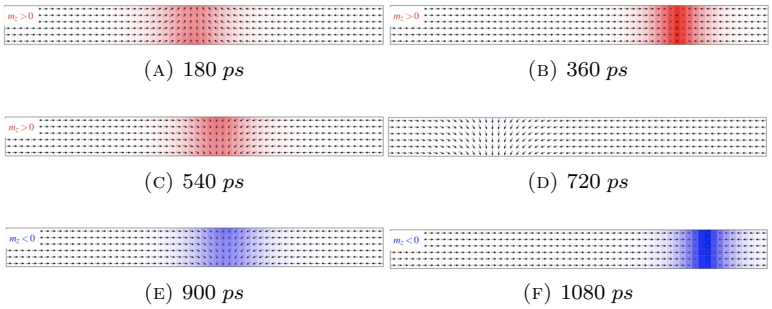


FIGURE 10. Magnetization configuration at initial time for head-to-head domain wall.



(A) 180 *ps* (B) 360 *ps*

(C) 540 *ps* (D) 720 *ps*

(E) 900 *ps* (F) 1080 *ps*

FIGURE 11. The magnetization dynamics.

to stop. We can click the button `Terminate` or `Keep for later` when it's done. As for nanohub, we can go to community, enter `Groups`. Search for oommf and go to forum for oommf.

(2) Windows: We need first install tcl/tk https://www.tcl-lang.org. `ActiveTcl` may be easy to install on windows. As for the binary source, make sure the version should be lager than `8.6.*`. When tcl is installed, we can go to the oommf software https://math.nist.gov/oommf/. Here's the link for OOMMF series tutorial https://math.nist.gov/oommf/oommf_

tutorial/tutorial.html. Go down to the software page. We can download the developed or stable version releases of oommf. In the downloaded folder, there's `oommf.tcl` to launch. When load problems, choose the directory `/oommf/apps/oxs/examples`. Then we click `run` and pause, go to file and click `Exit All OOMMF`. The main step is seen in quick start documentation https://math.nist.gov/oommf/doc/userguide20a2/userguide/quickstart.html.

(3) MacOS: Goto App store and download the Xcode and install command line tools for Xcode. Open terminal: `xcode-select -h`, `xcode-select --install` (install the command line tools), `clang++ --version`, and download oommf and build-in. We grab the source in the software section. `ls -ltr Downloads/`, `tar xf Downloads/oommf.*.tar.gz`, `cd oommf`, `tclsh`, `info pat`, (on Mac, we need 8.6.9 or more), `exit` (get out of the shell), `ls /usr/local/bin/tc*`, `whereis tclsh`, `tclsh8.6`, `tclsh8.6 oommf.tcl +platform`, `tclsh8.6 oommf.tcl pimake` (to build), we can move the directory around, `./oommf.tcl`

(4) Linux or Unix (Ubuntu etc.) Do a demo of WSL of the Windows. The steps: `cat /etc/os-release`, `uname -a` (see the kernel), `curl -O https://math.nist.gov/oommf/dist/oommf20a2_20190930.tar.gz`, `tar xf oommf2*.tar.gz`, `cd oommf`, `sudo apt install tcl`, `sudo apt install tk`, `apt list tcl* | grep -i dev`, `sudo apt install tcl-dev tk-dev`, `tclsh oommf.tcl +platform`, `tclsh oommf.tcl pimake`, `tclsh oommf.tcl`, (Here need to install Xwindows, (Xlaunch, Xming) to visualize in the WSL.) We can use `tclsh oommf.tcl oxsregression` to test the benchmark samples.

As an final part of this session, we give the initial configuration that we set up on the Mac shown in Figure 12.

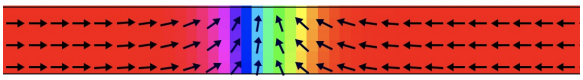


FIGURE 12. Magnetization configuration at initial time for head-to-head domain wall.

1.2. **Note on Session 2.** This take place in `OOMMF Tutorial #2: May, 26, 2020.` Topics for the OOMMF basics. Center for Theoretical and Computational Materials Science http://www.ctcms.nist.gov/. Here are some standard problems from μmag https://www.ctcms.nist.gov/~rdm/mumag.org.html in Figure 13.

