Lewis Fry Richardson's forecast factory – for real

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The idea that supercomputers are an important part of making forecasts of the weather and climate is well known amongst the general population. However, the details of their use are somewhat mysterious. A concept used to illustrate many undergraduate numerical weather prediction courses is the idea of a giant 'forecast factory', conceived by Lewis Fry Richardson in 1922. In this article, a way of using the same idea to communicate key ideas in numerical weather prediction to the general public is outlined and tested amongst children from local schools.

The emergence of the forecast factory

An excellent and very readable review of the emergence of numerical weather prediction has been given by Lynch (2006). Here we provide a short review of the developments leading to Lewis Fry Richardson's forecast factory idea in his *Weather Prediction by Numerical Process* (WPNP) (Richardson, 1922).

At the start of the century, weather forecasting relied mainly on a combination of analogue methods (comparing present conditions with similar historical precedent) and empirical, highly local, forecasting rules. This approach was challenged by, amongst others, Cleveland Abbe (1901), Vilhelm Bjerknes (1904) and Felix Exner (1908) who proposed that forecasting should be based on the solution of mathematical equations that represent the physical processes that govern the atmosphere. Richardson was amongst those who set out to develop practical methods to produce weather forecasts on this basis. In WPNP, he sought to develop ways of solving the primitive equations on a grid of points distributed over the globe and in several layers above the Earth's surface. Details of his numerical schemes and their equivalents in modern numerical models are examined by Lynch (2006). Richardson then attempted to forecast the horizontal momentum, pressure, humidity and stratospheric temperature over central Europe, using initial conditions from an analysis by Bjerknes for 20 May 1910. This forecast was manually computed by Richardson between 1916 and 1918, when, as a Quaker (and therefore a pacifist), he served as an ambulance driver in Champagne, France. Famously, his forecast produced very large tendencies in most of its components – much larger than those observed in the real atmosphere (Lynch, 2006, p.133, discusses the reasons for this). Nonetheless, the principles of Richardson's forecast, particularly the application of mathematical techniques to solving the primitive equations on a grid representing the atmosphere over the Earth's surface, were sound and remain in use for many modern numerical weather prediction methods.

Richardson recognised that his underlying idea for weather forecasting was indeed robust, and in WPNP imagined the now famous 'forecast factory':

> *After so much hard reasoning, may one play with fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the Antarctic in the pit. A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation.*

This description of a 'forecast factory' is both fabulously evocative and, as noted by Lynch, remarkably prescient. Chapter 12 of Lynch's book notes the various ways in which the description matches modern numerical weather prediction by massively parallel processors. The aim of our project was to design a scaled-down version of the forecast factory which could be worked on by children at secondary schools. We hoped that, by encouraging them to take part in an activity of this sort, we could communicate two key elements of modern numerical weather prediction:

1. Forecasts are made by solving mathematical equations which represent the physical laws governing the atmosphere.
2. Forecasts are often made on a grid of points which represent different geographical locations.

A scaled-down forecast factory

In order to make the problem tractable for secondary-school-age children and to make it possible to complete the activity in a reasonably short time (~30 minutes) it was necessary to design a forecast factory which solved a much simpler problem than that used by Richardson. Of course, the most difficult part of this scaling down was to retain enough of his original idea so that we could still communicate the key principles to participants. To this end, instead of solving the full primitive equations, we solved a simple two-dimensional advection equation on a single level (http://en.wikipedia.org/wiki/Advection). The velocity field is fixed and prescribed at the start of the experiment (Figure 1(a)) and there is no feedback between our advected variable (which we call temperature for ease of communication) and the velocity field.

The equation is solved on a 4×4 grid using a forward, upstream, finite-difference scheme. By setting the velocity field to always blow from the north and west it is possible to ensure that the scheme is stable by effectively making it an upwind scheme. The grid spacing used is 100 kilometres, and four time steps of 3600 seconds each are taken. The initial and final fields for the advected variable are shown in Figures 1(b) and (c), respectively, and are produced using an implementation of the scheme in Matlab. On a typical laptop computer it takes less than five seconds to run the code. As can be seen, the initial conditions and flow field are designed so that cold air blows into the domain from the north and west and is advected towards the eastern boundary. Although this bears little resemblance to a real meteorological situation, it is a useful schematic way of illustrating to the participants the way in which advection of different air masses can have profound effects on local weather conditions.

