FACULTY OF SCIENCES

DEPARTMENT OF SOLID STATE SCIENCES

DYNAMAT GROUP

MUMAX3-WORKSHOP SESSION 4

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IEEE MAGNETICS

NVIDIA

CSPINTRONICS

SCHEDULE

Monday 08/31, 6PM-8PM CET

Session 1: general introduction to micromagnetics in mumax3

Session 2: mumax3 ecosystem, workflow and a first simulation

Monday 09/07, 6PM-7:30PM CET

Session 3: basic examples

>homework

Monday 09/14, 6PM-7:30PM CET

Session 4: advanced features and more extensive examples

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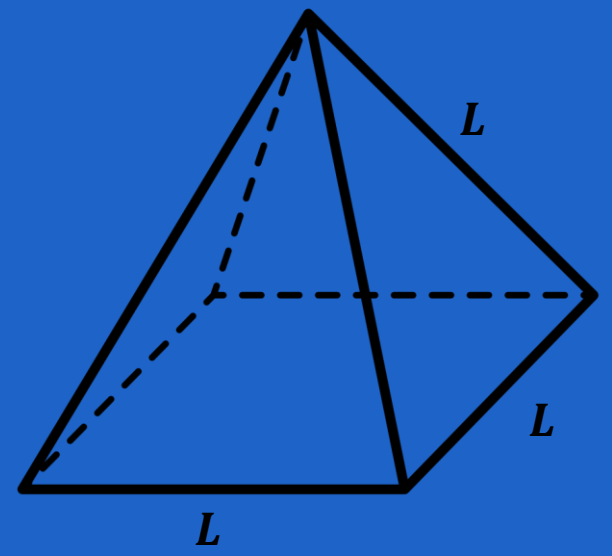
HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Consider a ferromagnetic equilateral square pyramid with the following material parameters

- Exchange stiffness $A = 13\ \mathrm{pJ/m}$
- Saturation magnetization $M_{sat} = 800\ \mathrm{kA/m}$

Find the magnetic ground state of this structure for different side lengths L ranging from 50 nm to 100 nm.



Hint: this is exercise is very similar to standard problem 3

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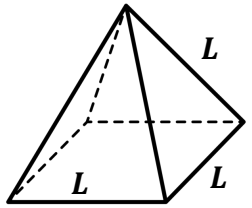
HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID



Side length: L

Pyramid height: $h = \frac{L}{\sqrt{2}}$

Simulation box size: $L \times L \times h$

Simulation grid size: $N_x \times N_x \times N_z$

Defining the grid size (powers of 2)

```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)
```

Max cell size: $\left(\frac{L_{max}}{N_x}, \frac{L_{max}}{N_x}, \frac{h_{max}}{N_z}\right)$

$= (1.56\ \text{nm}, 1.56\ \text{nm}, 2.21\text{nm})$ ✓

Uniform material parameters

```
Msat = 800e3
Aex  = 13e-12
```

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```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Two stable states (similar to ferromagnetic cube):

- Vortex state
- Flower state (quasi uniform)

Don’t know which states are stable? → Relax multiple random configurations

Output scheduling

```
Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")
```

```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

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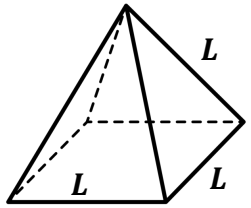
HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID



Side length: L

Pyramid height: $h = \frac{L}{\sqrt{2}}$

Simulation box size: $L \times L \times h$

Simulation grid size: $N_x \times N_x \times N_z$

Simulation cell size: $\frac{L}{N_x} \times \frac{L}{N_x} \times \frac{h}{N_z}$

Dihedral angle: $\arctan(\sqrt{2})$

Gradually increase the pyramid side length L by changing the cell size:

```
for L=50e-9 ; L<=100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx, L/Nx, height/Nz)

    …
}
```

```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

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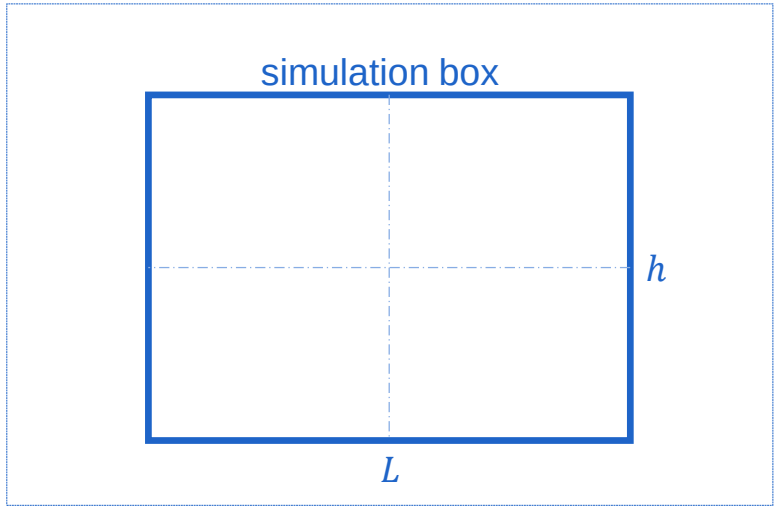
HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Creating a pyramid shape (with the top in the center)

```
s1 := zrange(-inf,0).rotY( angle)
s2 := zrange(-inf,0).rotY(-angle)
s3 := zrange(-inf,0).rotX( angle)
s4 := zrange(-inf,0).rotX(-angle)
pyramid := s1.intersect(s2).intersect(s3).intersect(s4)
```

Step-by-step pyramid construction



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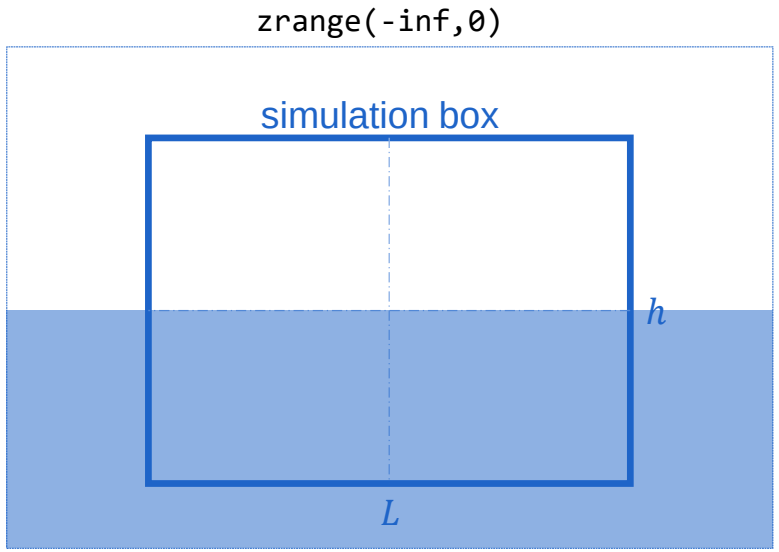
```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Creating a pyramid shape (with the top in the center)

```
s1 := zrange(-inf,0).rotY( angle)
s2 := zrange(-inf,0).rotY(-angle)
s3 := zrange(-inf,0).rotX( angle)
s4 := zrange(-inf,0).rotX(-angle)
pyramid := s1.intersect(s2).intersect(s3).intersect(s4)
```



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```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

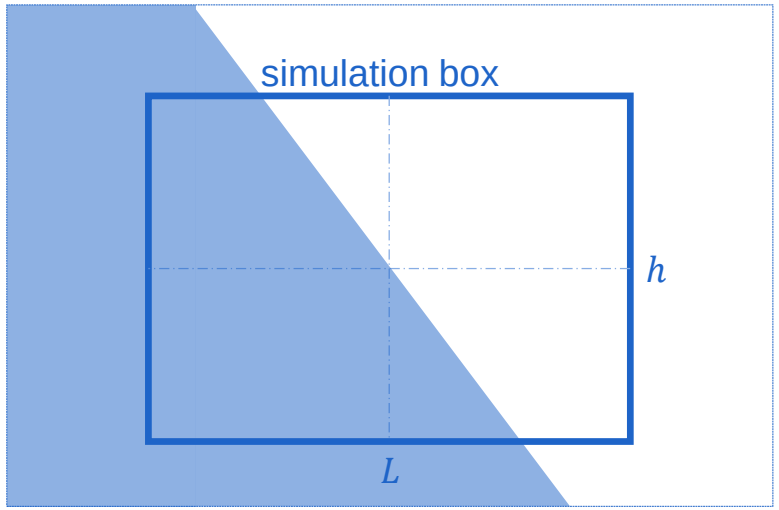
HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Creating a pyramid shape (with the top in the center)

```
s1 := zrange(-inf,0).rotY( angle)
s2 := zrange(-inf,0).rotY(-angle)
s3 := zrange(-inf,0).rotX( angle)
s4 := zrange(-inf,0).rotX(-angle)
pyramid := s1.intersect(s2).intersect(s3).intersect(s4)
```

s1 := zrange(-inf,0).rotY(angle)



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```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

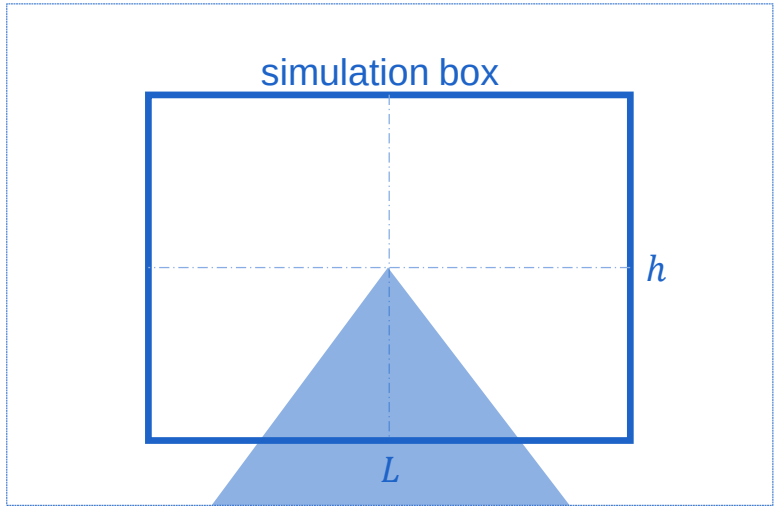
HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Creating a pyramid shape (with the top in the center)

```
s1 := zrange(-inf,0).rotY( angle)
s2 := zrange(-inf,0).rotY(-angle)
s3 := zrange(-inf,0).rotX( angle)
s4 := zrange(-inf,0).rotX(-angle)
pyramid := s1.intersect(s2).intersect(s3).intersect(s4)
```

```
s1 := zrange(-inf,0).rotY( angle)
s2 := zrange(-inf,0).rotY(-angle)
s1.intersect(s2)
```



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```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

HOMEWORK ASSIGNMENT 1

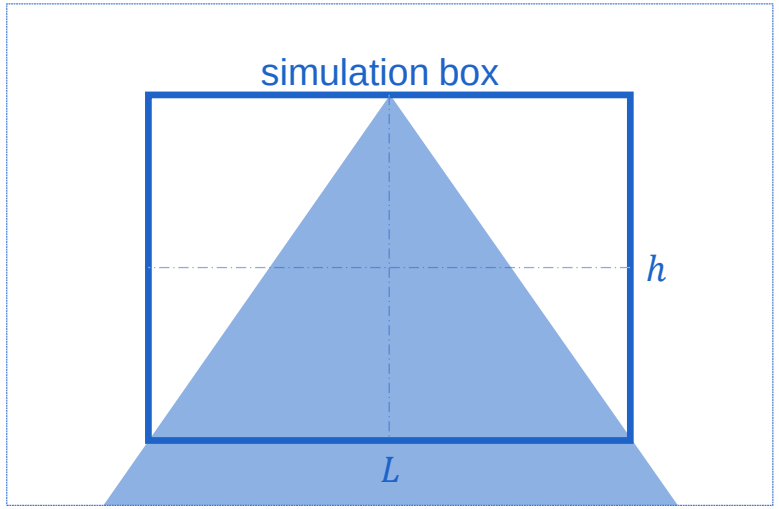
THE FERROMAGNETIC PYRAMID

Moving the pyramid up to fit in the simulation box
(+ a fraction of the cell size to avoid rounding errors)

```
dz := height/2 + 0.1*height/Nz
pyramid = pyramid.transl(0,0,dz)

setgeom(pyramid)
```

```
pyramid = pyramid.transl(0,0,height/2)
```



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```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Relax the uniform state and compute the energy

```
m = uniform(1,0,1)
minimize()
Eflower = E_total.get()
```

Relax the vortex state and compute the energy

```
m = vortex(1,-1)
minimize()
Evortex = E_total.get()
```

Write the results to the table