The contents of OOMMF software contains that

(1) Finite difference code; graphical user interface; Windows, Linux, MacOS (multi-platform); binaries and source code;
(2) Tcl/Tk and C++ based modular architecture; 250 page user's manual; available at nanoHUB; Extensible structure allows numerous third party extensions.

OOMMF file layout: app (contains solver), config (local, platforms), doc (progman, userguide), pkg. The details are shown in Figure 14.

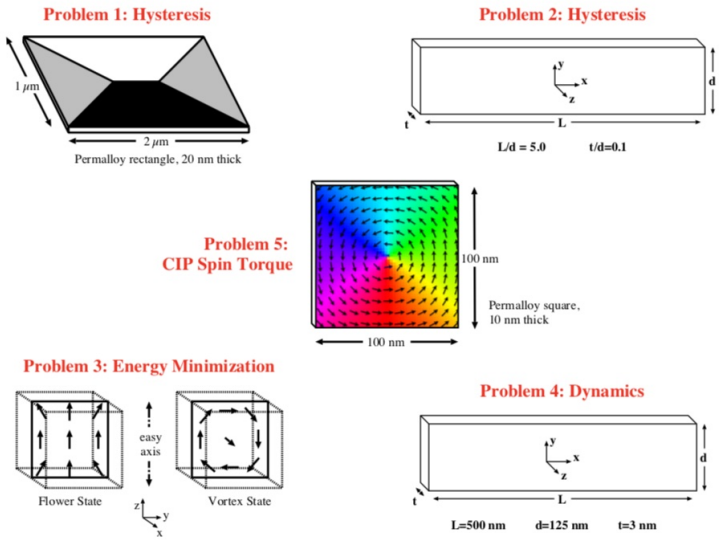


FIGURE 13. Illustration of standard problem from μmag.

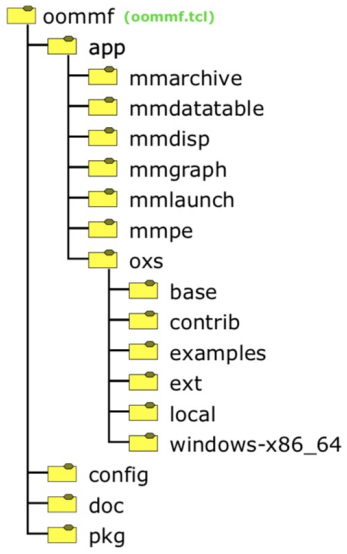
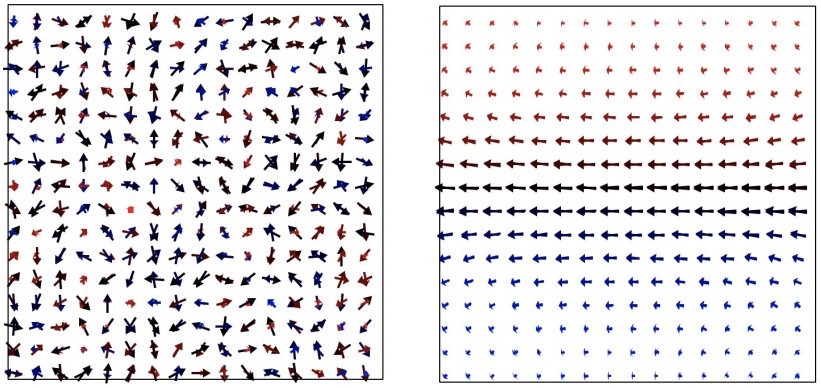


FIGURE 14. Illustration of file layout.

Widget overview: mmLaunch,Oxsii, mmDisp, mmDataTable, mmGraph, mmArchive, mmProbEd.

If we take standard problem 3 as an example, which gives the initial configuration for magnetization and the evolved dynamics presented in Figure 15.

Let's look at the 3D input MIF file, take the standard prob 4 as an example which is shown in Figure 16.



(A) Initial configuration

(B) Magnetization at some time t

FIGURE 15. Magnetization profile.

