Remembering Bertram Broberg

The ENIAC Forecasts: A Recreation

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Swedish National Committee for Mechanics
Irish Society for Scientific & Engineering Mechanics
Outline of the lecture

- Introduction
- Preparing the Ground
- The First Computer Forecast
- Into Operations
- Recreating the Forecasts
Pioneers of Scientific Forecasting

Cleveland Abbe, Vilhelm Bjerknes, Lewis Fry Richardson
By 1890, the American meteorologist Cleveland Abbe had recognized that:

*Meteorology is essentially the application of hydrodynamics and thermodynamics to the atmosphere.*

Abbe proposed a mathematical approach to forecasting.
Vilhelm Bjerknes

A more explicit analysis of weather prediction was undertaken by the Norwegian scientist Vilhelm Bjerknes.

He identified the two crucial components of a scientific forecasting system:

- Analysis
- Integration
Lewis Fry Richardson

The English Quaker scientist Lewis Fry Richardson attempted a direct solution of the equations of motion.

He dreamed that numerical forecasting would become a practical reality.

Today, forecasts are prepared routinely using methods similar to Richardson’s . . .

. . . his dream has indeed come true.
Richardson’s Forecast Factory

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Richardson’s Forecast Factory

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64,000 Computers: The first Massively Parallel Processor
Crucial Advances, 1920–1950

- Dynamic Meteorology
  - Quasi-geostrophic Theory
- Numerical Analysis
  - CFL Criterion
- Atmospheric Observations
  - Radiosonde
- Electronic Computing
  - ENIAC
The Meteorology Project

Project established by John von Neumann in 1946.

Objective of the project:
To study the problem of predicting the weather using a digital electronic computer.

A Proposal for Funding listed three “possibilities”:

- New methods of weather prediction
- Rational basis for planning observations
- Step towards influencing the weather!
The ENIAC
The **ENIAC** was the first multi-purpose programmable electronic digital computer. It had:

- 18,000 vacuum tubes
- 70,000 resistors
- 10,000 capacitors
- 6,000 switches
- Power: 140 kWatts
ENIAC was a **decimal machine**. No high-level language. Assembly language. Fixed-point arithmetic: \[-1 < x < +1\].

10 registers, that is,

Ten words of high-speed memory.

**Function Tables:**
624 6-digit words of “ROM”, set on ten-pole rotary switches.

“Peripheral Memory”:

**Punch-cards.**

**Speed:** FP multiply: 2ms (say, 500 Flosps).

**Access to Function Tables:** 1ms.

**Access to Punch-card equipment:** You can imagine!
Evolution of the Project

- **Plan A: Integrate the Primitive Equations**
  
  *Problems similar to Richardson’s would arise*

- **Plan B: Integrate baroclinic Q-G System**
  
  *Too computationally demanding*

- **Plan C: Solve barotropic vorticity equation**
  
  *Very satisfactory initial results*

\[
\begin{bmatrix}
\text{Absolute Vorticity} \\
\text{Vorticity}
\end{bmatrix} = \begin{bmatrix}
\text{Relative Vorticity} \\
\text{Vorticity}
\end{bmatrix} + \begin{bmatrix}
\text{Planetary Vorticity}
\end{bmatrix} \quad \eta = \zeta + f.
\]

- The atmosphere is treated as a single layer.
- The flow is assumed to be nondivergent.
- Absolute vorticity is conserved.

\[
\frac{d(\zeta + f)}{dt} = 0.
\]

This equation looks deceptively simple. But it is nonlinear:

\[
\frac{\partial}{\partial t} [\nabla^2 \psi] + \left\{ \frac{\partial \psi \, \partial \nabla^2 \psi}{\partial x \, \partial y} - \frac{\partial \psi \, \partial \nabla^2 \psi}{\partial y \, \partial x} \right\} + \beta \frac{\partial \psi}{\partial x} = 0,
\]
Charney, Fjørtoft, von Neumann

Charney  Fjørtoft  von Neumann

Numerical integration of the barotropic vorticity equation

*Tellus, 2, 237–254 (1950).*
Solution method for BPVE

\[
\frac{\partial \zeta}{\partial t} = J(\psi, \zeta + f)
\]

1. Compute the Jacobian
2. Step forward (Leapfrog scheme)
3. Solve Poisson equation \( \nabla^2 \psi = \zeta \) (Fourier expansion)
4. Go to (1).