```
tablesave()
```

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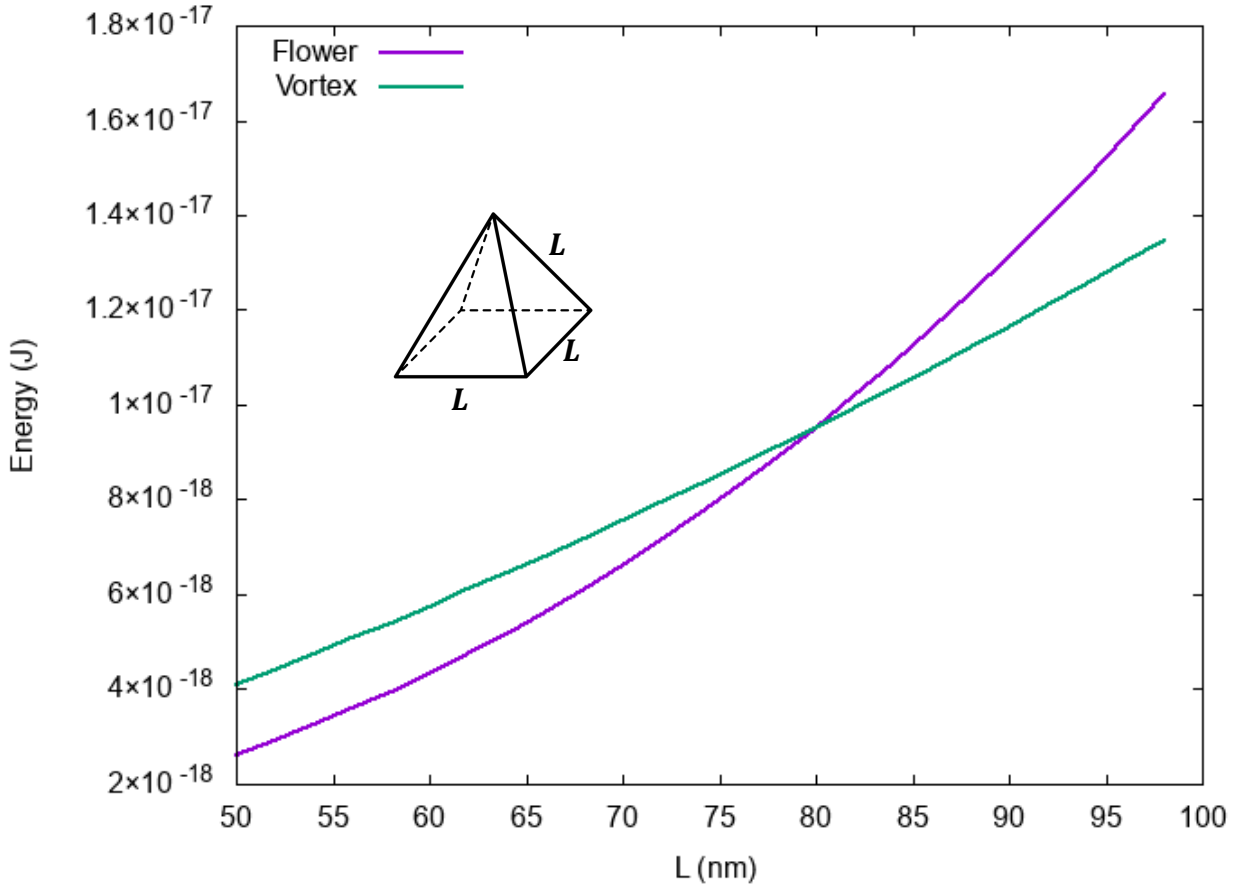
```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

HOMEWORK ASSIGNMENT 1

THE FERROMAGNETIC PYRAMID

Table.txt:




```
Nx := 64
Nz := 32
setgridsize(Nx,Nx,Nz)

Msat = 800e3
Aex  = 13e-12

Eflower := 0.0
Evortex := 0.0
L := 0.0
tableAddVar(L,"L","m")
tableAddVar(Eflower,"Eflower","J")
tableAddVar(Evortex,"Evortex","J")

for L=50e-9 ; L <= 100e-9; L+=2e-9 {

    height := L/sqrt(2)       // pyramid height
    angle  := atan(sqrt(2))   // dihedral angle

    setcellsize(L/Nx,L/Nx,height/Nz)

    s1 := zrange(-inf,0).rotY( angle)
    s2 := zrange(-inf,0).rotY(-angle)
    s3 := zrange(-inf,0).rotX( angle)
    s4 := zrange(-inf,0).rotX(-angle)
    pyramid := s1.intersect(s2).intersect(s3).intersect(s4)

    dz := height/2 + 0.1*height/Nz
    pyramid = pyramid.transl(0,0,dz)

    setgeom(pyramid)

    m = uniform(1,0,1)
    minimize()
    Eflower = E_total.get()

    m = vortex(1,-1)
    minimize()
    Evortex = E_total.get()

    tablesave()
}
```

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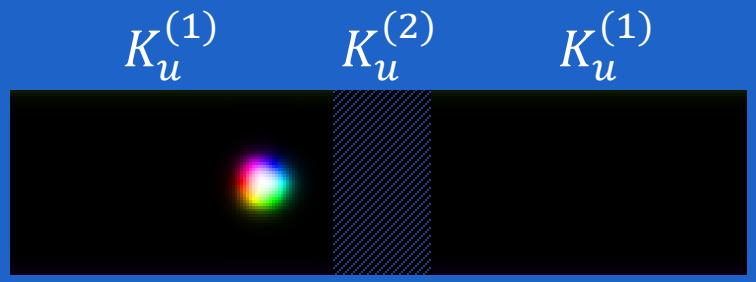
HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

Goal: use a local voltage controlled magnetic anisotropy (VCMA) to create a skyrmion gate on a skyrmion racetrack [1]

Use the input script of the skyrmion racetrack as a starting point
Add a region in the center in which the uniaxial anisotropy is increased by 5% (i.e. the VCMA)



$$K_u^{(2)} = K_u^{(1)} + K_u^{VCMA} = 1.05K_u^{(1)}$$

What is the maximal current density for which the region with the VCMA acts as a skyrmion gate?

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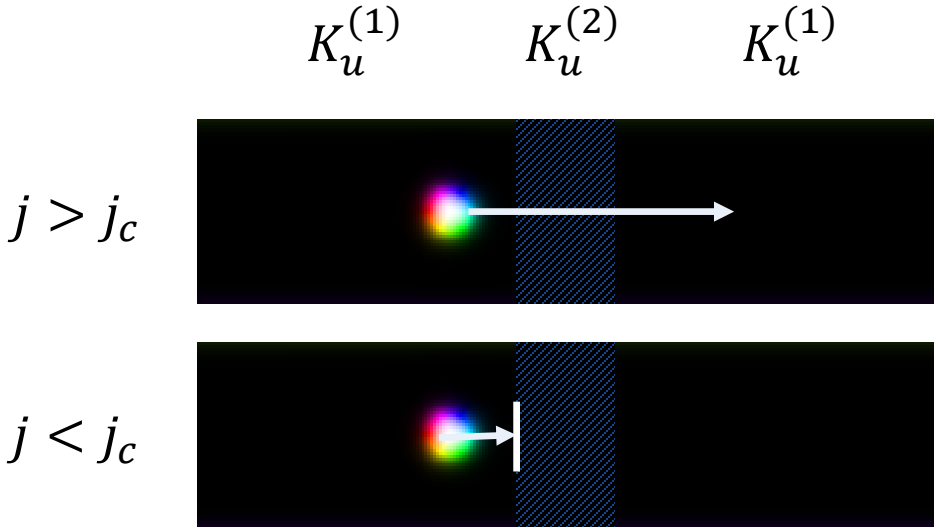
[1] **Voltage Controlled Magnetic Skyrmion Motion for Racetrack Memory**
Wang Kang, Yangqi Huang, Chentian Zheng, Weifeng Lv, Na Lei, Youguang Zhang, Xichao Zhang, Yan Zhou & Weisheng Zhao
Scientific reports **volume 6**, pages 23164 (2016)

HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE



$$K_u^{(2)} = K_u^{(1)} + K_u^{VCMA} = 1.05K_u^{(1)}$$

Threshold current j_c?

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HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

Building the skyrmion racetrack

(see session 3 of this workshop for more information)

```
setgridsize(128,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
Pol   = 0.4
xi    = 0.2
```

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```
setgridsize(128,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
Pol   = 0.4
xi    = 0.2

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
saveas(m,"../m0")
flush()

defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, 1.05*Ku1.GetRegion(0))

cutofftime := 1e-8

for jx:=2e12; jx>0; jx-=1e11 {

    j = vector(-jx,0,0)
    print("Set current density:", jx, "A/m2")

    m.loadfile("m0.ovf")  // reset m to the initial state
    t = 0                 // reset the time

    runwhile( ext_bubblepos.Get().X()<0 && t<cutofftime)

    if (ext_bubblepos.Get().X() > 0 ) {
        print("Skyrmion got through after", t*1e9 ,"ns")
    } else {
        print("Skyrmion didn't get through!")
        exit()
    }

    cutofftime = 2*t  // adjust cut-off time
}
```

HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

Relax a skyrmion and save this state
(we will need this later)

```
m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
saveas(m,"../m0")
flush()
```

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```
setgridsize(128,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
Pol   = 0.4
xi    = 0.2

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
saveas(m,"../m0")
flush()

defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, 1.05*Ku1.GetRegion(0))

cutofftime := 1e-8

for jx:=2e12; jx>0; jx-=1e11 {

    j = vector(-jx,0,0)
    print("Set current density:", jx, "A/m2")

    m.loadfile("m0.ovf")  // reset m to the initial state
    t = 0                 // reset the time

    runwhile( ext_bubblepos.Get().X()<0 && t<cutofftime)

    if (ext_bubblepos.Get().X() > 0 ) {
        print("Skyrmion got through after", t*1e9 ,"ns")
    } else {
        print("Skyrmion didn't get through!")
        exit()
    }

    cutofftime = 2*t  // adjust cut-off time
}
```

HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

Simulate the VCMA effect by increasing the anisotropy strength in the center

```
defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, 1.05*Ku1.GetRegion(0))
```

Define the cut-off time

If the skyrmion did not get through the gate before the cut-off time, then it probably never will

```
cutofftime := 1e-8
```

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```
setgridsize(128,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
Pol   = 0.4
xi    = 0.2

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
saveas(m,"../m0")
flush()

defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, 1.05*Ku1.GetRegion(0))

cutofftime := 1e-8

for jx:=2e12; jx>0; jx-=1e11 {

    j = vector(-jx,0,0)
    print("Set current density:", jx, "A/m2")

    m.loadfile("m0.ovf")  // reset m to the initial state
    t = 0                 // reset the time

    runwhile( ext_bubblepos.Get().X()<0 && t<cutofftime)

    if (ext_bubblepos.Get().X() > 0 ) {
        print("Skyrmion got through after", t*1e9 ,"ns")
    } else {
        print("Skyrmion didn't get through!")
        exit()
    }

    cutofftime = 2*t  // adjust cut-off time
}
```

HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

Gradually decrease the current density

Reset the simulation state in each iteration

```
for jx:=2e12; jx>0; jx-=1e11 {

    j = vector(-jx,0,0)
    print("Set current density:", jx, "A/m2")

    m.loadfile("m0.ovf")  // reset m to the initial state
    t = 0                 // reset the time

    …
}
```

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```
setgridsize(128,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
Pol   = 0.4
xi    = 0.2

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
saveas(m,"../m0")
flush()

defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, 1.05*Ku1.GetRegion(0))

cutofftime := 1e-8

for jx:=2e12; jx>0; jx-=1e11 {

    j = vector(-jx,0,0)
    print("Set current density:", jx, "A/m2")

    m.loadfile("m0.ovf")  // reset m to the initial state
    t = 0                 // reset the time

    runwhile( ext_bubblepos.Get().X()<0 && t<cutofftime)

    if (ext_bubblepos.Get().X() > 0 ) {
        print("Skyrmion got through after", t*1e9 ,"ns")
    } else {
        print("Skyrmion didn't get through!")
        exit()
    }

    cutofftime = 2*t  // adjust cut-off time
}
```

HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

Run until the skyrmion got through the gate or if the cut-off time has passed

```
runwhile( ext_bubblepos.Get().X()<0 && t<cutofftime)
```

Check if the skyrmion got through the gate

```
if (ext_bubblepos.Get().X() > 0 ) {
    print("Skyrmion got through after", t*1e9 ,"ns")
} else {
    print("Skyrmion didn't get through!")
    exit()
}

cutofftime = 2*t  // adjust cut-off time
```