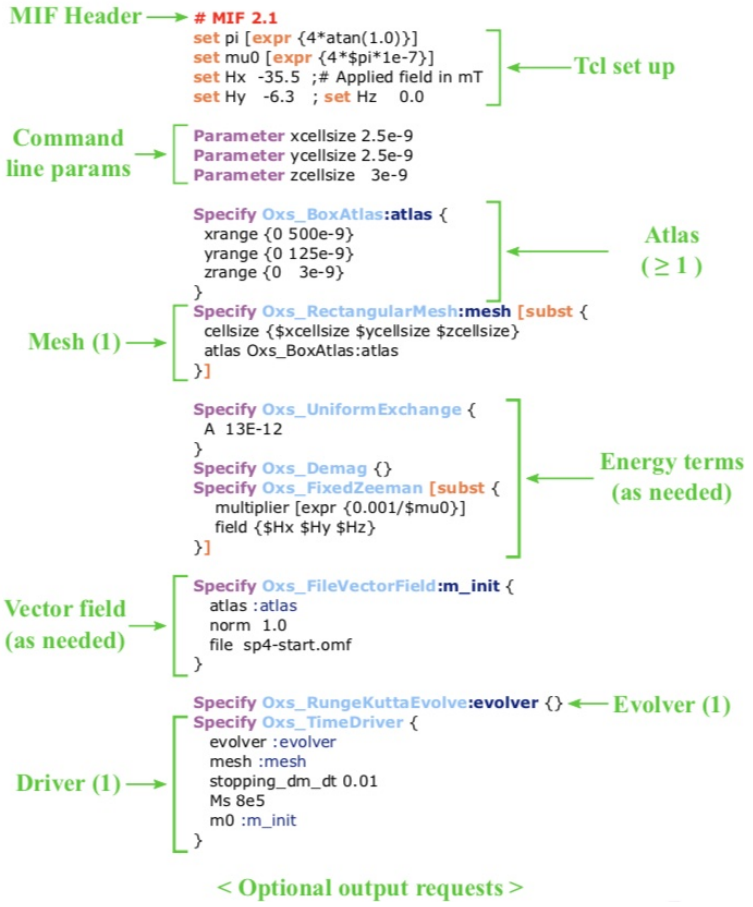


FIGURE 16. Illustration of mif file.

Tour of `Oxs_Ext` classes:

(1) Atlases:Oxs_BoxAtlas; Oxs_ImageAtlas; Oxs_ScriptAtlas;Oxs_MultiAtlas;
(2) Meshes: Oxs_RectangularMesh; Oxs_PeriodicRectangularMesh;
(3) Scalar fields:Oxs_UniformScalarField; Oxs_AtlasScalarField; Oxs_ScriptScalarField; Oxs_RandomVectorField; Oxs_VecMagScalarField; Oxs_ImageScalarField;
(4) Vector fields: Oxs_UniformVectorField; Oxs_AtlasVectorField; Oxs_ScriptVectorField; Oxs_RandomVectorField; Oxs_MaskVectorField; Oxs_FileVectorField;
(5) Energies: Oxs_UniaxialAnisotropy; Oxs_Demag; Oxs_UZeeman; Oxs_StageZeeman; Oxs_UniformExchange; Oxs_Exchange6Ngbr; Oxs_TwoSurfaceExchange; Oxs_DMExchange6Ngbr;
(6) Evolvers: Oxs_CGEvolve; Oxs_RungeKuttaEvolve; Anv_SpinTEvolve;
(7) Drivers: Oxs_MinDriver; Oxs_TimeDriver;

An example to show the tcl programming here in Figure 17.

