The Amount of Data in Science Disciplines

Roy Jenne
25 Aug 2000

- Information about data volume in several science areas.

- The volume from selected high rate instruments.

- The volume of model data from fast computers.
Selected Information About the Amount of Data

Roy Jenne
21 Aug 2000

Several sections below give information about the amount of data in meteorology and in other science areas.

1. NRC study on long-term data retention
   ▪ This is a useful study

2. Two US large datasets: GOES satellites and weather radars
   ▪ These drive a lot of the data volume in meteorology
   ▪ Weather radars now give 56 TB/year (but 5 TB/yr if compressed)
   ▪ 21 years of GOES data is 257 TBytes (about 125 TBytes if compressed)

3. Data from NASA EOS satellites
   ▪ Main start of Dec 1999; about 200 to 300 TB per year.

4. Data Support (our NCAR group) activities and plans

5. Lots of data comes from computer models
   ▪ Show the amount of data stored at three computer modeling centers (NCAR, ECMWF, and NASA Goddard).

6. Handle lots of data and control costs

7. Astronomy and planetary
   ▪ Cosmic flood (Astronomy magazine, June 1999)
   ▪ The Sloan sky will give 40 TB over 5 years (or 8 TB per year)
   ▪ Europe’s science machine. Four large telescopes will give a combined total of 7.3 TBytes per year (Astronomy magazine, June 1999)

8. Physicists and astronomers
   ▪ Prepare for a data flood (Science magazine, 3 Dec 1999, p 1840)

9. Biology: Drowning in data
   ▪ From The Economist, June 26, 1999, page 93

10. Managing STACS and STACS of data
    ▪ See the 2-page article (Computerworld, June 12, 2000)
    ▪ Clas starts in 1997 and gives 300 TB/year
    ▪ Phenix starts in 1999 and gives 600 TB/year
    ▪ Atlas starts in 2004 and gives 2000 TB/year

11. Using tapes to send large amounts of data
Study on the Long-term Retention of Selected Scientific and Technical Records of the Federal Government

Working Papers

Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1995
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STEERING COMMITTEE FOR THE STUDY ON THE LONG-TERM RETENTION OF SELECTED SCIENTIFIC AND TECHNICAL RECORDS OF THE FEDERAL GOVERNMENT

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III

Report of the Atmospheric Sciences Data Panel

Werner Baum,* Marjorie Courain, William Haggard, Roy Jenne, Kelly Redmond, and Thomas Vonder Haar

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1 INTRODUCTION

Scientific data and records often have uses that continue long past their original purpose. The purpose of this report is to assist a steering committee providing advice to the National Archives and Records Administration (NARA), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA) regarding the long-term retention of scientific and technical records of the federal government related to the atmospheric sciences. This report of the Atmospheric Sciences Data Panel has concentrated on the particular data archiving problems of its disciplines, largely meteorology and climatology. Most of these problems are generic to the earth sciences. However, the atmospheric sciences are both blessed and plagued by perhaps the largest data sets of any scientific discipline. Some of the small, but important, data sets from the atmospheric sciences consist of some of the longest time series in any science of data acquired contemporaneously with the events measured (in contrast to evidence of past events). The panel has concentrated on procedures needed for ensuring the survival of irreplaceable environmental data that may be needed in the future.