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```
setgridsize(128,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
Pol   = 0.4
xi    = 0.2

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
saveas(m,"../m0")
flush()

defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, 1.05*Ku1.GetRegion(0))

cutofftime := 1e-8

for jx:=2e12; jx>0; jx-=1e11 {

    j = vector(-jx,0,0)
    print("Set current density:", jx, "A/m2")

    m.loadfile("m0.ovf")  // reset m to the initial state
    t = 0                 // reset the time

    runwhile( ext_bubblepos.Get().X()<0 && t<cutofftime)

    if (ext_bubblepos.Get().X() > 0 ) {
        print("Skyrmion got through after", t*1e9 ,"ns")
    } else {
        print("Skyrmion didn't get through!")
        exit()
    }

    cutofftime = 2*t  // adjust cut-off time
}
```

HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

Snippet out of log.txt:

```
…
//Set current density: 1.2e+12 A/m2
//Skyrmion got through after 0.9582254939672915 ns
//Set current density: 1.1e+12 A/m2
//Skyrmion got through after 1.0764332835966428 ns
//Set current density: 1e+12 A/m2
//Skyrmion got through after 1.2385932085022286 ns
//Set current density: 9e+11 A/m2
//Skyrmion got through after 1.4873588596687457 ns
//Set current density: 8e+11 A/m2
//Skyrmion got through after 1.9984716839327563 ns
//Set current density: 7e+11 A/m2
//Skyrmion didn't get through!
```

⇒Threshold current density between 0.7 A/μm² – 0.8 A/μm²

Repeat procedure for smaller Δj to increase the precision

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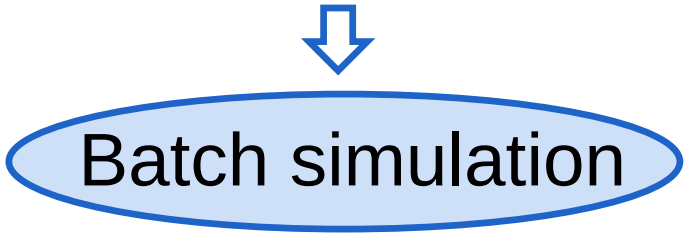
```
setgridsize(128,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
Pol   = 0.4
xi    = 0.2

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
saveas(m,"../m0")
flush()

defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, 1.05*Ku1.GetRegion(0))

cutofftime := 1e-8

for jx:=2e12; jx>0; jx-=1e11 {

    j = vector(-jx,0,0)
    print("Set current density:", jx, "A/m2")

    m.loadfile("m0.ovf")  // reset m to the initial state
    t = 0                 // reset the time

    runwhile( ext_bubblepos.Get().X()<0 && t<cutofftime)

    if (ext_bubblepos.Get().X() > 0 ) {
        print("Skyrmion got through after", t*1e9 ,"ns")
    } else {
        print("Skyrmion didn't get through!")
        exit()
    }

    cutofftime = 2*t  // adjust cut-off time
}
```

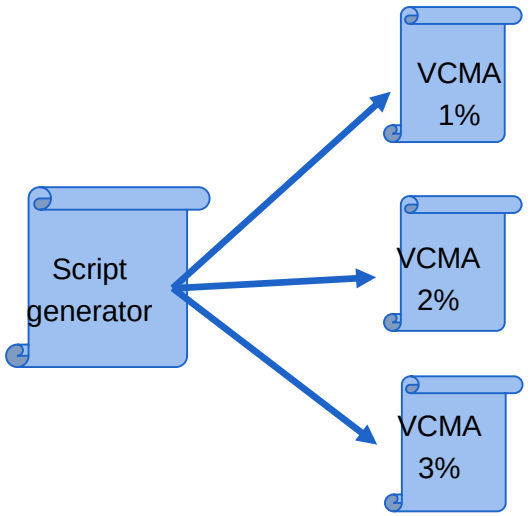
HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

What if we want to make use of multiple GPUs?

What if we want to repeat the simulation for different VCMA values?





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HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

homework2_batch_template.txt

```
setgridsize(126,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat  = 580e3
Aex   = 15e-12
Dind  = 3.0e-3
Ku1   = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()

defRegion(1,rect(50e-9,inf))
Ku1.setRegion(1, (1+$VCMA/100.0)*Ku1.GetRegion(0) )

Pol = 0.4
xi  = 0.2
j   = vector(-$JX,0,0)

runwhile( ext_bubblepos.Get().X() < 0 && t < $TCUT )

if ext_bubblepos.Get().X() > 0 {
    print("PASSED!")
}  else {
    print("STOPPED!")
}
```

homework2_batch_setup.py

```
from string import Template
import os

# specify the values for which we want to generate the scripts
vcma_values = [ 1, 2, 3, 4, 5 ]
jx_values   = [ 1e11*i for i in range(1,11) ]
tcut        = 1e-8

# read template script
with open("homework2_batch_template.txt",'r') as f:
    scripttmpl = Template(f.read())

for vcma in vcma_values:

    # create a directory for each vcma value
    dirname = "vcma_simulations/vcma_%02d"%vcma
    os.makedirs(dirname)

    for jx in jx_values:

        # write the script for each combination of VCMA and jx value
        script = scripttmpl.substitute(dict(VCMA=vcma, JX=jx, TCUT=tcut))
        scriptfile = os.path.join(dirname, "jx_%g.mx3"%jx)
        with open(scriptfile,'w') as f:
            f.write(script)
```

HOMEWORK ASSIGNMENT 2

THE VCMA SKYRMION GATE

homework2_batch_post.py

```
import os
import matplotlib.pyplot as plt

# specify the values for which we want to generate the scripts
vcma_values = [ 1, 2, 3, 4, 5 ]
jx_values   = [ 1e11*i for i in range(1,11) ]

results = []
for vcma in vcma_values:
    for jx in jx_values:

        logfile = "vcma_simulations/vcma_%02d/jx_%g.out/log.txt"%(vcma, jx)
        if os.path.exists(logfile):
            with open(logfile, 'r') as f:
                log = f.read()
                if "//PASSED" in log:
                    results.append( (vcma,jx,True) )
                if "//STOPPED" in log:
                    results.append( (vcma,jx,False) )

vcma,jx,passed = zip(*results)
color = ["green" if p else "red" for p in passed]

plt.scatter(vcma,jx,color=color,s=200)
plt.xlabel("VCMA (%)")
plt.ylabel("Current density $j$ (A/m2)")
plt.show()
```

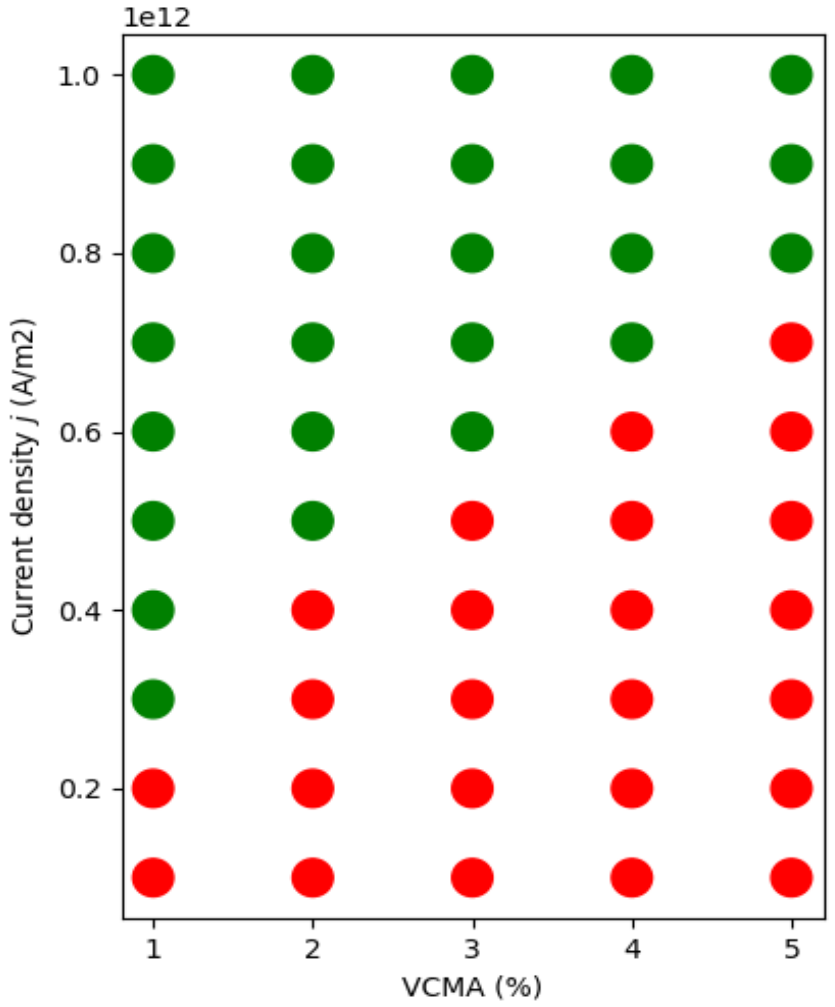

TABLE OF CONTENTS

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DOMAIN WALL CREEP

System

Transverse domain wall in permalloy nanostrip

Task

Calculate the motion of the domain wall

- driven by a spin transfer torque
- at nonzero temperature
- in the presence of material disorder

Input file: session4_example1.txt

Titan RTX: 111 min

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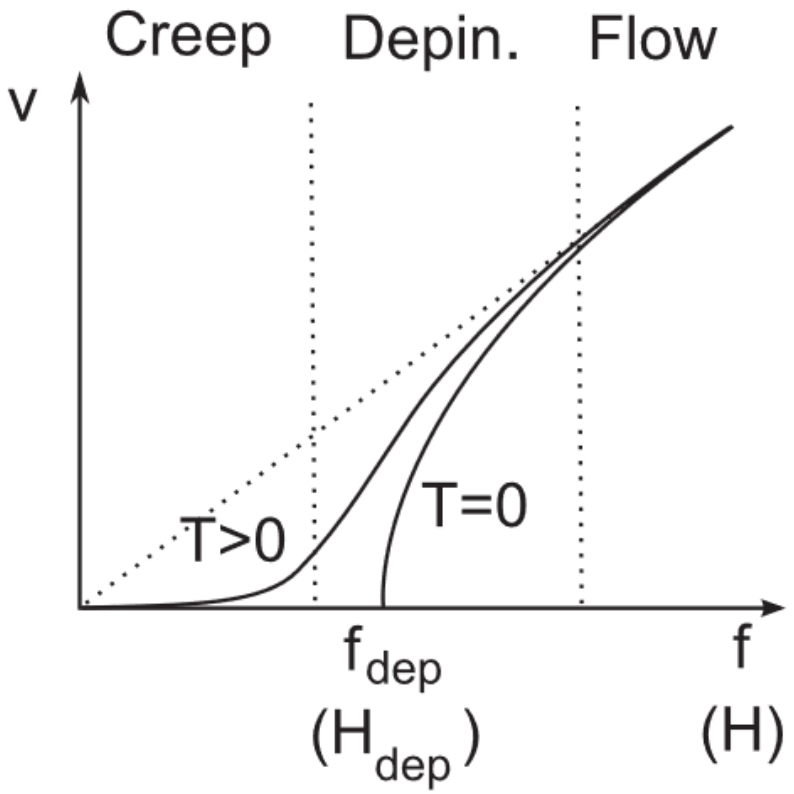
"Creep turns linear in narrow ferromagnetic nanostrips"
Scientific Reports, 6, article number 20472 (2016)

CREEP?



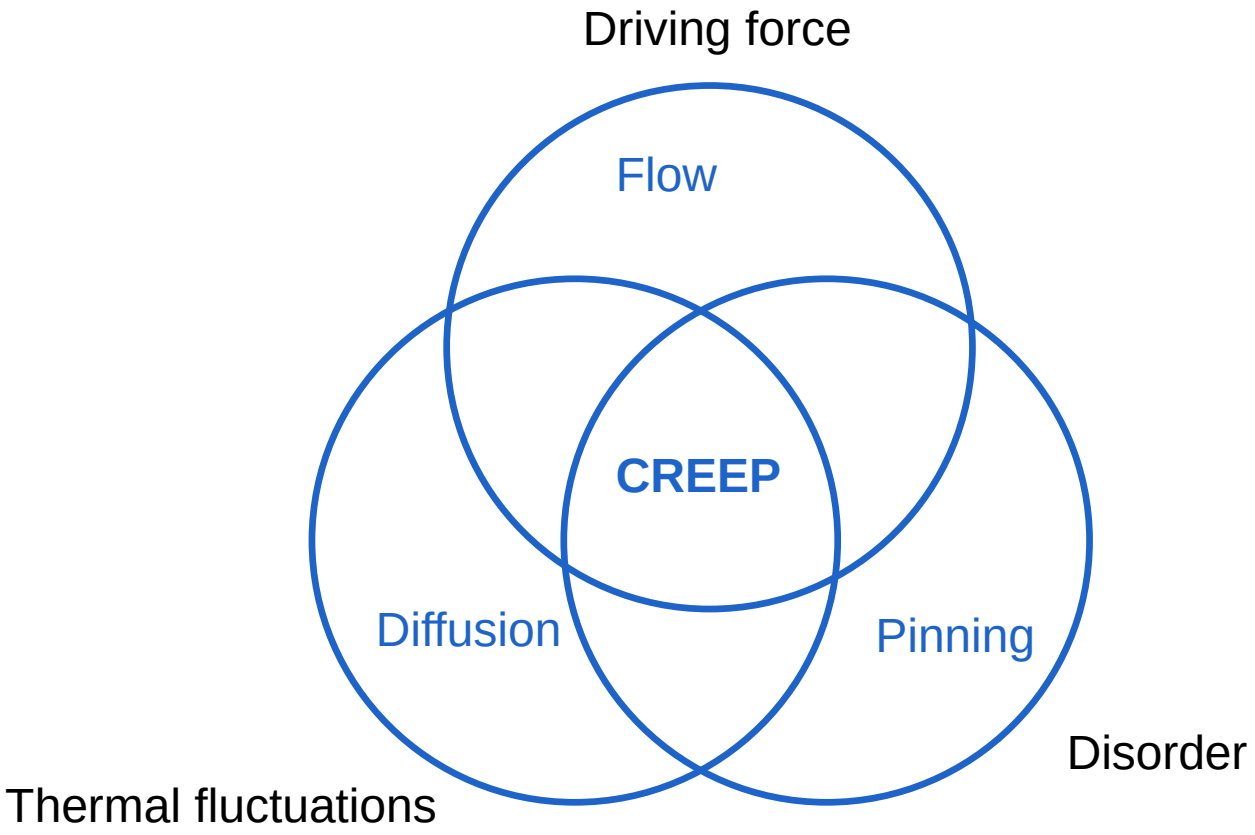


Figure reproduced from P. Metaxas, et al., "Creep and Flow Regimes of Magnetic Domain-Wall Motion in Ultrathin Pt/Co/Pt Films with Perpendicular Anisotropy", Phys. Rev. Lett. **99**, 217208 (2007)

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INPUTFILE