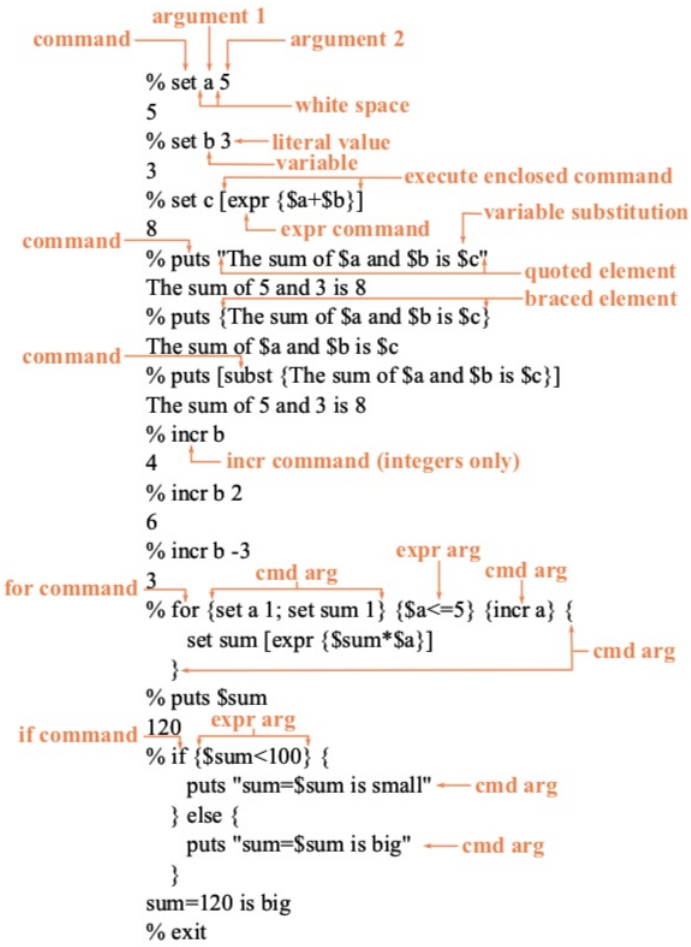


FIGURE 17. Annotation of tcl programming.

The reference for Tcl:

(1) https://www.tcl-lang.org/;
(2) https://wiki.tcl-lang.org/page/Online+Tcl+and+Tk+Tutorials;
(3) https://wiki.tcl-lang.org/page/Dodekalogue.

Homework 1 (Homework: Problem 1, Part A)**.** *Write a MIF file for this problem which has part dimensions of* $500\ nm \times 200\ nm \times 0.6\ nm$ *with* $M_s = 1.1e6\ A/m$*, exchange coupling* $A = 1.6e-11\ J/m$*,* $K_1 = 5.1e5\ J/m^3$ *along the* $(0,0,1)$ *axis, with DMI* $D = 3.5e-3\ J/m^3$*, free boundaries. (Hint: Use the Oxs_DMExchange6Ngbr extension to model the DMI, see the reference https://www.lps.u-psud.fr/spip.php?article2252. This would be a little bit tricky for the initialized configuration that ignoring z-coords. Let P be the point* $(50\ nm, 50\ nm)$ *relative to the lower left hand corner of the simulation. Set* $\boldsymbol{m} = (0,0,1)$ *for all points closer to P than* $16\ nm$*. Set* $\boldsymbol{m} = (0,0,-1)$ *for all points farther from P than* $23\ nm$*. For points in-between, set m to point towards P. Write a Tcl proc to use with Oxs_ScriptVectorField https://math.nist.gov/oommf/doc/userguide20a2/userguide/Standard_Oxs_Ext_Child_Clas.html#SVF to set up this initial configuration. This initial configuration is illustrated below in Figure 14.*

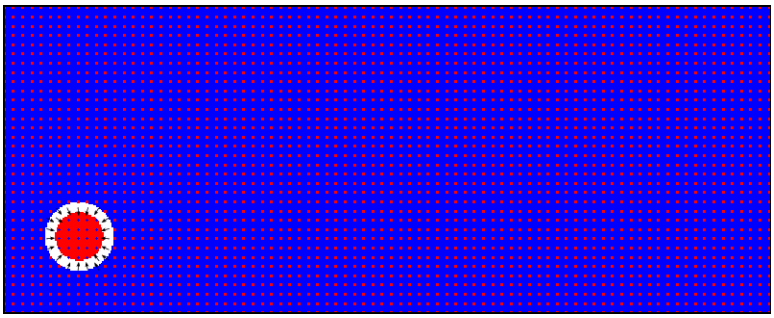


FIGURE 18. Initial magnetization. Background color indicates$z$-component of magnetization, with red indicating out of plane ($z > 0$), blue is into plane ($z < 0$), and white is in plane ($z = 0$).

Relax to equilibrium: *Also, use Oxs_CGEvolve to relax the initial state towards equilibrium. Try different cell sizes in the range* $1\ nm$ *to* $4\ nm$*. The magnetization should relax into a skyrmion. If the skyrmion forms but wanders away from the initial location, introduce a small region with larger* K_1 *near P. to pin the skyrmion. See how small* K_1 *needs to be to hold the skyrmion in place. In Part B we will introduce a spin current to move the skyrmion.) The equilibrium state should be similar to the following two figures in Figure 19 and Figure 20.*

At the end of this session, we can refer to https://math.nist.gov/oommf/doc/userguide20a0/userguide/Standard_Oxs_Ext_Child_Clas.html to write the `*.mif` and run it.