*Panel chair. The authors' affiliations are, respectively, Florida State University; Consultant, East Orange, New Jersey (deceased, January 14, 1994); Climatological Consulting Corporation; National Center for Atmospheric Research; Desert Research Institute; and Colorado State University.
<table>
<thead>
<tr>
<th>Type of Data Set</th>
<th>Comments</th>
<th>Dates</th>
<th>Years</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmospheric In Situ Observations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World upper air</td>
<td>Two times per day, 1,000 stations</td>
<td>1962-1993</td>
<td>32</td>
<td>25 GB</td>
</tr>
<tr>
<td>World land surface</td>
<td>Every 3 hours, 7,500 stations</td>
<td>1967-1993</td>
<td>27</td>
<td>60 GB</td>
</tr>
<tr>
<td>World ocean surface</td>
<td>Every 3 hours (~40,000 observations per day)</td>
<td>1854-1993</td>
<td>139</td>
<td>15 GB</td>
</tr>
<tr>
<td>World observations during First GARP Global Experiment</td>
<td>Surface and aloft, but not satellite</td>
<td>1978-1979</td>
<td>1</td>
<td>10 GB</td>
</tr>
<tr>
<td>U.S. surface</td>
<td>Daily, now 9,000 stations</td>
<td>1990-1993</td>
<td>94</td>
<td>15 GB</td>
</tr>
<tr>
<td><strong>Selected Analyses</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mostly global)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main National Meteorological Center analyses</td>
<td>Two times per day, increasing at 4 GB/year</td>
<td>1945-1993</td>
<td>48</td>
<td>50 GB</td>
</tr>
<tr>
<td>National Meteorological Center advanced analyses</td>
<td>Four times per day, increasing at 19 GB/year</td>
<td>1990-1993</td>
<td>4</td>
<td>58 GB</td>
</tr>
<tr>
<td>National Center for Atmospheric Research's ocean observations and analyses</td>
<td>Thirty-eight data sets</td>
<td></td>
<td></td>
<td>8 GB</td>
</tr>
<tr>
<td>European Center for Medium Range Weather Forecasting advanced analyses</td>
<td>Four times per day, increasing at 8 GB/year</td>
<td>1985-1993</td>
<td>9</td>
<td>76 GB</td>
</tr>
<tr>
<td><strong>Selected Satellites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA geostationary satellites</td>
<td>Half-hour, visible and infrared</td>
<td>1978-1993</td>
<td>16</td>
<td>130 TB</td>
</tr>
<tr>
<td>NOAA polar orbiting satellites</td>
<td>1978-1993</td>
<td>15</td>
<td>720 GB</td>
<td></td>
</tr>
<tr>
<td>Sounders (TIROS Operational Vertical Sounder)</td>
<td>1978-1993</td>
<td>15</td>
<td>720 GB</td>
<td></td>
</tr>
<tr>
<td>Advanced Very High Resolution Radiometer (4-km coverage, 5 channel)</td>
<td></td>
<td></td>
<td>5 TB</td>
<td></td>
</tr>
<tr>
<td>NASA Earth Observing Satellite-AM</td>
<td>In development, 88 TB/year, level-1 data</td>
<td>1998-</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>U.S. Radar Data</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Domains of 30 to 60 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Next Generation Radar System (NEXRAD)</td>
<td>650 GB per radar each year, 104 TB/year for 160-site system</td>
<td>1997-</td>
<td></td>
<td>100s TB</td>
</tr>
</tbody>
</table>

Notes: Many other atmospheric data sets have volumes of only 1 to 500 MB.  
1 MB (megabyte) = 10^6 bytes; 1 GB (gigabyte) = 10^9 bytes; 1 TB (terabyte) = 10^{12} bytes.

*First radars were deployed in 1993.

Historical Climate Network (HCN) is a specialized subset of the Cooperative Climate Network with data from selected stations that have a long record from sites where the surrounding environment has remained stable for decades; these data are important particularly for detecting climate trends within the United States.