```
SetMesh(128, 32, 1, 3.125e-09, 3.125e-09, 10e-09, 0, 0, 0)
Msat = 800e3
Aex = 1e-11
alpha = 0.1
```

```
m=twodomain(1,0,0,  0,1,0,  -1,0,0)

//remove edge charges
BoundaryRegion := 0
MagLeft        := 1
MagRight       := -1
ext_rmSurfaceCharge(BoundaryRegion, MagLeft, MagRight)

relax()
```

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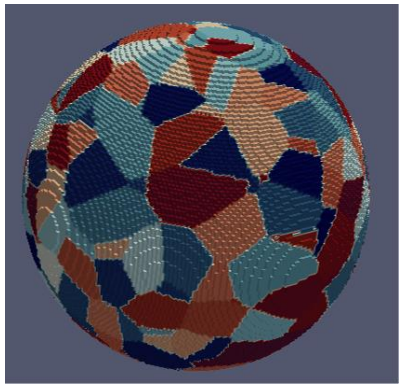
GRAINS

```
// define grains with region number 0-255
grainSize  := 40e-9
randomSeed := 1234567
maxRegion  := 255
ext_makegrains(grainSize, maxRegion, randomSeed)
```

Also 3D grains are possible

```
ext_make3dgrains(grainSize, StartingRegion, NumberOfRegions, Shape, randomSeed)
```



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More info on grains in mumax3:

"Current-driven domain wall mobility in polycrystalline Permalloy nanowires: A numerical study"
Journal of Applied Physics 115, 233903 (2014)

GRAINS

procedural texture using Voronoi Tessellation

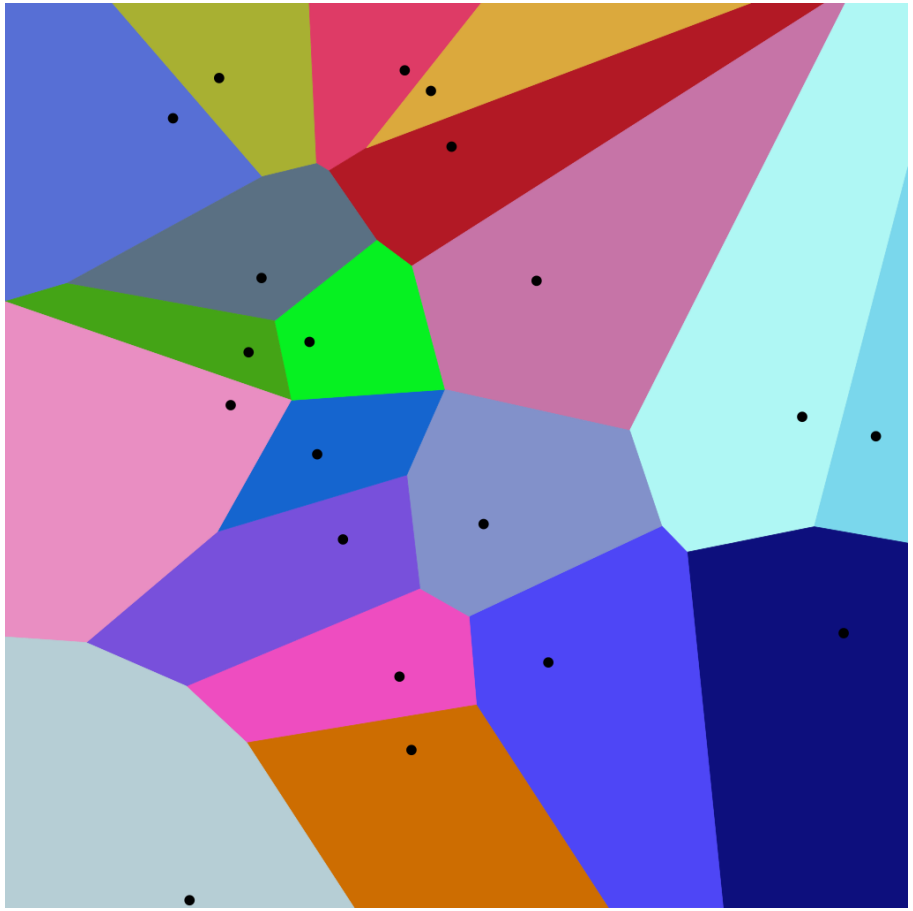

Figure reproduced from wikimedia commons, by Balu Ertl, CC-BY-SA-4.0 license

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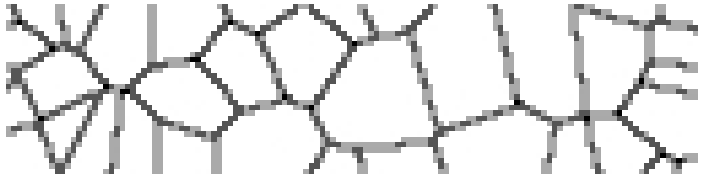
MATERIAL DISORDER

```
// set random anisotropy per region
for i:=0; i<maxRegion; i++{
    // random uniaxial anisotropy direction on the unit sphere
    axis  := vector(randNorm(), randNorm(), randNorm())
    // note: axes are normalized by mumax3
    AnisU.SetRegion(i, axis)

    // random 10% anisotropy variation
    K := 1e3
    Ku1.SetRegion(i, K + randNorm() * 0.1 * K)
}
```

```
// reduce exchange coupling between grains by 10%
for i:=0; i<maxRegion; i++{
    for j:=i+1; j<maxRegion; j++{
        ext_ScaleExchange(i, j, 0.9)
    }
}
```



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TEMPERATURE AND DRIVING FORCE

```
//set temperature and solver with adaptive time stepping
temp=300
Thermseed(12345)
setsolver(5)
fixdt=0  //default
```

```
//driving force: spin transfer torque
Pol=0.4
xi=0.2
j=vector(-1e12,0,0)
```

```
//keep wall centered: moving window
ext_centerwall(0)

//schedule output
tableadd(ext_dwxpos)
tableautosave(1e-10)

