Parallelization of a Magnetohydrodynamics Model for Plasma Simulation
Research groups

CeNAT

CINESPÁ
PCell

- Software for visualization and study of magnetic fields on plasma cells in 2D
- Solves a set of differential equations
- Generates visualizations of the magnetic field evolution in time

- Visualization of magnetic fields of plasma eddies with PCell
Problem definition

- The original PCell version:
  - Limited the amount of spatial points that could be simulated
  - Was inefficient, specially when increasing the time scale of the simulations

- The researchers wanted to expand the model and accelerate it to broaden the simulation ranges and decrease the execution time
Magnetohydrodynamics

- Studies the interaction between electromagnetic fields and conductive fluids in motion
- Magnetic fields induce electric currents on conductive fluids in motion
- These currents affect the magnetic fields reciprocally
- It is a combination of Maxwell’s electromagnetism and hydrodynamics
- Under this approach, plasma is seen as a single fluid with very high conductivity
Magnetic Reynolds number

- It is a scalar parameter analogous to the Reynolds number used in fluid mechanics.
- It determines the turbulence of the fluid, and therefore its magnetic field.
Methodology
## Code analysis and profiling

<table>
<thead>
<tr>
<th></th>
<th>% time</th>
<th>cumulative seconds</th>
<th>self seconds</th>
<th>calls</th>
<th>self ms/call</th>
<th>total ms/call</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>convect</td>
<td>91.94%</td>
<td>0.34</td>
<td>0.34</td>
<td>100</td>
<td>3.40</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>mean_field</td>
<td>5.41%</td>
<td>0.36</td>
<td>0.02</td>
<td>100</td>
<td>0.20</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>potinc</td>
<td>2.70%</td>
<td>0.37</td>
<td>0.01</td>
<td>1</td>
<td>10.00</td>
<td>10.00</td>
<td></td>
</tr>
<tr>
<td>itoa</td>
<td>0.00%</td>
<td>0.37</td>
<td>0.00</td>
<td>100</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>reverse</td>
<td>0.00%</td>
<td>0.37</td>
<td>0.00</td>
<td>100</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>convec_plasma</td>
<td>0.00%</td>
<td>0.37</td>
<td>0.00</td>
<td>1</td>
<td>0.00</td>
<td>360.17</td>
<td></td>
</tr>
<tr>
<td>create_form_Convection</td>
<td>0.00%</td>
<td>0.37</td>
<td>0.00</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>create_gnuplot</td>
<td>0.00%</td>
<td>0.37</td>
<td>0.00</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>
Code analysis and profiling

- Search for areas where there is:
  - Data dependency
  - Functional dependency
  - Processing bottlenecks
Improvements to the program

- Replacement of static, fixed-dimension arrays for dynamic ones
- Removal of unnecessary and repetitive cycles and functions
- Optimization of the iteration over the spatial matrix
- Memory leak removal with the help of Valgrind
Hardware used

- Kabré cluster at CeNAT
- Intel Xeon Phi architecture
- 64 physical cores on each node
Original program flow

1. POTINC
2. CONVEXT
3. 
   - $t \geq T_{\text{lim}}$
   - $t = t + 1$
4. 
   - $n > 4$
   - $n = n + 1$
5. 
   - $x \geq X_{\text{lim}}$
   - $x = x + 1$
6. 
   - $y \geq Y_{\text{lim}}$
   - $y = y + 1$
7. inducción($x, y$)
8. FIN
After paralelization
Evaluation of results

- Correlation index between the programs’ output
- Test of difference in means
- Descriptive analysis
- Output evaluation by an expert

Result: There’s no statistically significative difference between the outputs
Performance tests

Acceleration

Test
Test Result Average

Amount of threads

Acceleration
Spatial scalability

![Graph showing spatial scalability](image)
Temporal scalability

![Graph showing temporal scalability](image)
Contributions

- Applying a parallelization methodology to a scientific software
- Improvement of spatial and temporal scales of the simulation model
- Decreasing the total execution time (~41x acceleration)
- Parallel algorithm for simulation of electromagnetic fields in convective plasma cells
Future work

- Expand the model to three spatial dimensions
- Integrate with ParaView to improve visualization
- Parallelization with MPI