In addition to national observational programs, numerous efforts take place at the regional and local levels. Some of these are federal, some are state-funded, some are through regional commissions, and a few are private. Meyer and Hubbard (1992) identified nearly 100 such networks in the United States, encompassing over 600 stations. Since that report another 100-200 sites have been instrumented. These other networks mostly have been deployed in support of a principal operational mission, although they also may have other "accidental" applications.
<table>
<thead>
<tr>
<th>Observing System</th>
<th>Present Station Count</th>
<th>Quantities Measured</th>
<th>Observing Interval</th>
<th>Record Length (years)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Weather Service (NWS) surface observations</td>
<td>1000</td>
<td>Pressure, temperature, humidity, precipitation, cloud cover, visibility, wind</td>
<td>1 hour</td>
<td>45</td>
<td>Some quantities are sampled more frequently.</td>
</tr>
<tr>
<td>U.S. Cooperative Network</td>
<td>5200*</td>
<td>Minimum and maximum temperature precipitation precipitation</td>
<td>1 day</td>
<td>10-100</td>
<td>*All temperature sites have rain gauges, but not all precipitation sites have temperature gauges. There are some river-stage gauges in the network.</td>
</tr>
<tr>
<td></td>
<td>7800*</td>
<td></td>
<td>1 day</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
<td>1 hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U.S. upper air</td>
<td></td>
<td>Temperature, humidity, winds</td>
<td>12 hours</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>World synoptic</td>
<td>8000</td>
<td>See list for NWS surface</td>
<td>3 hours</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>World upper air</td>
<td>1000</td>
<td>Temperature, humidity, winds</td>
<td>12 hours</td>
<td>45</td>
<td>Some stations only once daily.</td>
</tr>
<tr>
<td>Aircraft reports</td>
<td></td>
<td>Temperature, winds</td>
<td>45</td>
<td></td>
<td>Over 1 million observations per year are obtained.</td>
</tr>
<tr>
<td>Ships of opportunity</td>
<td>varies</td>
<td></td>
<td>3 hours</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Snowpack Telemetry (SNOTEL)</td>
<td>560</td>
<td>Snow water content, precipitation, temperature</td>
<td>1 day</td>
<td>15</td>
<td>Run by the Soil Conservation Service.</td>
</tr>
<tr>
<td>Remote Automated Weather Stations</td>
<td>600</td>
<td>Temperature, pressure, humidity</td>
<td>1 hour</td>
<td>9</td>
<td>Run by the Bureau of Land Management and the U.S. Forest Service.</td>
</tr>
<tr>
<td>Non-federal networks</td>
<td>700</td>
<td>Temperature, humidity, wind, solar radiation, soil moisture</td>
<td>15 minutes to 1 hour</td>
<td>10 or less</td>
<td>See Meyer and Hubbard 1992.</td>
</tr>
<tr>
<td>Automated Surface Observing System (ASOS)</td>
<td>30</td>
<td>Temperature, wind, visibility, cloud ceiling, precipitation</td>
<td>1 minute</td>
<td>1</td>
<td>The number of stations will soon grow to more than 400.</td>
</tr>
</tbody>
</table>

Note: All numbers are approximate.
Two Large Datasets: GOES Satellites and Weather Radars

Roy Jenne
18 Aug 2000

The datasets of GOES satellite data and weather radar data are two of the large datasets in atmospheric sciences. It turns out that they are easier and cheaper to handle if some data compression is used.

1. Data from US Geosynchronous Satellites (1979 – on)

The US has a long digital archive of data from NOAA geosynchronous satellites because of pioneering efforts by SSEC at the University of Wisconsin. They started storing some data around 1973. Since conventional tape technology was then too expensive and cumbersome to store this much data, they invented a different method using Sony recorders.

Their data archives are now mainly for 1979 – 2000 – on, now about 22 years. In Oct 1999, their total volume of archived data was 257 TBytes. This is the volume before any compression. In Sep 1997, they started to capture the new data onto IBM 3590 tapes, not the cassette tapes as before. The data from satellites during the past few years has 10-bit precision (the data has good packing, no compression). They invented a way to compress it by a factor of 2.2 to 1, with no loss. The older data only had about 8-bit precision. It may give a compression ratio of about 2.0 to 1. It will still be a big job to copy data from all of the old cassette tapes to new media. Some of this work has been done. At one time they had 38,250 video-cassette tapes in the archive. Some notes:

- The data volume from 1979 – Oct 99 is 257 TBytes.
- By using loss-less compression, the volume of the 257 TBytes will be reduced to about 125 TBytes in the archive.
- The reduced volume decreases archive costs and it decreases data transfer costs. The U of Wisc has a plan with attractive costs to copy this large archive to new media.
- Software is needed to easily decompress the data.

→ Conclusion: This large archive is cut in half by using compression. This is a big savings. Then users need simple decompress software. And it must be possible to still access the data 30 years from now.