//run
run(5e-7)
```

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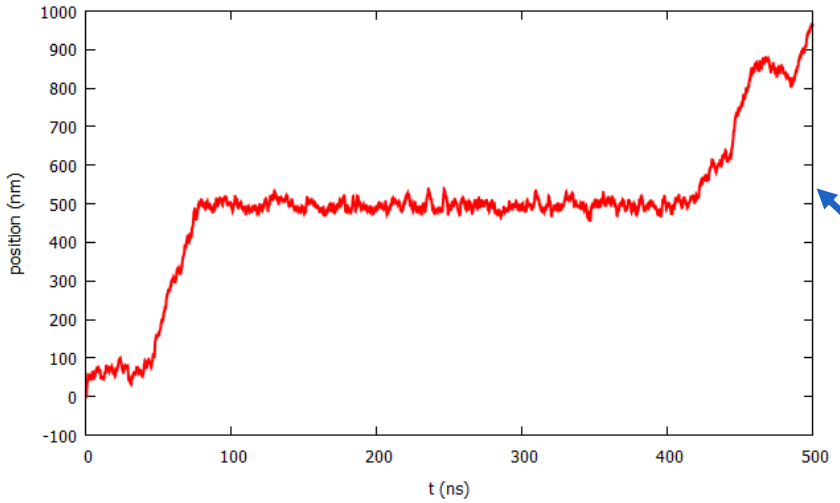
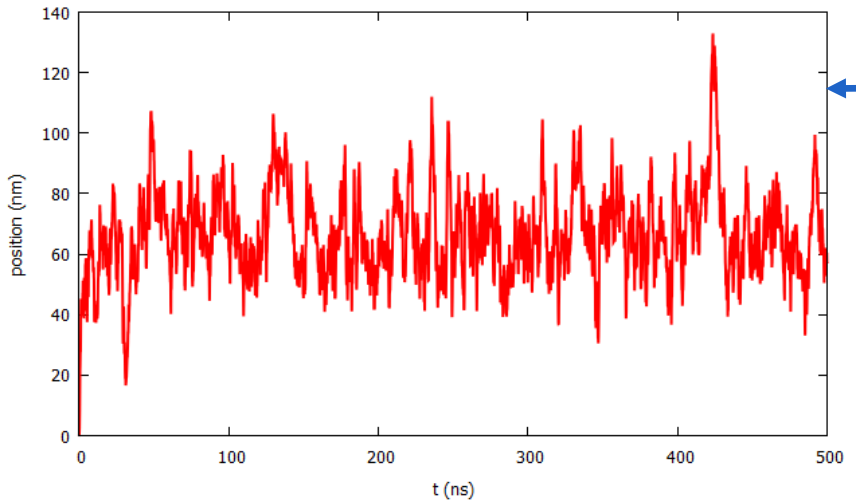
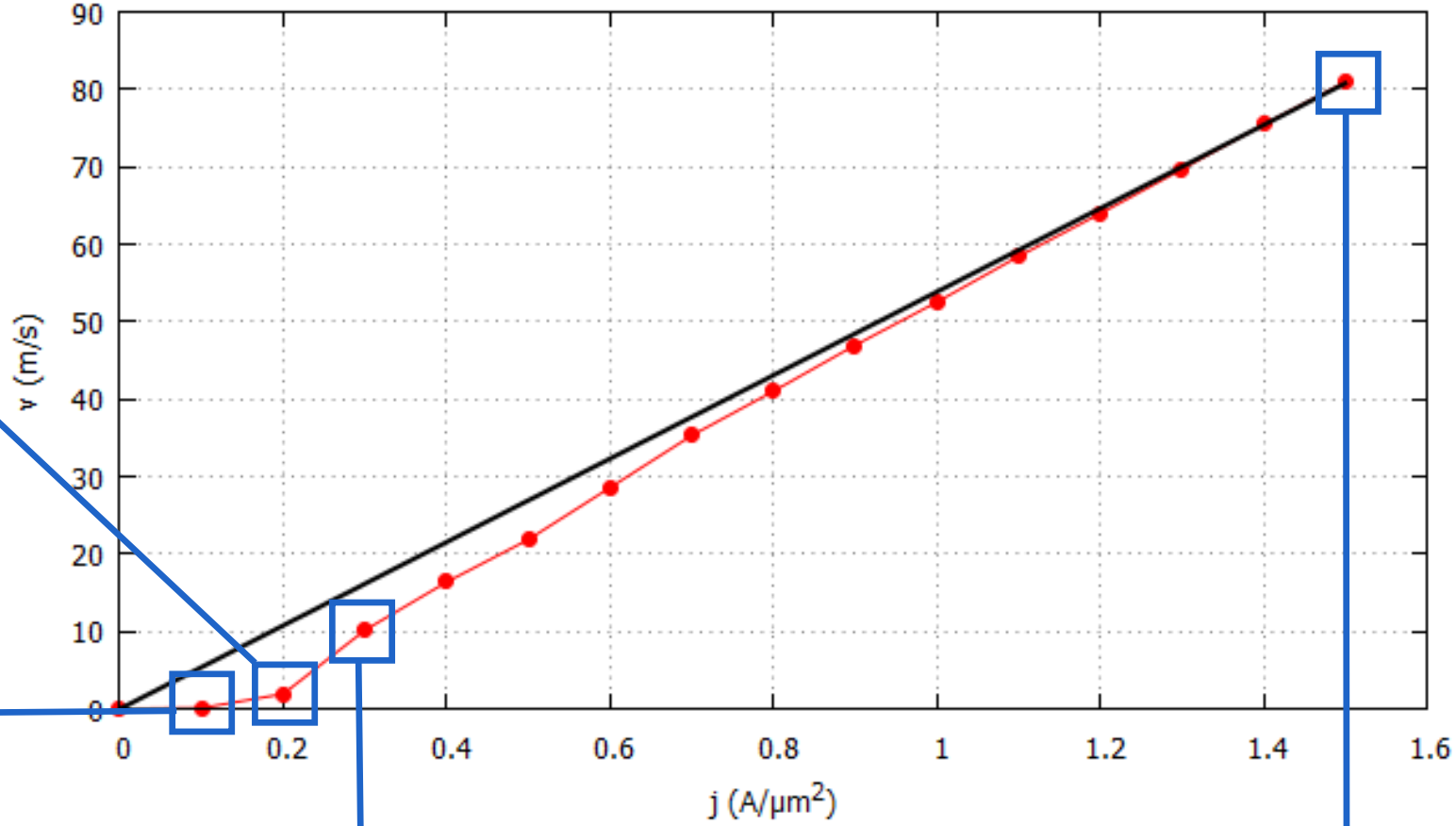
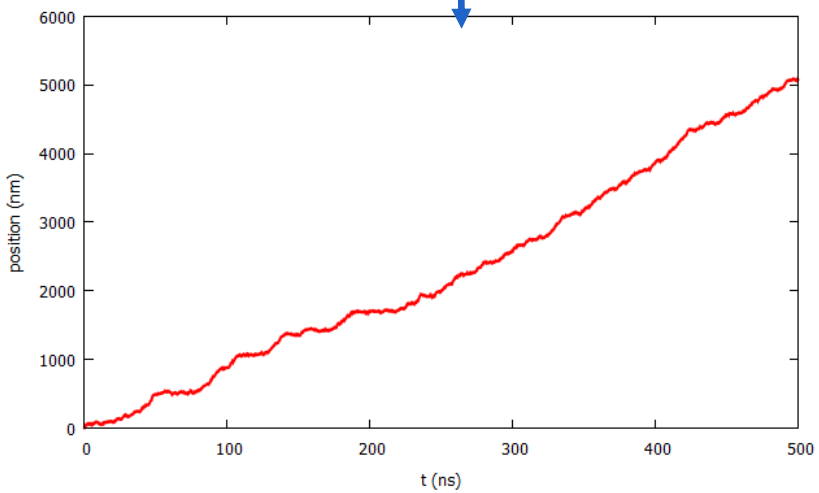
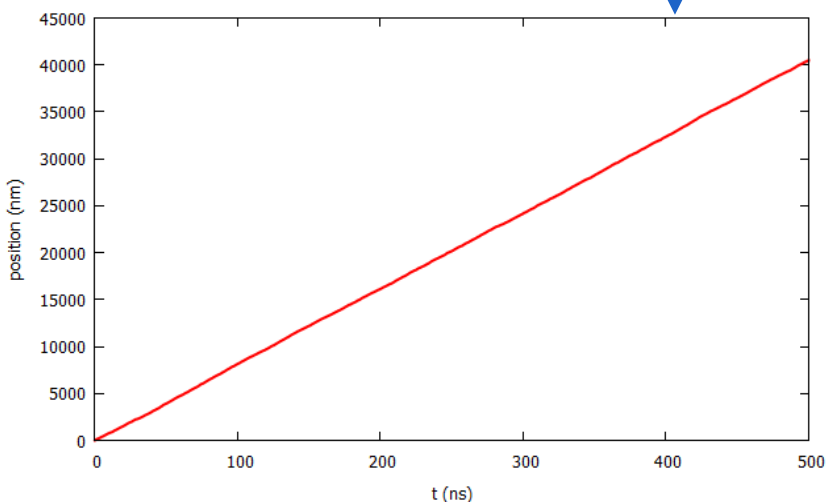
RESULTS











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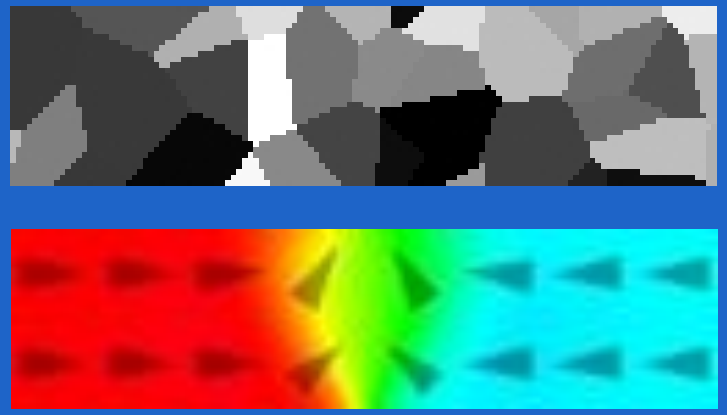
DOMAIN WALL CREEP



WHAT HAVE WE LEARNED?

- Including disorder in simulations
- Moving window
  - For domain walls: `ext_centerWall()`
  - For skyrmions: `ext_centerBubble()`

"Creep turns linear in narrow ferromagnetic nanostrips"
Scientific Reports, 6, article number 20472 (2016)

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SKYRMION RACETRACK REVISITED

System

Skyrmion driven by **spin-orbit torques (SOT)** in a chiral ferromagnetic strip

Input file: session4_example2a.txt

Titan RTX: 3.5 min

Input file: session4_example2b.txt

Titan RTX: 2 min

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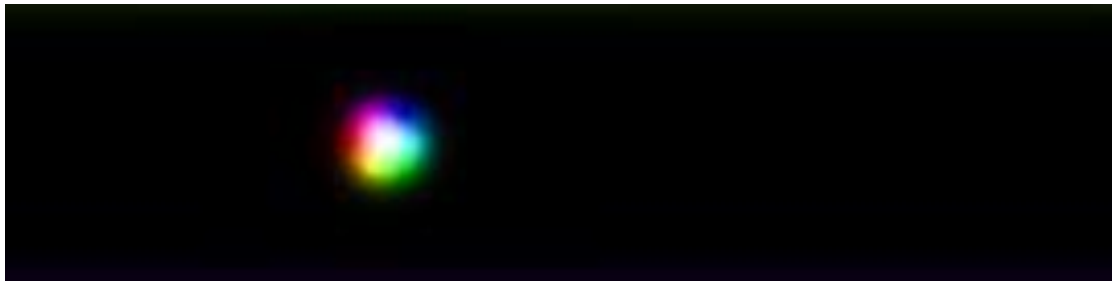
SKYRMION RACETRACK REVISITED

```
// Skyrmion racetrack

setgridsize(256,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat = 580e3
Aex = 15e-12
Dind = 3.0e-3
Ku1 = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()
```

```
Pol = 0.4
xi = 0.2
j = vector(-1e12,0,0)
```

```
autosave(m,1e-10)
tableAutosave(1e-11)
tableAdd(ext_bubblepos)

run(10e-9)
```



How to use

Spin-Orbit Torques (SOT)

instead of

Spin-Transfer Torques (STT)

?

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SPIN ORBIT TORQUE

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times \left(\mathbf{H}_{\text{eff}} + \boxed{a_J(\mathbf{m} \times \mathbf{p}) + b_J \mathbf{p}} \right) + \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

- M. Hayashi, et al., "Quantitative characterization of the spin-orbit torque using harmonic Hall voltage measurements" Physical Review B 89, 144425 (2014)

$$a_J = \| \frac{\hbar}{2 M_{\text{sat}} e} \frac{\alpha_{\text{H}} j}{d} \| \qquad \xi = \frac{b_J}{a_J}$$

$$\mathbf{p} = \text{sign}(\alpha_H) \mathbf{j} \times \mathbf{n}$$

Assuming a material with positive α_H (such as Pt) above the ferromagnet (**n**=-**z)** and a current pulse in –x direction (electrons move along +X)

$$\mathbf{p} = -\mathbf{e}_x \times -\mathbf{e}_z = -\mathbf{e}_y \longrightarrow \mathbf{p} = (0, -1, 0)$$

- F. Büttner, et al. "Field-free deterministic ultrafast creation of magnetic skyrmions by spin–orbit torques" Nature Nanotechnology volume 12, pages1040–1044(2017)

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SPIN ORBIT TORQUE

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times \left(\mathbf{H}_{\text{eff}} + \boxed{a_J(\mathbf{m} \times \mathbf{p}) + b_J \mathbf{p}} \right) + \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

- SOT is not explicitly implemented in mumax3
- Solution -> Use the custom fields functionality to add it as an effective field term

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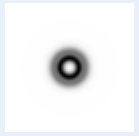
CUSTOM QUANTITIES

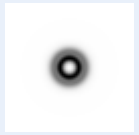
```
//Define constant number or vector
Const(float64) Quantity
ConstVector(float64, float64, float64) Quantity

//pointwise addition, multiplication and division
Add(Quantity, Quantity) Quantity
Mul(Quantity, Quantity) Quantity
Div(Quantity, Quantity) Quantity

//Weighted addition: Madd(Q1,Q2,c1,c2) = c1*Q1 + c2*Q2
Madd(Quantity, Quantity, float64, float64) *mAddition

//vector dot and cross product
Dot(Quantity, Quantity) Quantity
Cross(Quantity, Quantity) Quantity

//shifted quantity
Shifted(Quantity, int, int, int) Quantity
```

EXAMPLE: CUSTOM QUANTITIES

```
cs := 1e-9
setcellsize(cs,cs,cs)
setgridsize(64,64,1)

// Use central finite differences to approximate the spatial derivatives of m
mL := Shifted(m,-1,0,0) // shift left
mR := Shifted(m,1,0,0)  // shift right
mD := Shifted(m,0,-1,0) // shift down
mU := Shifted(m,0,1,0)  // shift up
dmdx := Mul( Const(1/(2*cs)), Madd(mR,mL,1,-1) )
dmdy := Mul( Const(1/(2*cs)), Madd(mU,mD,1,-1) )

// Define the topological charge density
chargeDensity := Mul( Const(1/(4*pi)), Dot(m, Cross(dmdx,dmdy)))

m = neelskyrmion(1,-1)
Save(m)

// Save the topological charge density of a skyrmion
saveas(chargeDensity, "chargeDensity.ovf")

// As reference solution: implementation in mumax3
Saveas(ext_topologicalchargedensity, "reference.ovf"
```

$$\frac{1}{4\pi}\mathbf{m}\cdot\left(\frac{d\mathbf{m}}{dx}\times\frac{d\mathbf{m}}{dy}\right)$$





EXAMPLE: CUSTOM ANISOTROPY FIELD

```
// Define custom quantities
Ms := 1100e3
K  := 0.5e6
u  := ConstVector(1, 0, 0)
anisField := Mul( Const(2*K/Ms)  , Mul( Dot(u, m), u))
anisEdens := Mul( Const(-0.5*Ms) , Dot( anisField, m))

// promote anisField to an effective field term
AddFieldTerm(anisField)

// promote anisEdens to an energy density term
AddEdensTerm(anisEdens)

// Add a column with the energy related to the custom field
tableAdd(E_custom)
```

$$\vec{\mathbf{B}}_{\text{anis}} = \frac{2K_{\text{u1}}}{B_{\text{sat}}} \left(\vec{\mathbf{u}} \cdot \vec{\mathbf{m}} \right) \vec{\mathbf{u}}$$

SPIN-ORBIT TORQUE: CUSTOM FIELDS