We give the solution to `Hw #1`:

Solution 1. *One solution is shown below. Note that it contains no Oxs_Demag (dipole-dipole) component. With these parameter values the demagnetization field overpowers the magnetocrystalline anisotropy and destroys the skyrmion. However, if you want a simulation with Ox_Demag, you can reduce Ms from* $1100\ kA/m$ *to* $200\ kA/m$*. This variant behaves similarly to the original, both in terms of the*

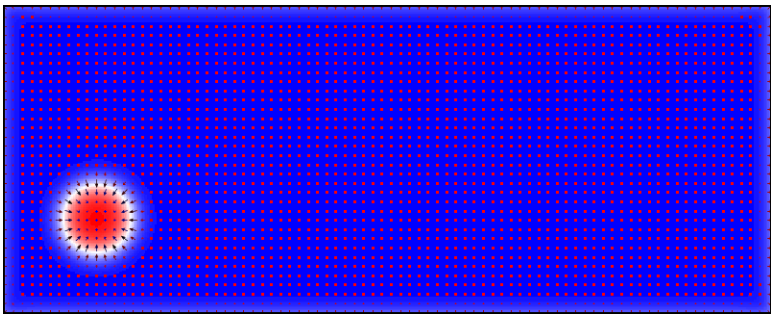


FIGURE 19. Equilibrium magnetization. As above, background color indicates z-component of magnetization, with red indicating out of plane ($z > 0$), blue is into plane ($z < 0$), and white is in plane ($z = 0$).

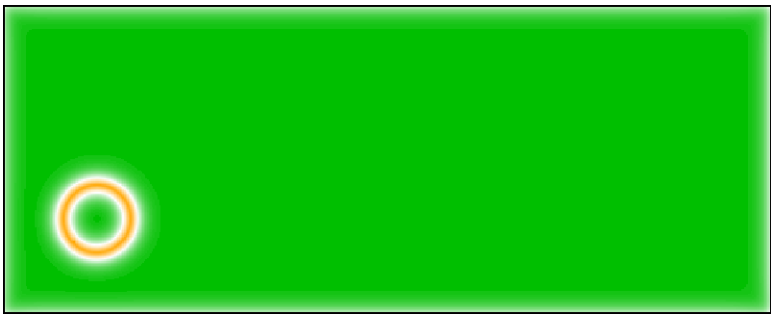


FIGURE 20. Anisotropy energy density in equilibrium configuration. Background color indicates magnitude of energy density, where orange is $\approx 500\ kJ/m3$ and green is close to zero.

