Reviews

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Computing tomorrow's weather

Jim Reed/Science Photo Library

Weather watch
Computer modelling has transformed weather forecasting.

Weather by the Numbers
Kristine C Harper
2008 MIT Press
$40.00/£25.95hb
328pp

The development of computer models that simulate the Earth's atmosphere, allowing us to predict weather and anticipate climate change, is one of the triumphs of 20th-century science. Weather forecasting used to be very hit-and-miss, based on rough rules of thumb and the assumption that similar weather patterns would evolve in a similar manner. But from 1950 onwards, digital computers revolutionized the field, transforming it from a woolly empirical activity to a precise, quantitative, science-based procedure. Weather forecasting was among the first computational sciences and is still a major application for high-end computers today. In *Weather by the Numbers*, the historian Kristine Harper tells the fascinating story of how numerical weather prediction became possible.

For the first few decades of the 20th century, there were virtually no academic programmes in meteorology in the US. In Europe, research focused on climate and theoretical meteorology, with little or no emphasis on practical weather forecasting. But weather has a major influence on military operations, and with the Second World War looming, it became clear that the Allied war effort would require many well-trained, practically minded meteorologists. The D-Day landings provided a stark example of meteorologists' utility in warfare: the success of Operation Overlord depended on a brief window of fair weather in a very stormy period of June 1944. Although the Allied forecasting team was able to predict such a respite accurately, the effort strained its abilities almost to breaking point: long-range forecasting was simply impossible, and one American meteorologist compared the process to a game of poker.

The war spawned a boom in the number of professional meteorologists, as the community grew from 400 before the hostilities to 6000 after. Many of these researchers had excellent mathematics and physics knowledge, and were anxious to treat the forecasting problem in a scientific manner – if only they knew how! With this dilemma in mind, the Meteorology Project was established in 1946 to investigate scientific weather prediction. The project was funded by the US Government and led by the mathematician John von Neumann. Based at the Institute for Advanced Study in Princeton, the goal of the project was to develop accurate weather forecasts by using a computer to integrate the equations governing the behaviour of the Earth's atmosphere.

Harper sketches the role of the key players associated with the project: Francis Reichelderfer, head of the US Weather Bureau; the outstanding Swedish–American meteorologist Carl-Gustav Rossby; and Jule Charney, who led the project for six years. She also describes the role played by what she terms the "Scandinavian Tag Team": a series of European, mainly Scandinavian, meteorologists who successively visited Princeton.

One problem that the project had to address was the error-prone nature of the solutions to the equations that were then used to forecast the weather. The atmosphere is described by a system of coupled nonlinear partial differential equations. Many of the desired quantities are represented as differences between large terms. This means that a small error in a large term results in a large error in the result. For example, the divergence, or net outflow from a particular point, is the difference between influx and outflow. Hence, a minor error in the reported wind speed can lead to a spuriously large divergence, producing high-frequency noise in the solutions and thus corrupting the forecast. But Charney realized that, since divergence occurs in two of the forecasting equations (known as the vorticity and continuity equations), it can be eliminated by combining them. The resulting "potential vorticity" equation describes the slow evolution of the atmosphere without interference from high-frequency noise.

Harper describes a hierarchy of models of increasing realism and accuracy that members of the Meteorology Project considered. In the end, limitations on computer power compelled the group to choose a model known as the barotropic vorticity equation (BVE) for its first test forecasts. This model treats the atmosphere as a single layer, with variations in the vertical dimension smoothed out by integration. The absolute vorticity (the spin due to the motion of the atmosphere and the Earth's rotation combined) is conserved following the flow; that is, an individual parcel of atmosphere maintains its initial vorticity as it moves along.

The BVE was first integrated in March 1950 on the famous Electronic Numerical Integrator and Computer, or ENIAC, the only machine available at the time. Using the results of the integration, project scientists were able to make four one-day forecasts covering North America and the North Atlantic Ocean. While far from perfect, they were at least realistic – that is, they looked like plausible predictions. These results had an electrifying effect on the meteorological community. Leading scientists realized immediately that something really important had been achieved, and initially hoped that numerical prediction would soon yield results of practical value. However, many obstacles remained, including the acquisition and analysis of observations in timely fashion, and the question of how to represent mathematically a wide range of physical processes such as radiation, convection, precipitation and turbulence.

In summarizing the project's efforts, Harper correctly notes that it "serves as a unique example of a military-funded effort leading to significant scientific advances that had immediate civilian applications". However, exploiting these developments in practice required a more structured organizational framework. This proved difficult to achieve, because the US Weather Bureau, Air Force and Navy all had operational forecasting units with aspirations to lead the emerging field of numerical weather prediction.