- Timestep : \( \Delta t = 1 \) hour
- Gridstep : \( \Delta x = 750 \) km (at North Pole)
- Gridsize : \( 19 \times 16 \approx 300 \) points
- Elapsed time for 24 hour forecast: About 24 hours.

Each forecast involved punching about 25,000 cards. Most of the time was spent handling card-decks.
Flow-chart for the computations.

ENIAC: First Computer Forecast
Key people in the ENIAC endeavour
The Joint Numerical Weather Prediction Unit was established on July 1, 1954:

- **Air Weather Service of US Air Force**
- **The US Weather Bureau**
- **The Naval Weather Service.**

Operational numerical weather forecasting began in **May, 1955**, using a three-level quasi-geostrophic model.
The ENIAC integrations have been recreated using:

- A MATLAB program to solve the BVE
- Data from the NCEP/NCAR reanalysis

The matlab code is available on the author’s website
http://maths.ucd.ie/~plynch/eniac
The initial dates for the four forecasts were:

- January 5, 1949
- January 30, 1949
- January 31, 1949
- February 13, 1949

When a reconstruction was first conceived, a laborious digitization of hand-drawn charts appeared necessary.
The NCEP/NCAR 40-Year Reanalysis Project


Bulletin of the American Meteorological Society, March, 1996
The NCEP–NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation


Editor’s note: This article is accompanied by a CD-ROM that contains the complete documentation of the NCEP–NCAR Reanalysis and all of the data analyses and forecasts. It is provided to members through the sponsorship of SAIC and GSC.

Bulletin of the American Meteorological Society, February, 2001
\[ \frac{d}{dt}(\zeta + f) = \frac{\partial \zeta}{\partial t} + \mathbf{V} \cdot \nabla (\zeta + f) = 0 \]

\[ \mathbf{V} = (g/f)\mathbf{k} \times \nabla z; \quad \mathbf{V} = \mathbf{k} \times \nabla \psi. \]

\[ \zeta = g\nabla \cdot (1/f) \nabla z = (g/f) \nabla^2 z + \beta u/f \]

\[ \mathbf{V} \cdot \nabla \alpha = -\frac{g}{f} \frac{\partial z}{\partial y} \frac{\partial \alpha}{\partial x} + \frac{g}{f} \frac{\partial z}{\partial x} \frac{\partial \alpha}{\partial y} = -\frac{g}{f} J(\alpha, z). \]

\[ \frac{\partial}{\partial t} (\nabla^2 z) = J \left( \frac{g}{f} \nabla^2 z + f, z \right) \]

The barotropic vorticity equation
The computational grid for the integrations
ENIAC Forecast for Jan 5, 1949

a

b

c
d
Recreation of the Forecast

(A) INITIAL ANALYSIS

(B) VERIFYING ANALYSIS

(C) ANALYSED & FORECAST CHANGES

(D) FORECAST HEIGHT
<table>
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<tr>
<th>Case</th>
<th>Mean error (Fcst.)</th>
<th>Mean error (Pers.)</th>
<th>RMS error (Fcst.)</th>
<th>RMS error (Pers.)</th>
<th>S1 Score (Fcst.)</th>
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Mean error (bias), RMS error and S1 scores
Charney et al used the equation in the height form

\[ \frac{\partial}{\partial t} (\nabla^2 z) = J \left( \frac{g}{f} \nabla^2 z + f, z \right) \]

They could have used the streamfunction form

\[ \frac{\partial}{\partial t} (\nabla^2 \psi) = J \left( \nabla^2 \psi + f, \psi \right) \]

They would then not have to have ignored the beta-term
<table>
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<th>$\psi$-EQN</th>
<th>z-EQN</th>
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Scores for height equation and streamfunction equation
George Platzman, during his Starr Lecture, re-ran an ENIAC forecast. The algorithm was coded on an IBM 5110, a desk-top machine. The program execution was completed during the lecture (about one hour). The program eniac.m was run on a Sony Vaio (model VGN-TX2XP). The main loop of the 24-hour forecast ran in about 15 ms.
Thank You