remanent state and also the response to an applied current (i.e., the Session 3 *homework problem). The mif file is attached here.*

```
# MIF 2.2
#
# This file was based in part on the skirmion.mif example file included with
# the Oxs_DMExchange6Ngbr extension class by  S. Rohart and A. Thiaville
# (Laboratoire de Physique des Solides, Université Paris-Sud, Orsay, FRANCE).
# Please quote S. ROHART and A. Thiaville Phys. Rev. B 2013 when using the
# Oxs_DMExchange6Ngbr class.

Parameter D 3.5
set DD [expr {$D/1000.}]

Parameter film_thickness 0.6e-9

Parameter xcell 2.0e-9
Parameter ycell 2.0e-9
Parameter zcell $film_thickness
```

```
set Ms 1.1e6

set init_skyrmion_r 50e-9
set init_skyrmion_x $init_skyrmion_r
set init_skyrmion_y $init_skyrmion_r
set init_skyrmion_rsq_inner [expr {0.1*$init_skyrmion_r*$init_skyrmion_r}]
set init_skyrmion_rsq_outer [expr {0.2*$init_skyrmion_r*$init_skyrmion_r}]

set xmax [expr {10*$init_skyrmion_r}]
set ymax [expr {4*$init_skyrmion_r}]

set divot_r [expr {4*$xcell}]
Specify Oxs_MultiAtlas:atlas [subst {
atlas { Oxs_BoxAtlas:divot {
xrange { [expr {$init_skyrmion_r-$divot_r}] [expr {$init_skyrmion_r+$divot_r}] }
yrange { [expr {$init_skyrmion_r-$divot_r}] [expr {$init_skyrmion_r+$divot_r}] }
zrange { 0 $film_thickness }
}}
atlas { Oxs_BoxAtlas:world {
xrange { 0 $xmax }
yrange { 0 $ymax }
zrange { 0 $film_thickness }
} }
}]

Specify Oxs_RectangularMesh:mesh [subst {
cellsize { $xcell $ycell $zcell }
atlas :atlas
}]

Specify Oxs_UniformExchange:HeisenbergEx {
A 1.6e-11
}

#uniform DMI is used here
Specify Oxs_DMExchange6Ngbr:DMEx [subst {
default_D $DD
atlas :atlas
D {
world world $DD
}
}]

set K1 0.51e6
set K1_divot [expr {1.03*$K1}]
Specify Oxs_UniaxialAnisotropy:Anisotropy [subst {
axis {0 0 1}
```

```
K1 { Oxs_AtlasScalarField {
atlas :atlas
default_value $K1
values {
divot $K1_divot
}
}}
}]

proc Skyrmion { x y z } {
global init_skyrmion_x init_skyrmion_y
global init_skyrmion_rsq_inner init_skyrmion_rsq_outer
set xoff [expr {$init_skyrmion_x-$x}]
set yoff [expr {$init_skyrmion_y-$y}]
set rsq [expr {$xoff*$xoff+$yoff*$yoff}]
if {$rsq<$init_skyrmion_rsq_inner} { return [list 0. 0.  1.] }
if {$rsq>$init_skyrmion_rsq_outer} { return [list 0. 0. -1.] }
return [list $xoff $yoff 0]
}

Specify Oxs_CGEvolve {}
Specify Oxs_MinDriver [subst {
evolver Oxs_CGEvolve
stopping_mxHxm 1e-5
mesh :mesh
Ms $Ms
m0 { Oxs_ScriptVectorField {
script Skyrmion
atlas :atlas
script_args rawpt
} }
}]
```

1.3. **Note on Session 3.** This take place in `OOMMF Tutorial #3: June 2, 2020`. Topics for advanced simulations.

(1) Pitfalls: Mesh size; symmetry breaking; Field step size; stopping criteria; energy minimization;
(2) MIF details;
(3) Command line tools;
(4) OOMMF extensions;
(5) MIF magic: spatially varying properties;Patterned structures;Layered structures;Time varying field;Current pulse; Infinite strips;

Some trick for the homework: The first is the skyrmion initialization:

```
Specify Oxs_CGEvolve
Specify Oxs_MinDriver evolver Oxs_CGEvolve stopping_mxHxm 1e-5
{ }
[ subst {
mesh :mesh
Ms $Ms
```

```
m0 { Oxs_ScriptVectorField {
script Skyrmion atlas :atlas script_args rawpt
}} }]
```

and then

```
proc Skyrmion { x y z } {
global skyrmion_x skyrmion_y
global skyrmion_rsq_inner skyrmion_rsq_outer
set xoff [expr {$skyrmion_x-$x} ]
set yoff [expr {$skyrmion_y-$y}]
set rsq [expr { $xoff*$xoff+$yoff*$yoff } ]
if {$rsq<$skyrmion_rsq_inner} {return {0. 0. 1. }}
if {$rsq>$skyrmion_rsq_outer} {return {0. 0. -1.}}
return [ list $xoff $yoff 0]
}
```

and then for the exchange and DMI energy terms

```
Specify Oxs_UniformExchange:HeisenbergEx {
A 1.6e-11
}
#uniform DMI is used here
Specify Oxs_DMExchange6Ngbr:DMEx [ subst {
default_D $DD
atlas :atlas
D{
world world $DD
}
}]
```

Here, we do not incorporate the demag field into the code. The other thing is anisotropy and pinning:

```
set divot_r [expr {4*$xcell}]
Specify Oxs_MultiAtlas : a t l a s [ subst { atlas { Oxs_BoxAtlas:divot {
xrange { [ expr { $skyrmion_r-$divot_r } ]
[expr {$skyrmion_r+$divot_r}] }
yrange { [ expr { $skyrmion_r-$divot_r } ]
[expr {$skyrmion_r+$divot_r}] }
zrange { 0 $film_thickness }
}}
atlas { Oxs_BoxAtlas:world {
xrange { 0 $xmax }
yrange { 0 $ymax }
zrange { 0 $film_thickness }
}} }]
```