2. Data from Weather Radars, A High Volume

During the early 1990s, the US installed 158 new weather radars, and 120 of these are at sites belonging to the National Weather Service. If all of the radar scan data is saved from all 158 radars, the data volume would be about 100 Terabytes per year. The data are mainly saved on Exabyte tapes at the radars, and are sent to Asheville to be copied. About 1995, I was told that the hardware compression on Exabyte drives was giving a very good compression of about 8 to 1. But then the full volume still has to flow through the computer data channels, so that processing is slow.

During about 1999, they found that they could achieve nearly 15 to 1 data reduction using software compression. In this case, the processing and the data delivery can be much faster because the data remains compressed when it is in the computer channels.

There are reasons that the archive does not receive all of the radar data. During 1998, they actually received about 56 TBytes of data. Some notes are:

- The total volume of data to archive is about 56 TBytes per year.
- Assume that they can achieve 12 to 1 compression.
- This would reduce the data to archive to about 4.7 TBytes per year.

→ Conclusion: The data compression gives big benefits. Do not make any general format choices. That would make these gains impossible. The user will need decompress software that can be easily used.
Data from NASA EOS Satellites

Roy Jenne
23 Aug 2000
Rev Sep 7

- TRMM launched Nov 18, 1997
- Landsat-7 was launched about Apr 1999
- The big EOS-AM satellite was launched Dec 1999
  - Now called Terra

The Data Volume

An old sheet of mine which gives the data rates for each main instrument is included.

- But the total volume of EOS primary data is about 71 TB per year.

- The data products increase this to 319 TBytes per year in early plans (1992), but I think that the amount of products are being scaled back.
  - My guess is that the total volume may end up as 200 to 300 TB per year.
MEMO TO: Distribution  
FROM: Roy Jenne  
SUBJECT: Data Rates for EOS

1. Data Rates from EOS

The July 1991 requirements specification for the EOSDIS Core System gave daily data rates for the 15 core instruments as follows:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Data from Spacecraft (Gbytes/day)</th>
<th>Total Data for Archive (Gbytes/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS</td>
<td>21.60</td>
<td>85.72</td>
</tr>
<tr>
<td>ASTER</td>
<td>89.64</td>
<td>380.65</td>
</tr>
<tr>
<td>MODIS-N</td>
<td>58.32</td>
<td>284.06</td>
</tr>
<tr>
<td>MODIS-T</td>
<td>16.20</td>
<td>101.18</td>
</tr>
<tr>
<td>Other 11 instruments</td>
<td>9.27</td>
<td>22.08</td>
</tr>
<tr>
<td>TOTAL</td>
<td>195.03</td>
<td>873.69</td>
</tr>
<tr>
<td>Annual rate</td>
<td>(TB/year)</td>
<td>(TB/year)</td>
</tr>
<tr>
<td></td>
<td>71.19</td>
<td>318.90</td>
</tr>
</tbody>
</table>

The volume of the total EOS archive in the above table is much higher than the volume of data from the satellite, because NASA usually assumed two more versions of all of the basic data. And each of these versions is in a format that increases the volume of the basic satellite data by about 46%. Some volume increase is probably necessary to include location data. This much increase usually is not necessary, or desirable, when handling high-rate data.

2. Data on the NCAR Mass Store

The total data volume on the NCAR mass store has been as follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>Volume (Tbytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 1986</td>
<td>2.0</td>
</tr>
<tr>
<td>12 Aug 1990</td>
<td>14.43</td>
</tr>
<tr>
<td>3 Aug 1992</td>
<td>27.27</td>
</tr>
</tbody>
</table>
The Increasing Volume of Data

- The amount of data is increasing rapidly. There are many stories about this.
- It does take work to deal with lots more data.
- People now use data stories to sell huge new programs.
- The level of data “hype” is much too high. The hype can get in the way of good data programs and good management.
- And hype can be used to build data empires.
- We want interesting data stories and we want good programs to handle the data.

