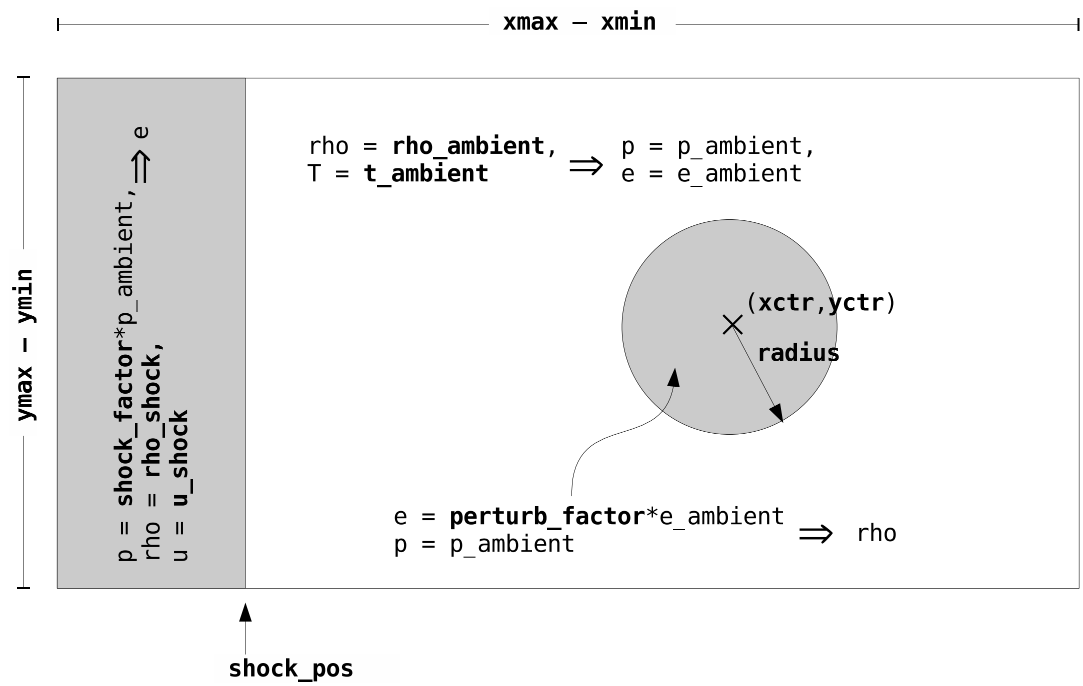
PHY 688: The Application of Simulation in Astrophysics
Final Project
Due: Wed. May 10, 2006

Project Description

In this project, we will use FLASH to study an interesting physics problem, built from the `example` setup we studied in class. Consider the initial conditions diagrammed below. All boldface parameters are runtime parameters in the setup we will use.



Here, the domain is initialized with an ambient density `rho_ambient` and ambient temperature `t_ambient`. Using the equation of state, the ambient pressure (`p_ambient`) and ambient specific internal energy (`e_ambient`) are found. From these we can initialize all of the thermodynamic variables in FLASH.

There are two perturbations on the grid:

- In a circular region ('bubble') centered on (`xctr`, `yctr`), with radius `radius`, we increase the internal energy by a factor `perturb_factor` over the ambient internal energy, keeping the pressure constant. From the specific internal energy and the pressure, we can compute the density using the EOS. Since this region is in pressure equilibrium, it will be stable.
- Finally, for all $x <$ `shock_pos`, we raise the pressure by a factor `shock_factor` over the ambient pressure. The density and velocity in this region are set by `rho_shock` and `u_shock` respectively. By default, the density is the ambient density and the velocity is zero. This is in effect a Riemann problem, and from our class discussions and numerical experiments, we expect a shock wave to develop (along with a contact and rarefaction). This shock wave will hit our bubble, and interesting dynamics will ensue.

This setup can be used as a toy model to explore several astrophysical scenarios. There are two interesting cases to study.