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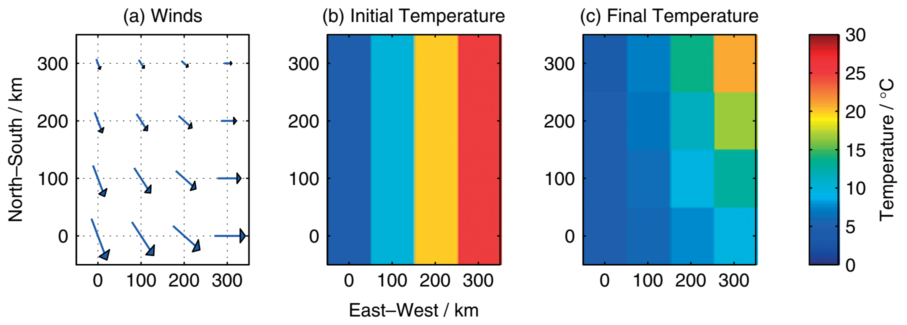

Figure 1. (a) Fixed wind field; (b) initial temperature field and (c) final temperature field for fixed boundary conditions. Colours show the temperature reading at each point in the 4x4 domain.

The choices we have made here are by no means the only way in which a forecast factory for public communication could be designed. Indeed, with older students of greater mathematical competence (say, to degree level) a more complex problem might be solved (perhaps a simplified system of the primitive equations with no physics). Recreating Richardson's original forecast using his original computing forms (Lynch, 2006, p129) would of course be a mammoth task given that it took Richardson over two years to complete his calculations.

Making it work with local school children

The first tests of the forecast factory experiment were carried out on 19 March 2009 during a National Science and Engineering Week (NSEW) open day at the University of Reading which was jointly hosted by the Department of Meteorology and the Walker Institute (Charlton-Perez *et al.,* 2010). The experiment was carried out four times in a standard university classroom using different groups of 14–16-year-old school children. Desks were arranged in a 4x4 grid: one student sat at each desk and was joined by a volunteer member of staff from the University. Two students remained at the front of the classroom to act as data collectors throughout the experiment. This arrangement mirrors that of the sketch of the forecast factory which appears in Gandin (1965). This sketch along with other depictions of the forecast factory can be viewed on Peter Lynch's website (http://maths.ucd.ie/~plynch/Dream/ForecastFactory/FF.html).

Before starting the experiment, a short introduction to the forecast factory and numerical weather prediction was given to the students. No equations were shown, but a diagram indicating that temperature at each grid-point would depend on the strength of the wind and the local temperature gradient was shown to explain the concept to the students. In order to communicate the idea that each student represented a grid-point calculator at a different physical location in the UK, several props were distributed to the students including flags, hats, and even a model sheep.

To start the experiment, initial conditions for wind components and temperature were passed to the students on coloured pieces of card. Each student used a computing form (Figure 2) to calculate a prediction for the local temperature change over an hour at their grid-point, using both the local initial conditions and those at upstream grid-points (to the north and west). Following each calculation, student data collectors were sent to each grid-point to retrieve predictions and these were then quickly displayed on a computer screen. The results were then compared with the exact calculations made using the computer code described.

Remarkably, predictions from the human computers compared favourably with those of the computer code, although calculations took about 30 million times as long (around 0.2×10^{-4} seconds per time step for the Matlab code on a standard laptop and around 10 minutes per time step for the students). It was also found to be an excellent educational opportunity to avoid correcting any calculation errors at each time step, even if they resulted in large temperature changes at a grid point. Students could clearly observe the propagation of this erroneous temperature through the field as they repeated calculations for three more time steps. It was possible for all four groups to complete four time steps in each 45-minute session, with the help and guidance of volunteers.

The experiment was repeated during the NSEW event on 16 March 2010, again involving four groups of 14–16-year-old students. The same procedure was followed, but in this instance time-evolving boundary conditions were used in order to make the calculations at the western boundary more interesting. A trial of a wireless data-input system for the students had to be abandoned because of faulty equipment, but this may be a useful future development.

Reaction of students and teachers

We conducted a formal assessment of the reaction of pupils and teachers to the NSEW open day activities, which also included a gravity-current experiment in the fluids laboratory and a radiosonde launch. Overall, responses from the students and teachers on both open days were very favourable (Figure 3). We also collected comments from the students on the day – some of the more interesting were:

> *To predict and read the weather is more difficult than I originally thought.*
> *It's more interesting when you can actually see what happens and how it works.*
> *I learnt how much work goes into predicting the weather into the future and how to do it manually.*
> *I learnt how to predict the weather with equations.*
> *Exciting and interesting.*