Note: People make decisions about how much data to generate. People should not be allowed to generate lots of data and then use the most expensive methods to take care of it.

Roy Jenne
12 Sep 2000
Data Support Activities and Plans

Roy Jenne, Sep 1999,
Revised 16 Jun 2000

- Reanalysis: Help huge projects that will analyze the world’s atmosphere for 50-years, each 6-hours (determine temperature, winds, radiation, etc. at 28 levels), and soil conditions.
  - We have delivered the world’s surface and upper air observations for 50 years (1948 – 1997) to help these projects.
  - We help deliver the output to users.
  - We are working to prepare more observations.

- Handle data from three newer mesoscale models (for North America).

- Help many climate assessment research projects (crops, rivers, forests, etc.)

- Help users obtain access to many datasets.
  - Bulk data delivery
  - Internet server

- Summary of the types of data we have.

- Develop new ways to handle documents.

The next 4 pages.
What Types of Data are in DSS Archives?
(By Roy Jenne and Dennis Joseph, NCAR, Sep 1999)

Our Data Support Section at NCAR started work in 1965 and has been working on various large projects, building the data archives and helping users ever since. The Data Support Section (DSS) maintains a large, organized archive of computer-accessible research data that is made available to scientists around the world. The archive represents an irreplaceable store of observed data and analyses and is used for major national and international atmospheric and oceanic research projects.

There are now over 500 distinct datasets in the archive, ranging in size from less than 1MB to over 1TB. The total volume of data in the DSS archive was 2.4 terabytes (TB) in August 1990 and 10 TB in October 1998. We have been adding a lot of reanalysis data and other analyses.

A. A broad summary of our data holdings follows (valid Oct 1998):

<table>
<thead>
<tr>
<th>Count of Main Datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Output data from NCEP/NCAR reanalysis, 50 years (4X/day)</td>
</tr>
<tr>
<td>a. Volume about 3.5 TB for NCEP plus ECMWF</td>
</tr>
<tr>
<td>2. Separate CD-ROMs from reanalysis</td>
</tr>
<tr>
<td>a. Volume on 27 unique CDs is 18 GB</td>
</tr>
<tr>
<td>3. Observations for reanalysis (in 1997, surface and upper air data)</td>
</tr>
<tr>
<td>a. About 180 GB, not level 1 satellite data</td>
</tr>
<tr>
<td>4. Mesoscale model data (North America)</td>
</tr>
<tr>
<td>5. Datasets of surface observations and related data</td>
</tr>
<tr>
<td>6. Datasets about the earth’s surface</td>
</tr>
<tr>
<td>7. COADS world ship and buoy data</td>
</tr>
<tr>
<td>8. Other datasets (not COADS) for ocean work</td>
</tr>
<tr>
<td>9. Various analysis grids</td>
</tr>
<tr>
<td>10. Main operational analyses from NCEP (was NMC)</td>
</tr>
<tr>
<td>11. Main operational analyses from ECMWF</td>
</tr>
<tr>
<td>12. Climate model data for assessment studies</td>
</tr>
<tr>
<td>13. Climate trends datasets</td>
</tr>
<tr>
<td>14. Climatology and circulation statistics</td>
</tr>
<tr>
<td>15. Cloud data</td>
</tr>
<tr>
<td>16. Stratospheric datasets, mostly gridded</td>
</tr>
<tr>
<td>17. Datasets for the very high atmosphere (70-1000 Km)</td>
</tr>
<tr>
<td>18. Main radiance data from satellites</td>
</tr>
<tr>
<td>19. Data for the FGGE year (1979)</td>
</tr>
</tbody>
</table>

Comment: The above list has about 464 datasets. Our actual list of datasets has over 500 items, but sometimes several logically different files of data are held within one dataset folder.
The Volume of Selected Observations and Analyses

Roy Jenne
14 Oct 1999
Rev Apr 2000
17 Apr

Our Data Support Section had 12,000 GB of data on the mass store in Sep 1999. We present information about the volume of our datasets for several reasons. The data volume can be matched with information about storage technology to see how hard it is to store the data, and how hard it is to move the data from our archive to a user. In other sections of this text, we will discuss changes in technology over time. Some of the component datasets follow:

1. An up-front summary of data volume (in Sep 99).

This list of data adds up to about 8500 GB compared with our total of 12,000 GB on the mass store in Sep 1999.

