How to Build a Universe

Elizabeth Tasker

‘So, what is it you do?’ This question rings out up and down the country at the start of every academic year as students meet their new friends for the first time. Normally, the answer is forgotten as soon as it is uttered, often with the help of copious amounts of alcohol. But I found my airy answer of ‘Oh, I build universes’ usually tends to stick in people’s mind.

Faced with a dumbstruck stare of incomprehension, I normally feel obliged to explain that I’m studying for a doctorate in astrophysics and that I use large computer simulations to model the formation of galaxies. This can often lead to a philosophical conversation about whether I was in fact creating a universe in which there would be another astrophysics student simulating another universe inside my one. Fortunately, this is not a problem I have to lose much sleep over as the resolution of my simulation does not allow me to see anything smaller than a cluster of stars. This is probably a good thing, as in the initial stages my program often tends to crash which could result in the human rights people breathing down my neck.

If the alcohol has not been flowing too freely that evening, I might then get asked how on earth you go about designing a program that will build a universe. Indeed, the task is so awesome that it seems impossible to know where to begin. Astrophysicists, after all, are a long way away from understanding all the mechanisms that go on in our Universe so how can you begin telling a computer how to build one from scratch? The answer is that you go back to a point where you are pretty sure you know what is going on, throw in all the laws of physics you can come up with and watch what happens.

How far do we have to go back before we can be sure we know what the setup in the Universe is? If we go back right to the beginning then we reach the Big Bang, which certainly is not well enough understood to use as a starting place. But if we wait too long, then stars and galaxies will have started to form. These are highly complicated objects, so again, no good for our initial point. What we want is a time in the Universe after the Big Bang but before the creation of any real structure. Here the density in the Universe will be constant everywhere except for small bumps or ‘perturbations’. These perturbations can be calculated very easily - in fact, an equation showing how they evolve can be written down using just some basic maths. This makes an excellent starting point and turns out to be at around 48 million years after the Big Bang. (For comparision, the age of the Universe today is about 14,000 million years.)

Having chosen our starting position, we now need to decide what we are going to put into our Universe at this point. Gas is needed to form stars, but there also needs to be a large component of dark matter. Is this a problem? We do not know what dark matter consists of, but it turns out not to be an issue in this case. All that is assumed is that the dark matter consists of particles that interact through gravity and whose velocity does not approach the speed of light. This is known as the 'cold dark matter model'. If we assume that the gas and dark matter do not interact, then we can compute their properties separately. The dark matter, as we have just seen, can be calculated from Newton's Laws of gravitation. For the gas, we can borrow from our lab physicist friends whose equations for fluid flow in gases on Earth are very well defined. You might question whether it a reasonable assumption that star dust (which is effectively what we are dealing with here) will behave like a gas on Earth. However, if the laws of Physics apply to the whole Universe then there is no reason to assume this will not be the case.

The next big question is purely a computational one. We have the equations that tell us how these particles are going to move and we have a starting point. Now, how are we going to calculate this so that we do not have to hang around a few billion years to get some results? Two main methods are employed in this area. The first is to track each of the particles you put in at the start and find out where they end up. The second involves a mesh system. Imagine putting a regular, wide spaced mesh, rather like chicken wire, over the Universe. Inside every mesh square we could average all the properties, like density and temperature so that each square only held one value. If the mesh was very coarse, there would only be a small number of values to calculate and the time it takes would be very small. The down side to this is that the resulting resolution would be very poor. Details of structures smaller than the mesh square would be totally obliterated. A way to get back this resolution would be to place a much finer mesh over the Universe. This would certainly preserve all the structure, but at the cost of greatly increasing the amount of computer time required. Also a lot of this time would be used needlessly; there are vast chunks of space which really have nothing in them at all and a much coarser mesh would amply suffice. What is really needed is a coarse, low computationally intensive mesh over the wide empty spaces and a very fine grid over the densely populated areas. This is the principle for 'Adaptive Mesh Refinement'. Here, a coarse grid is initially placed over the whole simulation. The density is calculated in each of the mesh squares. If the density is low, nothing much is assumed to be going on there and the mesh is left as it is. If, on the other hand, the density is high, a second finer mesh is placed within the square and the process is repeated. This ensures that the computational power is used only where it is needed.