Harper describes vividly the Machiavellian machinations of the contenders, in which the participants jockeyed for maximum influence, each struggling to have a dominant role, and the ultimate compromises leading to the creation of the Joint Numerical Weather Prediction Unit (JNWPU) in 1954. Under the agreement, the Weather Bureau assumed administrative control, but all three agencies provided funding for the unit. Considering that the Air Force, Navy and Weather Bureau all had different mission requirements, conflicts of interest were inevitable. Management of the unit was a bureaucratic nightmare. The tensions led ultimately to the demise of the unit in 1960, when the three agencies took different routes, each setting up and developing its own system. But the JNWPU was crucial in overcoming many obstacles on the path to operational numerical prediction, and in producing the first computer forecasts for use in practical applications.

The complexity and realism of atmospheric models have increased vastly since those early days. These models have greatly increased our understanding of the general circulation of the atmosphere and of the impact of human activities on the Earth's changing climate. Reliable weather forecasts are now available routinely. Of course, we also understand that the nature of the atmosphere is chaotic, and that this places limitations on deterministic forecasting. Telling the tale of how these challenges are addressed would, however, require another book.

Computer models are now crucial for operational weather forecasting. The remarkable story of how these models emerged is well told by Harper, and her scholarly book is highly recommended to all who wish to learn more about this story.

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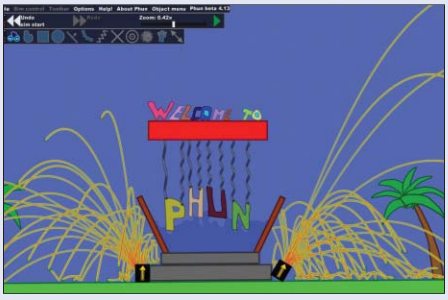
Web life: *Phun*



URL: www.phunland.com

So what is the site about?

Phun is a free, downloadable physics-simulation programme that bills itself as a "2D physics sandbox". The programme's limitless virtual space allows users to construct simple (and not-so-simple) machines out of levers, gears, motors and as many different shapes as they care to draw, then set them in motion. The results can be educational, bizarre or downright hilarious, depending on what you choose to do, but thanks to a sophisticated simulation engine, they will always be physically realistic – unless you decide to turn off friction and gravity.

Okay, so what can you do with it?

The possibilities are almost endless, but the programme provides a few sample "phunlets" to get you started. With the trebuchet, for example, you can try swapping the central hinge for a motor, changing the counterweight's mass (or filling it with water) and reducing friction on the sling. Clicking on most objects brings up a list of physical properties, including mass, area, moment of inertia, motor speed and kinetic energy. The "tracer" feature makes it easier to follow the paths of moving objects – useful if you accidentally fill your trebuchet projectile with helium – and the "hand" tool allows you to pick up your creations and fling them about (try it with the "ragdoll" phunlet). But this is the tip of the iceberg: the site's designers have deliberately left it "open for creativity and exploration", and the best way to find out more is simply to play with it for an hour or two.

Who created it, and who is it aimed at?

Phun began life as Emil Ernerfeldt's MSc project at Sweden's Umeå University. His supervisor, Kenneth Bodin, wanted a programme to use as a teaching tool at the Umevatoriet, a local science centre. However, the project quickly grew beyond its original scope, and now both Ernerfeldt and Bodin work for Algoryx, an interactive physics-software company Bodin founded in 2007 with colleagues from Umeå. Since then, Algoryx has developed a commercial version of *Phun* called *Algodoo*, which offers some nifty extra features like light beams and graphing tools. Lecture material, tutorials and a dedicated website for educators and learners are also in the works, Bodin told *Physics World*. With their bright, colourful interfaces and easy-to-understand controls, both *Algodoo* and its free cousin *Phun* were clearly designed with young people in mind, but those who left school years ago will still find plenty of interest.

Anything in particular I should look out for?

Phun has spawned a thriving online community of users who post tips on the main *Phun* site and videos of their creations on *YouTube*. If you want more *Phun* than catapults or cars can offer, these videos are full of ideas, and some are little short of amazing. Two videos by Probber show off an elaborate water-based Heath Robinson contraption, while in JDKmedeng's "Mars Mission", a four-stage rocket transports a rover vehicle onto a simulated red planet (where the force of gravity is, of course, reduced). For sheer silliness, it is hard to beat "Duckotron", which stars a singing mechanical duck and an accident-prone human. However, it is Phunico's multi-geared sushi-making machine that really takes the prize. The timing of each stage of the process (rice, nori wrap, salmon eggs) is astonishingly fine, and the explanation at the end makes it clear just how much work went into this particular bit of *Phun*.