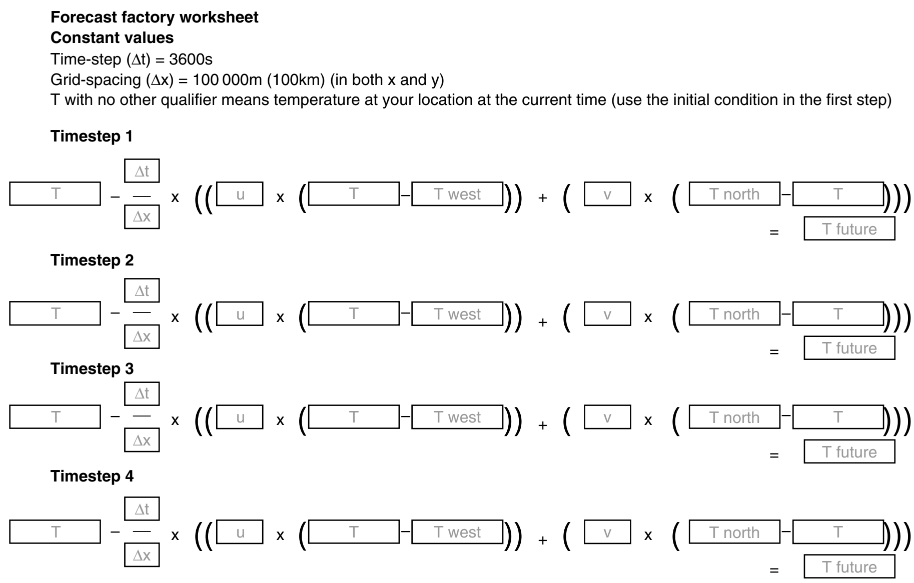

Figure 2. Student worksheet used to make calculations – designed to mimic the structure of the equation solved as much as possible.

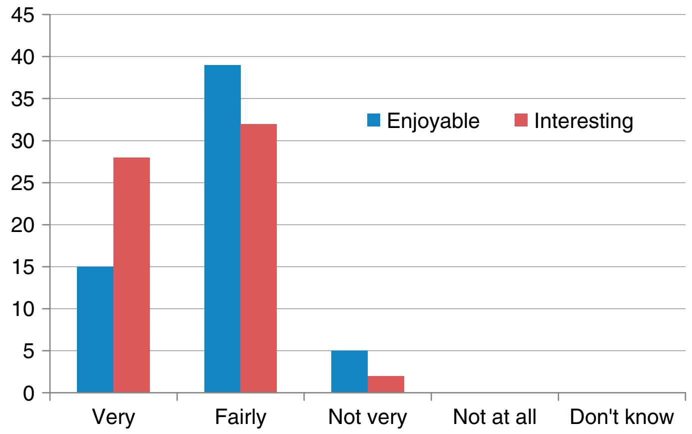

Figure 3. Results of the evaluation by students and teachers of their enjoyment and interest in the NSEW events in 2009 and 2010.

Next steps

This or a similar activity could be used in a number of ways to help communicate the basis of numerical weather prediction to different groups. We have produced background material for teachers which could be used for them to run the forecast factory experiment in schools with very limited equipment (pencil, paper, and calculator: please contact the authors for details). At university level, a similar activity could be used as an introduction to numerical modelling or numerical weather prediction courses. It would also be possible to make the activity more complex by solving a true predictive equation similar to that used by Richardson. Knox (2000) described using a similar forecast factory activity with college students in the United States to introduce the different elements which are required to make a weather forecast, including the taking and processing of observations. It should be emphasised, however, that this activity is simply descriptive and does not involve students making any calculations themselves (although it would be very easy to combine the activity described by Knox with our own forecast factory). There are also many other simple cases that might be used to illustrate particular meteorological phenomena. An interesting example is that of the generation of a front from a north–south temperature gradient distorted by a constant vortex (Lynch, Pers. Comm., 2010). An example Matlab code for this case can be found at http://mathsci.ucd.ie/met/msc/index.php?view=MatLab/main.txt

On a different scale, a mass participation exercise, involving several hundred people, along the lines of Richardson's original daydream, might be a fantastic attention-grabbing communication opportunity for meteorological science. Perhaps the Royal Albert Hall might be a potential venue!

The story of Richardson and WPNP is also an interesting lesson in science communication and the acceptance of novel ideas. Only about 500 copies of WPNP were sold and several reviewers suggested the book was difficult to understand (Ashford, 1985). Although Charney *et al.* (1950) were able to successfully apply numerical techniques to make a numerical forecast on the ENIAC computer, *the results from numerical weather prediction only really began to dominate those derived by the Bergen approach for 1- to 3-day forecasts in the middle 1980s* (Hunt, 1998).

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