```
// Define constants
AlphaH   := 0.15
e        := 1.6021766e-19
d        := 1e-9
Ms       := 580e3
hbar     := 1.0545718e-34
p        := Constvector(0,-1,0)
SOTxi    := -2.0
J_SOT    := abs(-2.e11)
```

$$a_J = \| \frac{\hbar}{2M_{\mathrm{sat}}e} \frac{\alpha_{\mathrm{H}} j}{d} \|$$

$$\xi = \frac{b_J}{a_J}$$

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times \left(\mathbf{H}_{\mathrm{eff}} + \boxed{a_J(\mathbf{m} \times \mathbf{p}) + b_J \mathbf{p}} \right) + \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

```
// Define prefactors aj and bj
aj := Const(J_SOT*(hbar/2.*alphaH/e/d/ms))
bj := Mul(aj,Const(SOTxi))
```

```
// Add damping-like SOT term

dampinglike := Mul(aj, Cross(m,p))
AddFieldTerm(dampinglike)
AddEdensTerm(Mul(Const(-0.5),Dot(dampinglike,M_full)))
```

```
// Add field-like SOT term

fieldlike:= Mul(bj,p)
AddFieldTerm(fieldlike)
AddEdensTerm(Mul(Const(-0.5),Dot(fieldlike,M_full)))
```

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SKYRMION RACETRACK

```
// Skyrmion racetrack

setgridsize(256,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat = 580e3
Aex = 15e-12
Dind = 3.0e-3
Ku1 = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()

//Add SOT

autosave(m,1e-10)
tableAutosave(1e-11)
tableAdd(ext_bubblepos)

run(2.5e-9)
```

```
// Define constants
AlphaH  := 0.15
e       := 1.6021766e-19
d       := 1e-9
Ms      := 580e3
hbar    := 1.0545718e-34
p       := Constvector(0,1,0)
SOTxi   := -2.0
J_SOT   := abs(-2.e11)

//Define prefactors aj and bj
aj       := Const(J_SOT*(hbar/2.*alphaH/e/d/ms))
bj       := Mul(aj,Const(SOTxi))

// Add damping-like SOT term
dampinglike := Mul(aj, Cross(m,p))
AddFieldTerm(dampinglike)
AddEdensTerm(Mul(Const(-0.5),Dot(dampinglike,M_full)))

// Add field-like SOT term
fieldlike:= Mul(bj,p))
AddFieldTerm(fieldlike)
AddEdensTerm(Mul(Const(-0.5),Dot(fieldlike,M_full)))
```

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IS THERE A BETTER WAY?

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times \left(\mathbf{H}_{\text{eff}} + \boxed{a_J(\mathbf{m} \times \mathbf{p}) + b_J \mathbf{p}} \right) + \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

$$\boxed{\mathbf{m} \times} \dot{\mathbf{m}} = -\gamma \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}}) - a_J \gamma \mathbf{m} \times (\mathbf{m} \times (\mathbf{m} \times \mathbf{p})) - \gamma b_J \mathbf{m} \times (\mathbf{m} \times \mathbf{p}) + \alpha \mathbf{m} \times (\mathbf{m} \times \dot{\mathbf{m}})$$

$$\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) = \mathbf{b}(\mathbf{a} \cdot \mathbf{c}) - \mathbf{c}(\mathbf{a} \cdot \mathbf{b})$$

$$(\mathbf{m} \cdot \dot{\mathbf{m}}) = 0$$

$$(\mathbf{m} \cdot \mathbf{m}) = 1$$

$$\mathbf{m} \times (\mathbf{m} \times (\mathbf{m} \times \mathbf{p})) = -\mathbf{m} \times \mathbf{p}$$

$$\mathbf{m} \times \dot{\mathbf{m}} = -\gamma \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})) + a_J \gamma \mathbf{m} \times \mathbf{p} - \gamma b_J \mathbf{m} \times (\mathbf{m} \times \mathbf{p}) - \alpha \dot{\mathbf{m}}$$

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IS THERE A BETTER WAY?

$$\mathbf{m} \times \dot{\mathbf{m}} = -\gamma \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})) + a_J \gamma \mathbf{m} \times \mathbf{p} - \gamma b_J \mathbf{m} \times (\mathbf{m} \times \mathbf{p}) - \alpha \dot{\mathbf{m}}$$

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times \left(\mathbf{H}_{\text{eff}} + a_J (\mathbf{m} \times \mathbf{p}) + b_J \mathbf{p} \right) + \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

$$\begin{aligned} (1+\alpha^2)\dot{\mathbf{m}} = & -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} - \alpha\gamma \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}}) \\ & - \gamma a_J \mathbf{m} \times (\mathbf{m} \times \mathbf{p}) - \alpha\gamma b_J \mathbf{m} \times (\mathbf{m} \times \mathbf{p}) \\ & - \gamma b_J \mathbf{m} \times \mathbf{p} + \alpha\gamma a_J \mathbf{m} \times \mathbf{p} \end{aligned}$$

Landau-Lifshitz torque

Spin-Orbit torque

$$\tau_{\text{SOT}} = -\frac{\gamma}{(1+\alpha^2)} a_J \left[(1+\xi\alpha)\mathbf{m} \times (\mathbf{m} \times \mathbf{p}) + (\xi - \alpha)(\mathbf{m} \times \mathbf{p}) \right]$$

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IS THERE A BETTER WAY?

$$\boxed{\tau_{\mathrm{SOT}} = -\frac{\gamma}{(1+\alpha^2)} a_J \left[(1+\xi\alpha)\mathbf{m}\times(\mathbf{m}\times\mathbf{p}) + (\xi-\alpha)(\mathbf{m}\times\mathbf{p})\right]}$$

Slonczewski STT in mumax3

$$\begin{cases} \tau_{SL} = \gamma\beta\dfrac{\epsilon-\alpha\epsilon'}{1+\alpha^2}(\mathbf{m}\times(\mathbf{m}_P\times\mathbf{m})) - \gamma\beta\dfrac{\epsilon'-\alpha\epsilon}{1+\alpha^2}\mathbf{m}\times\mathbf{m}_P \\ \beta = \dfrac{j_z\hbar}{M_{\mathrm{sat}}ed} \\ \epsilon = \dfrac{P\Lambda^2}{(\Lambda^2+1)+(\Lambda^2-1)(\mathbf{m}\cdot\mathbf{m}_P)} \end{cases}$$

$$\Lambda = 1 \longrightarrow \epsilon = \frac{P}{2}$$

$$\epsilon' = \xi\epsilon$$

$$\tau_{SL} = -\frac{\beta\gamma P}{2(1+\alpha^2)}\left[(1+\xi\alpha)(\mathbf{m}\times(\mathbf{m}\times\mathbf{m}_P)) + (\xi-\alpha)\mathbf{m}\times\mathbf{m}_P\right]$$

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IS THERE A BETTER WAY?

$$\tau_{\mathrm{SOT}} = -\frac{\gamma}{(1+\alpha^2)} a_J \left[(1+\xi\alpha)\mathbf{m}\times(\mathbf{m}\times\mathbf{p}) + (\xi-\alpha)(\mathbf{m}\times\mathbf{p})\right]$$

We can use the existing Slonczewski spin transfer torque implementation!

$$P = \frac{2a_J}{\beta} = \alpha_H$$

$$\tau_{SL} = -\frac{\beta\gamma P}{2(1+\alpha^2)} \left[(1+\xi\alpha)(\mathbf{m}\times(\mathbf{m}\times\mathbf{m}_P)) + (\xi-\alpha)\mathbf{m}\times\mathbf{m}_P\right]$$

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SKYRMION RACETRACK

```
// Skyrmion racetrack

setgridsize(256,64,1)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat = 580e3
Aex = 15e-12
Dind = 3.0e-3
Ku1 = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1

m = neelskyrmion(-1, 1).transl(-40e-9,0,0)
minimize()

//Add SOT

autosave(m,1e-10)
tableAutosave(1e-11)
tableAdd(ext_bubblepos)

run(2.5e-9)
```

```
//define constants and set slonczewksi parameters
SOTxi          := -2
AlphaH         := 0.15
Pol             = alphaH
Lambda          = 1
Epsilonprime    = alphaH/2 * SOTxi
Fixedlayer      = vector(0,-1,0)        //p

//define current
J               = vector(0,0,abs(-2e11))
```

$P = \frac{2a_J}{\beta} = \alpha_H$

$\Lambda = 1$

$\epsilon' = \xi\epsilon$

$\epsilon = \frac{P}{2}$

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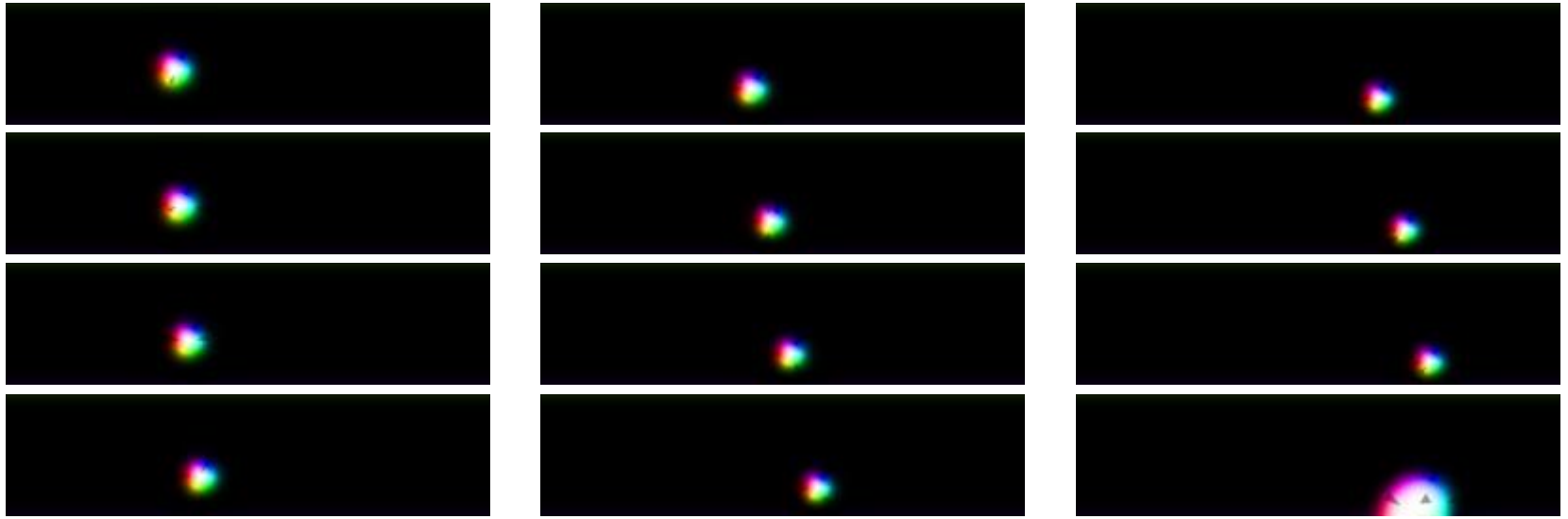
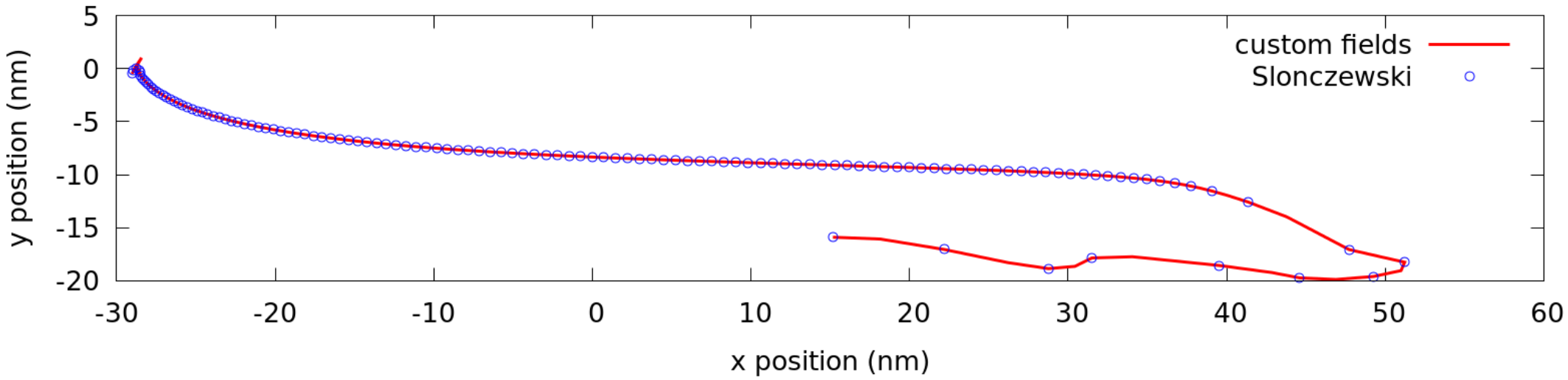
SKYRMION RACETRACK





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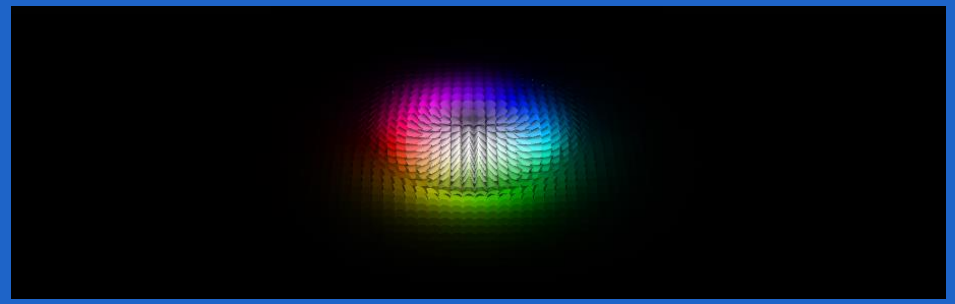
SOT–DRIVEN SKYRMION MOTION



WHAT HAVE WE LEARNED?

- The use of Spin-Orbit torques, using
  - Custom fields implementation
  - Slonczewksi STT implementation

Input file: session4_example2a.txt
Titan RTX: 3.5 min

Input file: session4_example2b.txt
Titan RTX: 2 min

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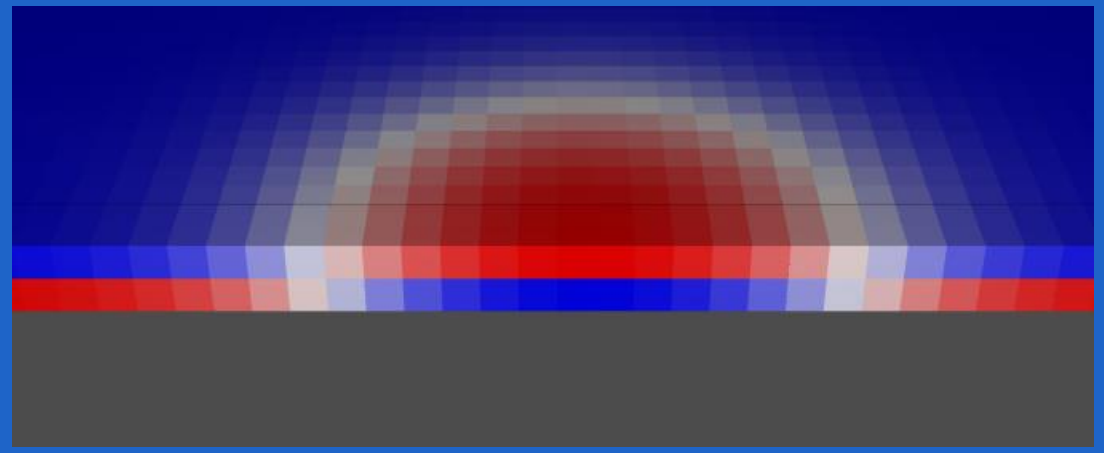
SKYRMION RACETRACK REVISITED 2

System

Skyrmion driven by spin-orbit torques (SOT) in a synthetic antiferromagnet



Input file: session4_example3a.txt

Titan RTX: 86 s

Input file: session4_example3b.txt

Titan RTX: 7 min

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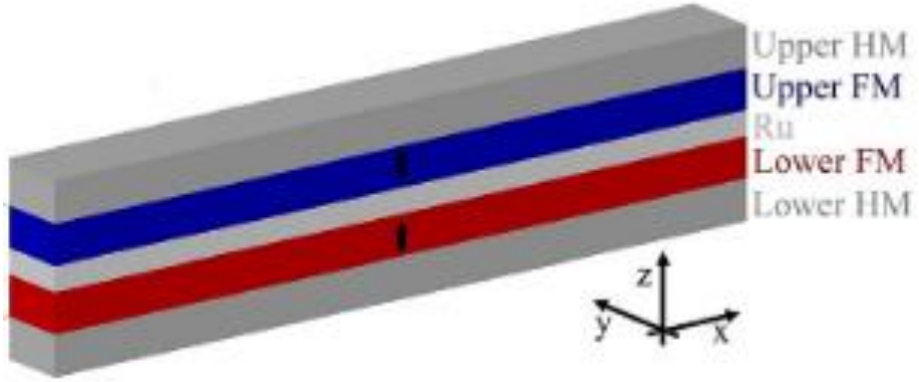
SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET

```
// Skyrmion racetrack

setgridsize(256,64,2)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat = 580e3
Aex = 15e-12
Dind = 3.0e-3
Ku1 = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
```




```
// define 2 layers
defregion(1,layer(1))
defregion(2,layer(0))

// set negative interlayer exchange
ext_InterExchange(1, 2, -5e-13)

// define initial magnetization
m.setregion(1,neelskyrmion(-1, 1).transl(-40e-9,0,0))
m.setregion(2,neelskyrmion(1, -1).transl(-40e-9,0,0))

Minimize()
```

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Figure reproduced from "Performance of synthetic antiferromagneticracetrack memory: domain wall versus skyrmion", R. Tomasello, et al. 2017 J. Phys. D: Appl. Phys. 50 325302

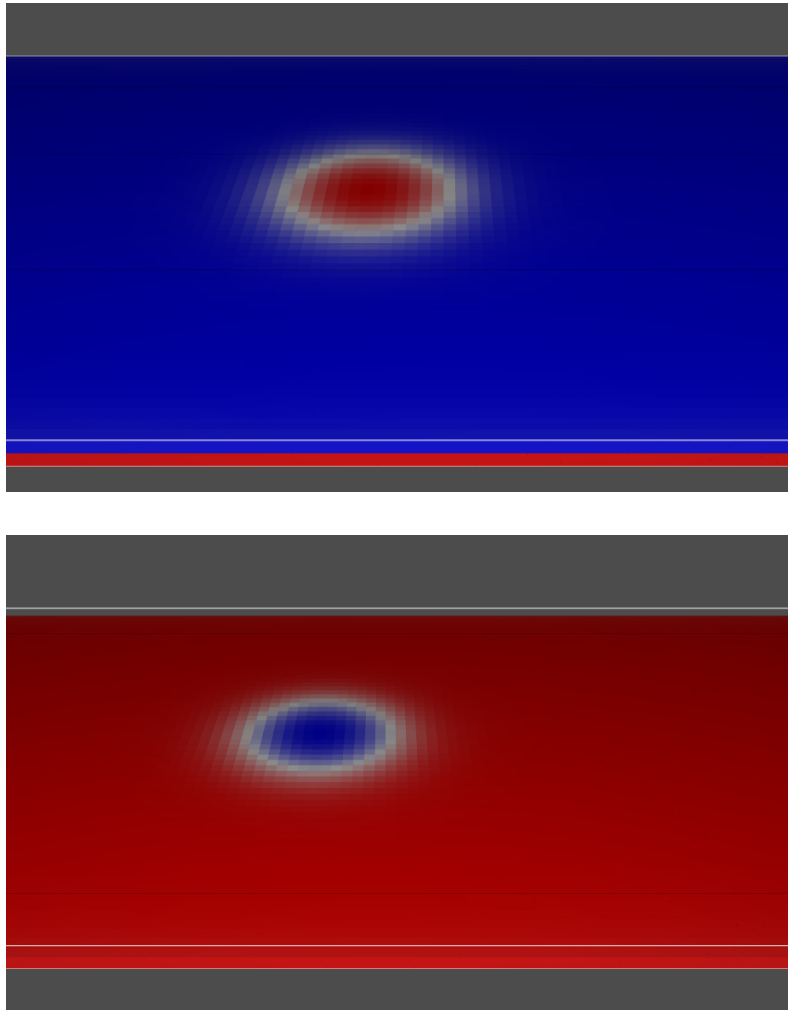
SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET

```
// define constants and set slonczewksi parameters
SOTxi         := -2
AlphaH        := 0.15
Pol            = alphaH
Lambda         = 1
Epsilonprime   = alphaH*SOTxi/2
Fixedlayer     = vector(0,-1,0)

// define current
J  = vector(0,0,2e11)

autosave(m,1e-10)
tableAutosave(1e-11)
tableAdd(ext_bubblepos)

run(2e-9)
```



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SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET

What about the spacer layer?

- We can't use `ext_InterExchange(1, 2, -5e-13)` because the two FM layers don't have an interface
- CustomFields can provide a solution!

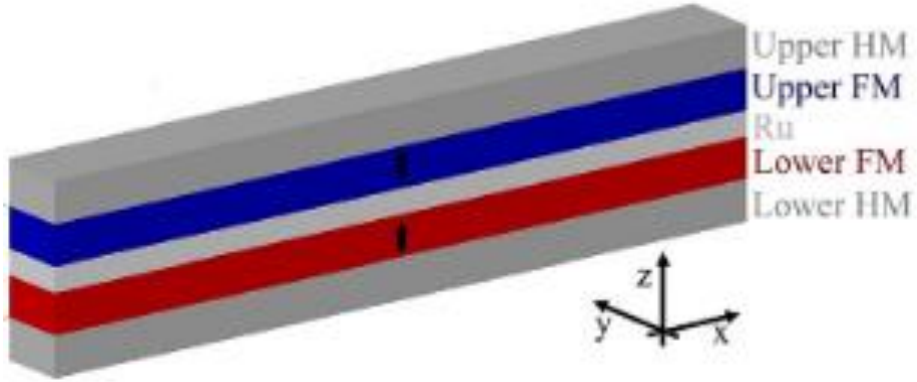
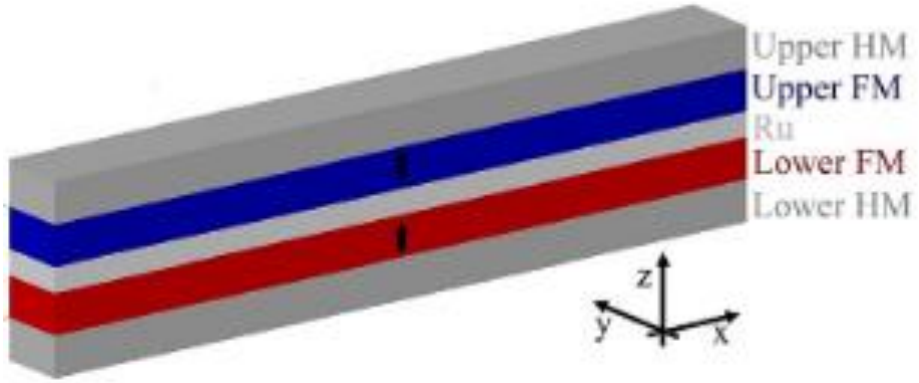


Figure reproduced from "Performance of synthetic antiferromagneticracetrack memory: domain wall versus skyrmion", R. Tomasello, et al. 2017 J. Phys. D: Appl. Phys. 50 325302

SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET




```
// Skyrmion racetrack

setgridsize(256,64,3)
setcellsize(1e-9,1e-9,1e-9)
setpbc(4,0,0)

Msat = 580e3
Aex = 15e-12
Dind = 3.0e-3
Ku1 = 0.8e6
AnisU = vector(0,0,1)
alpha = 0.1
```

```
// define 2 layers
defregion(1,layer(2))
defregion(2,layer(0))

//set geometry
Setgeom(layer(0).add(layer(2)))

//define initial magnetization
m.setregion(1,neelskyrmion(-1, 1).transl(-40e-9,0,0))
m.setregion(2,neelskyrmion(1, -1).transl(-40e-9,0,0))

Minimize()
```

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Figure reproduced from "Performance of synthetic antiferromagnetic racetrack memory: domain wall versus skyrmion", R. Tomasello, et al. 2017 J. Phys. D: Appl. Phys. 50 325302

SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET

```
//Custom Fields implementation for exchange between the 2 FM layers

cellsize:=1e-9
AFMAex:=-5e-13
Ms:=580e3
prefactorZ := Const( (2 * AFMAex) / (cellsize*cellsize*Ms))

up   :=   Mul(Add(Mul(Const(-1),m),Shifted(m,0,0, 2)),Shifted(Const(1),0,0, 2))
down :=   Mul(Add(Mul(Const(-1),m),Shifted(m,0,0,-2)),Shifted(Const(1),0,0,-2))

Bc :=Mul(prefactorZ,Add(up,down))

