CIDER 2018 Mineral Physics Tutorial 2: BurnMan

`BurnMan` is an open source Python toolkit that computes the thermo-elastic properties using an equation-of-state for composites at high pressures and temperatures. The equation-of-state parameters come from databases compiled from many experiments of minerals under high-(P,T) conditions. The code provides the tools to directly compare the computed velocities to seismically observed ones. Development of `BurnMan` started at CIDER 2012 when we didn't have the right tools to explore the composition of the lower mantle combining multiple disciplines.

To read more background on `BurnMan` see:

Cottaar, S, T Heister, I Rose, and C Unterborn. 2014. "`BurnMan` –a Lower Mantle Mineral Physics Toolkit." Geochem. Geophys. Geosyst. 15 (4): 1164–79.

To get started:
- Start up the Virtual Machine and login as 'mineralphysics'
- Open a terminal and `cd Desktop/sannecottaar-burnman`
- Here you see three ipynb files, which we will run in this tutorial

Step 1: Computing seismic velocities

Global geophysicists have an ongoing discussion on the degree of whole-mantle convection versus the degree of two-layered convection. There is good certainty that in the present day there is exchange of material between the upper and lower mantle in the form of downgoing slabs and upgoing mantle plumes. The question remains if this has always been the case and if this exchange has been sufficient to create a well-mixed mantle. One way to assess this is to test if the upper and lower mantles have similar compositions. For the upper mantle we have more direct samples from volcanoes. For the lower mantle we can attempt to determine the composition based on seismic velocity models.

Open the first notebook:

```
jupyter notebook practical_burnman_step1.ipynb
```

Run the different code blocks and check what they do. This script eventually plots the velocities of a simple compositional model with respect to PREM.

a. What assumptions are made in the script? For what reasons is this composition unrealistic? What could be changed to better fit the velocities and densities? You could try to implement a more realistic composition, or skip to the next step.

Step 2: More realistic models

We will now test two different compositional models for the lower mantle. The pyrolitic model represents a composition similar to the upper mantle (ignoring Al and other minor components):

- Pyrolitic model
  - 75% perovskite or bridgmanite $(Mg, Fe)SiO_3$ with 94% Mg and 6% Fe
  - 18% ferropericlase $(Mg,Fe)O$ with 80% Mg and 20%Fe
  - 7% Ca-perovskite $CaSiO_3$

The chondritic model is a competing model that suggests the composition the lower mantle should have if composition of the bulk Earth is represented by chondritic meteorites. In this case the lower mantle is enriched in Si relative to the upper mantle.

- Chondritic model
  - 88% perovskite/bridgmanite (Mg, Fe)SiO_3 with 94% Mg and 6% Fe
  - 5% ferropericlase (Mg,Fe)O with 80% Mg and 20%Fe
  - 7% Ca-perovskite $CaSiO_3$

Open the second notebook:

```
jupyter notebook practical_burnman_step2.ipynb
```

This script computes velocities for two compositions including an adiabatic geotherm.

b. Modify rock2 to represent the Chondritic model. Which model fits the velocities best?
c. Vary the ratio of perovskite to periclase, or the Mg/Fe ratio in the minerals. You can also change the temperature in line 164. With what composition can you improve the fit to radial velocities and density? You will find it is challenging (or impossible?) to fit all three at once.
d. In the lowermost mantle, lateral variations in shear wave velocity range from at least -3% to +3%. How much temperature anomaly is needed to explain such variations? How about iron content?

Step 3: Building a planet

Open the third notebook:

```
jupyter notebook practical_burnman_step3.ipynb
```

This script shows an example of how to build an entire planet and compute seismic travel times for this.

Option 1:
Try to improve the planet to imitate earth better. This requires diving into the mineral libraries or potentially adding your own mineral/material.

- How can the mantle composition be improved? (See step 2 as well)
- How can the mantle transition zone be improved?
- What is unrealistic about the currently implemented inner core?

Option 2:
Later this year a seismometer will land on Mars (INSIGHT mission). Adapt the script to represent Mars-like planet. The paper of Khan et al. (2018) is included which gives approximate Mars structure, mass, and moment of inertia.

- What phases could constrain the depth of the core-mantle boundary on Mars?

Explore more:

There are many examples included in `BurnMan` which you can find under BurnMan_developersversion/examples. Here are several that might be interesting to explore:

- example_user_input_material.py : Shows how to implement your own mineral.
- example_woutput.py : How to write out your output to a text file.
- example_optimize_pv.py : Example fitting amount of bridgmanite in the lower mantle, shows that results are different depending on which velocity one tries to fit.