1. If `perturb_factor` > 1, then the density in the perturbed region will be lower than the ambient density. In astrophysics, such a scenario can arise in galaxy clusters. Here it is common to observe under-dense regions (void). Shocks moving out from a central source can interact with these voids and transfer energy into the medium.

2. If `perturb_factor` < 1, then the density in the perturbed region will be higher than the ambient medium. In star forming regions, small density enhancements can be amplified by shocks from nearby supernovae, triggering subsequent star formation.

In this project, you will explore these different scenarios through a variety of numerical exercises using the FLASH code.

Setting Up

Copy ~`mzingale/example_shock/` into your `FLASH2.5/setups/` directory. This problem is configured as described above. You can set this problem up using

```
./setup example_shock -auto -site=SINC
```

and use `gmake` to build it. When you run it and look at the initial output file with `xflash`, you will see the configuration shown in the figure. Take some time to look at the different variables, so you understand which quantities vary in which part of the grid.

Numerical Experiments

a. Using the `query` function in `xflash` determine the left and right states for the Riemann problem defined at $x =$ `shock_pos`. You should record these in terms of the primitive variables $\{\rho, u, p\}$. To get an idea what to expect in the simulation described above, examine this Riemann problem along in FLASH. Here, you can use the `sod` setup in one-dimension. Set this up via:

```
./setup sod -auto -site=SINC -1d
```

And modify the runtime parameters, `rho_left`, `rho_right`, `u_left`, `u_right`, `p_left`, and `p_right` to correspond to the Riemann problem in the `example_shock` problem.

What wave structure do you see? Provide a plot of the solution, identifying the different waves. From this one-dimensional run, you now have an idea of how quickly the shock propagates, and how long it will take to interact with our bubble.

b. Return to the `example_shock` setup and run the problem for an over-dense and under-dense bubble. Provide plots of the evolution of the bubble throughout the shock interaction. In each case, discuss what happens to the shock structure as it interacts with the bubble, and give the physical reason for this behavior.

c. Now we want to get a feel for whether the solution is converging. Run either the over-dense or under-dense case at three different resolutions (you can do this by varying `lrefine_max`). Discuss how the solution differs with resolution, both *qualitatively* and *quantitatively.*

d. The above simulations watched not just the interaction of a shock with the bubble, but also the other hydrodynamic waves resulting from the initial Riemann problem. We can better choose the state to the left of `shock_pos` to produce only a strong shock. Recall from homework #2 that the post shock density and velocity, in terms of the post shock pressure, are:

$$\frac{\rho_\star}{\rho_R} = \frac{\frac{p_\star}{p_R} + \frac{\gamma-1}{\gamma+1}}{\frac{p_\star}{p_R}\frac{\gamma-1}{\gamma+1} + 1} \tag{1}$$

and

$$u_\star = u_R - \frac{2c_R}{\sqrt{2\gamma(\gamma-1)}} \frac{1 - \frac{p_\star}{p_R}}{\sqrt{1 + \frac{\gamma+1}{\gamma-1}\frac{p_\star}{p_R}}} \tag{2}$$

Here, $p_\star/p_R =$ `shock_factor`. We know all of the right-state information, so we can compute the post-shock velocity and density—these define the new left state. Verify, using the one-dimensional `sod` setup that when you use this new left state that only a single strong shock is produced—the other waves are eliminated. This is how test 4 in homework #4 was formulated. *Note:* by default, the equation of state uses $\gamma = 5/3$. You can override this using the `gamma` runtime parameter.

Now, modify change `u_shock` and `rho_shock` to correspond the state you determined above. Rerun the over-dense and under-dense cases with this modified, single-shock setup. Discuss the differences with the previous initial conditions. Provide plots showing the shock/bubble interaction.

Provide a write-up describing your results. In particular, discuss what happens to the shock as it passes through the over-/under-dense region, describe the convergence of the results, and talk about any instabilities you see in your simulations. Feel free to play around with the initial conditions and explore different scenarios (e.g. reflecting boundary on the right edge, multiple bubbles, ...).