We can also apply the current and observe that it can moves the skymion.

```
set K1 0.51e6
set K1_divot [ expr {1 .03*$K1 } ]

Specify Oxs_UniaxialAnisotropy [ subst
{ axis {0 0 1}
```

```
K1 { Oxs_AtlasScalarField {
atlas :atlas
default_value $K1 values {
divot $K1_divot }
}} }]
```

Now we look at the Hw #2:

Homework 2. *Write a MIF file: Using the equilibrium state from the Session* 2 *homework as the initial state, set up an STT simulation using the* `Anv_SpinTEvolve` *extension with these parameters:*

1. $u = 100\ m/s$;
2. $\alpha = 0.1$;
3. $\beta = 0.04$.

See the `Anv_SpinTEvolve` https://www.zurich.ibm.com/st/nanomagnetism/spintevolve.html *web page and sample problem to get started. (Note: This extension is installed by default in all standard OOMMF releases.)*

Run simulations: The skyrmion should move to the right, and slightly upward. Determine the speed of the skyrmion and the drift angle. Try varying alpha. For $\alpha = \beta$ *there should be no up or down drift. For* $\alpha < \beta$ *the drift should be downward. For that condition flip the initial state using* `Oxs_AffineOrientVectorField` *and* `Oxs_AffineTransformVectorField` *so the skyrmion can drift without running into the edge of the simulation. If the simulation goes unstable for small alpha try adding "*`method rkf54s`*" to the* `Anv_SpinTEvolve` *Specify block.*

Extra Credit: Reduce the saturation magnetization Ms *in the simulation to* $200\ kA/m$*, and enable dipole-dipole interactions by including an* `Oxs_Demag` *object. Solve for remanent equilibrium as in Session* 2 *homework, with increased pinning if necessary. Then run STT current simulations as above.*

We take the μmag standard problem 1 as an example in Figure 21.

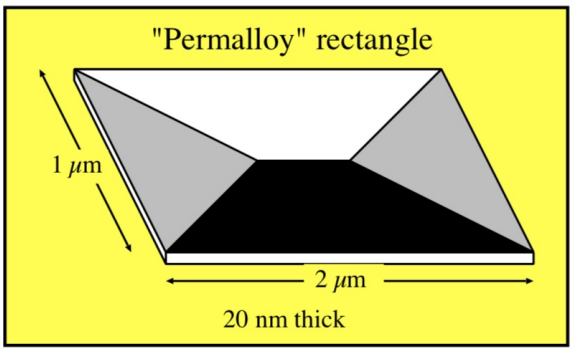


FIGURE 21. The setup for μmag standard problem 1.

Our task is to simulate the hysteresis loop. There are some results in 1996 and 1997 shown in Figure 22. We can see that the simulation results here are different. (The problem is that meshes are too coarse.) We need to double check the exchange lengths:

(1) Magnetocrystalline exchange length (for hard materials):

$$\ell_{\mathrm{ex,K}} = \sqrt{\frac{A}{K_u}};$$

(2) Magnetostatic exchange length (for soft materials):

$$\ell_{\mathrm{ex},M_s} = \sqrt{\frac{2A}{\mu_0 M_s^2}}$$

In this two scales, don't mesh any coarser than smaller of these two values and Don't confuse the latter with the "characteristic length":

$$R_0 = \sqrt{2\pi}\sqrt{\frac{2A}{\mu_0 M_s^2}} \approx 2.5\ell_{\mathrm{ex},M_s}.$$

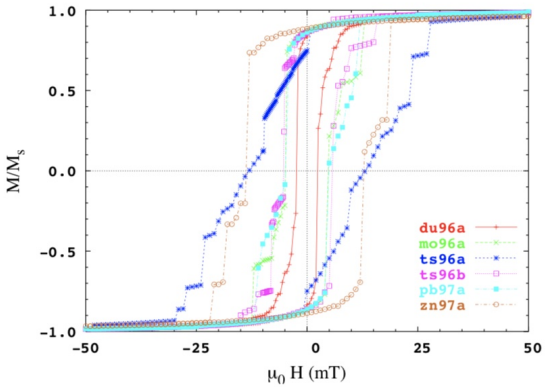


FIGURE 22. The simulation results for μmag standard problem 1.