Allowing the gas and dark matter to follow the fluid equations and Newton's Laws gives dense clumps of material. This is a good start, but what we now need are the conditions to light the universe up - that is, to form stars. We assume that once the density at a point gets above a certain value, nuclear fusion will take place and a star is born. This star will begin pouring out energy into our simulated universe in the form of light and heat and we need to tell the computer where to put this. The gas surrounding the new star will heat up and may form a star itself, or it may increase in velocity causing the pressure to rise and counteract gravity to prevent the galaxy from contracting. Then there are the products from the star formation. Suddenly, we have an input of helium from the fusion of hydrogen and then we move onto more heavier products. So we need yet more physical rules to govern the rate of production of these elements and where they are going to end up. Finally, the star may die in a huge explosion known as a supernova. This will send a shock wave of energy through our simulation shaking up all gas and dark matter in its path.

After all of this has been calculated, do we see an universe that is anything like our own? When asked this question, I may at first start with a confident 'yes!' but then follow it up after a pause with a 'well, not quite.' The overall picture we see of the simulated universe is really very good. There are clusters of galaxies of about the right mass and voids where nothing much is going on at all. The galaxy clusters are joined together by a filamentary strands of gas and dark matter which closely resembles what we observe. If this were the end of the subject, astrophysicists could say they had the physics of the Universe wrapped up. It is perhaps fortunate for future researchers in this field then, that this is not quite true. One problem is that while the galaxies form, they do not look entirely right. In disk galaxies, like our own Milky Way, the disk is rather smaller than we observe, even though our simulated galaxy has the same mass. This means that we must have missed some mechanism out that prevents the disks from contracting so much. If gravity is going to pull the galaxy in, there must be another kick of energy, in addition to the ones we have included, that pulls it out.

There are also weird and wonderful observed features in the Universe that could potentially be explained by these simulations. Where, for instance, do the super-massive black holes, now believed to be in the centre of every galaxy, come from? Do they form from mergers of little, star-collapsed black holes? Or are they the result of primeval black holes that have been around at the start of the Universe? By putting both models into a computer simulation, the results can be compared to observations to predict

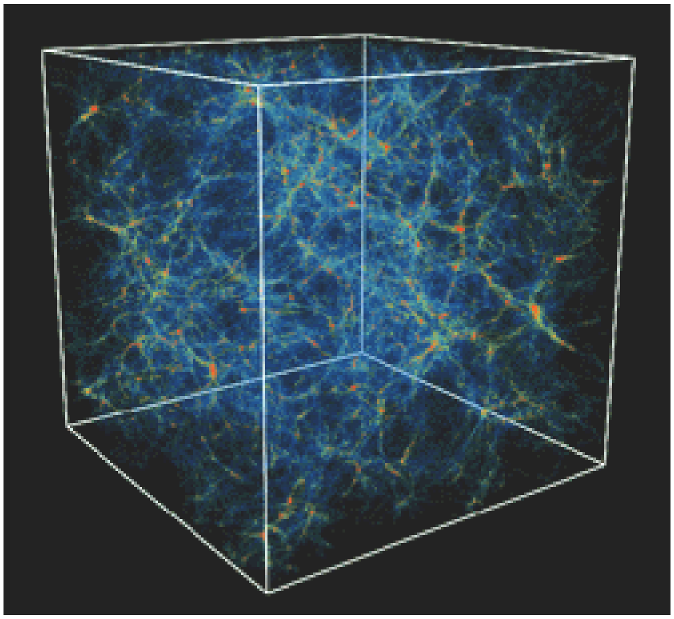

Figure 1: Image showing the density of gas inside a simulation box. The densest clumps are shown in orange and are where galaxies would form. The low density filamentary strands shown in blue closely resemble what is observed in the Universe. Work performed by Greg Bryan and Michael Norman at the Laboratory for Computational Astrophysics, National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.

the most likely answer.

If last orders has not been called at the bar by this stage, the final question I get presented with is, 'Great! Love the idea of computer simulations, why have these not all been run and the answers to life, the Universe and everything found?' The answer to this is two fold. The first part is computer power! Even though techniques like adaptive mesh refinement greatly improve computational time, these are still long calculations lasting days or even weeks on supercomputers. Secondly, because you cannot have an infinitely fine mesh, all results you get are approximations. They may be good, accurate approximations, but they also may give misleading results if used incorrectly. So it may not be a Nobel prize winning piece of new physics you've discovered - it might simply be that your computer code is wrong for that situation.

With all that taken into account, Computer simulations are undoubtably an unrivalled way to explore the physics of the Universe theoretically. Observational data, while improving all the time, can only ever see the Universe from a single perspective: from where we are on Earth. By modelling the evolution of the Universe as one complete system, real understanding of our origins can be obtained. And you thought computers were just for playing Half-life?