AddFieldTerm(Bc)
addEdensTerm(Mul(Const(-0.5),Dot(Bc,M_full)))
```

$$\vec{\mathbf{B}}_{\text{exch}} = 2\frac{A_{\text{ex}}}{M_{\text{sat}}}\sum_i \frac{\left(\vec{\mathbf{m}}_i - \vec{\mathbf{m}}\right)}{\Delta_i^2}$$

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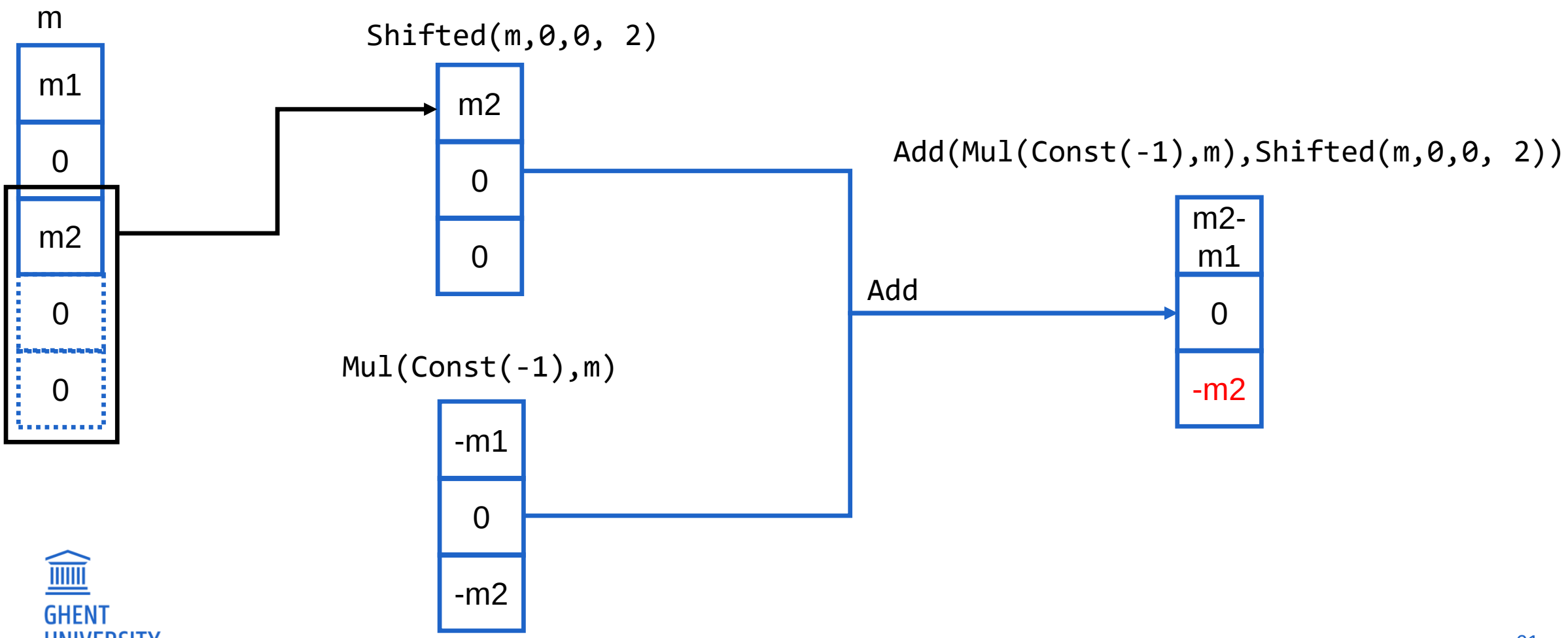
SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET

```
//what's happening here?
up :=          Mul(Add(Mul(Const(-1),m),Shifted(m,0,0, 2)),Shifted(Const(1),0,0,2))
```



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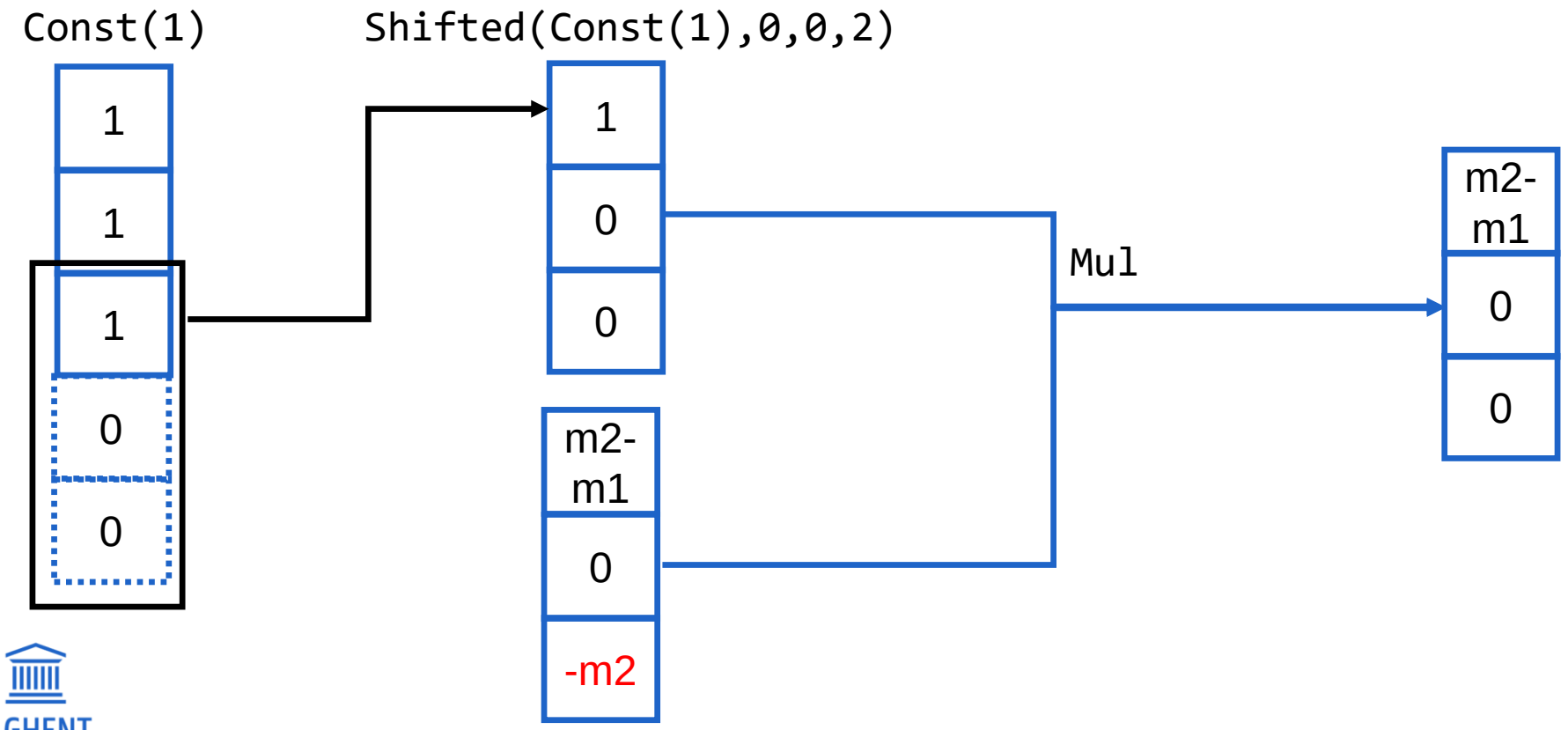
SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET

```
//what's happening here?
up :=        Mul(Add(Mul(Const(-1),m),Shifted(m,0,0, 2)),Shifted(Const(1),0,0,2))
```



Add(Mul(Const(-1),m),Shifted(m,0,0, 2))

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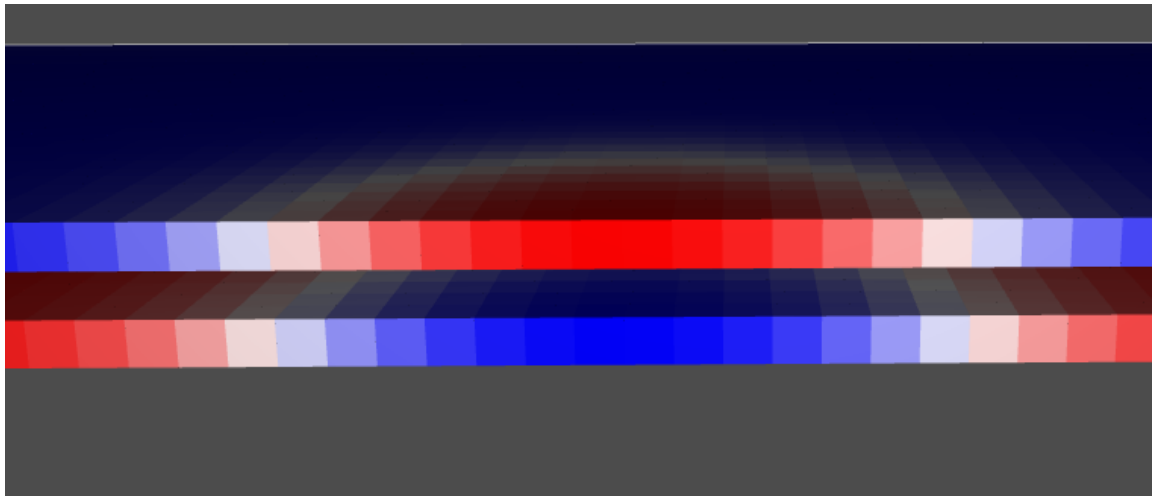
SKYRMION RACETRACK IN SYNTHETIC ANTIFERROMAGNET

```
// define constants and set slonczewksi parameters
SOTxi                := -2
AlphaH               := 0.15
Pol                   = alphaH
Lambda                = 1
Epsilonprime          = alphaH*SOTxi/2
Fixedlayer            = vector(0,1,0)
FREELAYERTHICKNESS    = 2.0e-9

// define current
J  = vector(0,0,-2e11)


autosave(m,1e-10)
tableAutosave(1e-11)
tableAdd(ext_bubblepos)


run(2e-9)
```



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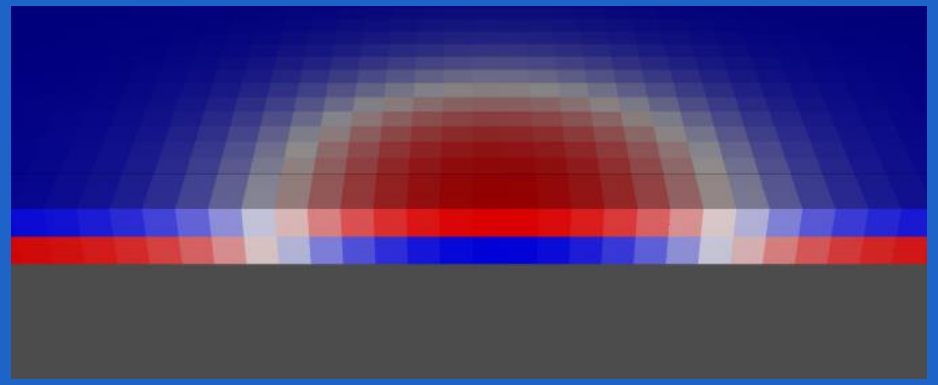
SKYRMION RACETRACK REVISITED

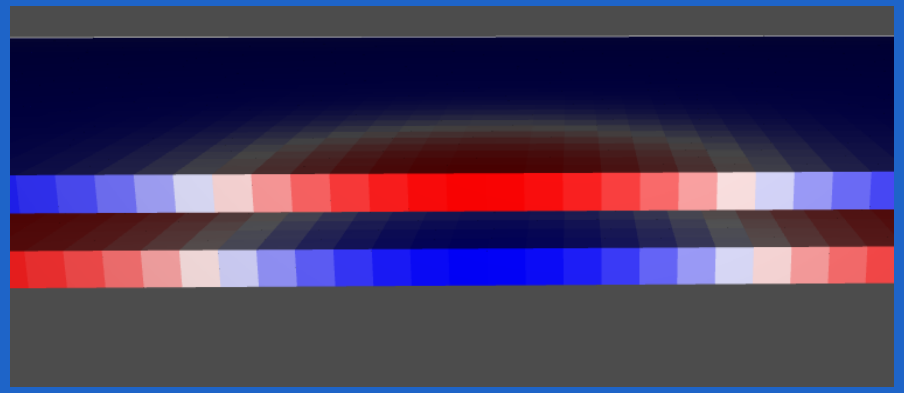
WHAT HAVE WE LEARNED?

- Interlayer exchange coupling
- Custom fields exchange coupling to explicitly include spacer layers

Input file: session4_example3a.txt
Titan RTX: 86 s

Input file: session4_example3b.txt
Titan RTX: 7 min





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POST PROCESSING (IN PYTHON)

This section will be presented in a Jupyter notebook which can be found on https://mumax.ugent.be/mumax3-workshop/

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