The example for ℓ_{ex} values presented in

TABLE 1. Example of ℓ_{ex} values.

Material	M_s (kA/m)	K (kJ/m^3)	A (pJ/m)	$\ell_{\mathrm{ex,K}}$ (nm)	ℓ_{ex,M_s} (nm)
Fe	1700	48	21	21	3.4
Co	1400	520	30	7.6	4.9
Ni	490	-5.7	9	40	7.7
Permalloy	800	0	13	-	5.7
$Nd_2Fe_{14}B$	1280	4500	13	1.7	3.6

we mention two types of domain wall (Bloch and Neel wall) are presented here in Figure 23.

Cell size recommendations:

(1) Don't mesh coarser than ℓ_{ex};

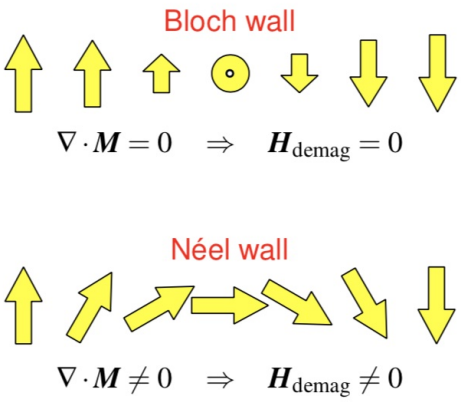


FIGURE 23. The Bloch wall and Neel wall.

(2) Check max neighbor angle: under 30° is usually reliable, over 90° is questionable, 180° is bogus.
(3) Run at multiple discretizations and check for convergence (if possible).

We comment about the symmetry breaking under applying the external field. we give the description in Figure 24.

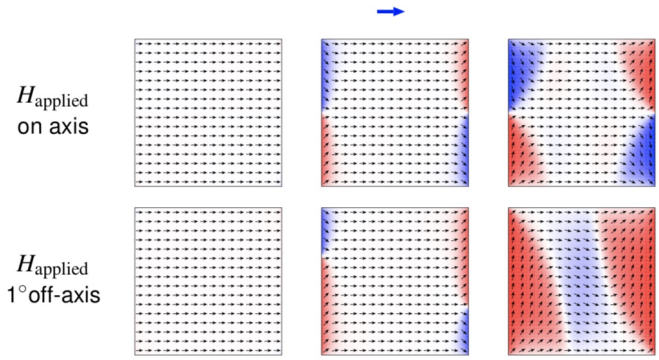


FIGURE 24. Illustration of symmetry breaking.

If the field step is big, there will happen premature switching. Now, another question is what the stopping criteria. That is

$$\boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} < \text{stoptorque}. \tag{7}$$

If we consider how to solve the standard problem 3 (energy minimization problem). We can do the steepest gradient method or conjugate gradient. The comparison is list in Figure 25.

About the MIF file, we have some comments:

(1) MIF files can be edited in any plain-text editor;
(2) Source code editors (e.g. Notepad++, Geany, Emacs, vi) can ease the task with syntax highlighting. Use Tcl mode for MIF files;

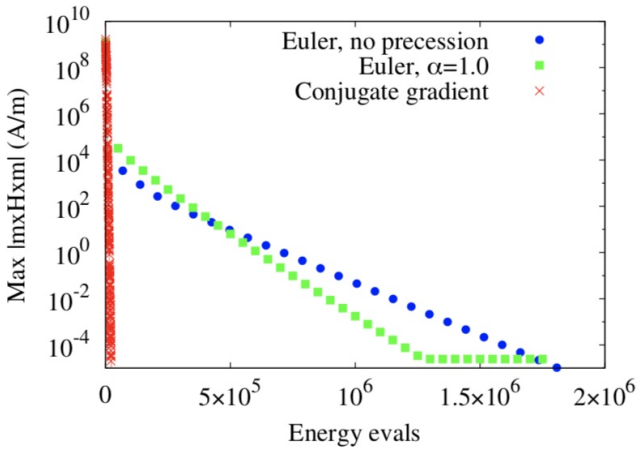


FIGURE 25. Illustration of energy minimization.

1.4. **Note on Session 4.**

REFERENCES