<table>
<thead>
<tr>
<th>Dataset Description</th>
<th>Primary (GB)</th>
<th>Total on MSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Data from NCEP/NCAR reanalysis</td>
<td>2530</td>
<td>3143</td>
</tr>
<tr>
<td>b. Data from NCEP-2 reanalysis</td>
<td>e900</td>
<td>1</td>
</tr>
<tr>
<td>c. Select surface and UA observations, 1962 – on</td>
<td>164.3</td>
<td>345</td>
</tr>
<tr>
<td>d. Meso scale analyses and forecasts</td>
<td>566.6</td>
<td>930</td>
</tr>
<tr>
<td>e. Advanced analyses from NCEP, global</td>
<td>191.4</td>
<td>383</td>
</tr>
<tr>
<td>f. Main satellite sounders</td>
<td>636</td>
<td>1380</td>
</tr>
<tr>
<td>g. NOAA GAC (4 km global satellite)</td>
<td>e2100</td>
<td></td>
</tr>
<tr>
<td>h. NOAA 1 km satellite data</td>
<td>210.3</td>
<td>210.3</td>
</tr>
<tr>
<td>i. Other sets listed below</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>j. Other sets not listed</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>

2. Volume of data from NCEP/NCAR reanalysis

This is for 1948 – on (51.3 years). The observations with model tags are 273 GB of this. All of the grids on 2.5° pressure surfaces are 158 Gbytes.

- The most used reanalysis data have 6 to 15 GB per year.

Extra data from reruns: There were about 11 years of reruns. We still have the poor first version (613 GB). This is in addition to the above volume and most will be thrown away.

- So total data on mass store is 3143 GB

3. Data from NCEP-2 reanalysis (1979 – 98)

Oct 99: Not completed yet; not at NCAR yet

4. Selected volume of some world surface and upper air observations, 1962 – on

<table>
<thead>
<tr>
<th>Year Period</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. World upper air observations from NCEP</td>
<td>3.36 GB</td>
</tr>
<tr>
<td>b. World 3-hr surface (NCEP), Jul 1976 – 12/98</td>
<td>53.88 GB</td>
</tr>
<tr>
<td>c. Navy 3-hr surface and UA 01/71 – 12/96</td>
<td>10.08 GB</td>
</tr>
</tbody>
</table>
f. The data volume in this section about observations

These world surface and upper air data above have a total volume of 164.3 Gbytes. There is a lot of duplication between the data sources, but most sources have a lot of data not in the other sources.

- Years of UA data here 1962 – 99
- Years of surface data 1967 – 99

These observed data mostly have two versions, one for reanalysis, plus partial backup. Factor is about 2.1.
- So total volume is about 345 GB.

5. Climatology and circulation statistics

~15 datasets (update this)

6. Ocean datasets

~40 datasets

7. FGGE year observations and older FGGE analyses

~8 datasets

Note: The best analyses are from recent big reanalysis; thus FGGE analyses are now just kept for history. See other.

8. Main datasets of satellite sounders, Level 1b (1972 – 99)

a. All NOAA VTPR sounding data (Nov 1972 – 28 Feb 1979)

b. NOAA TOVS sounders (Nov 78 – 1999), level 1, 20.8 years

At NCAR: Nov 78 through Mar 92, 13.4 years (one copy)

SSU Subset (stratosphere) 631 GB
MSU Subset (microwave) 68.4 GB

Note 1: We got 9 months of TOVS twice. The two copies aren’t quite identical. With the extra months, the total volume is 665.8 GB.
Note 2: The total archive volume of TOVS (631 + 68 + 15 + 665 GB) is 1380 GB.

9. Data from Mesoscale analyses and forecasts

a. LFM model data for 31 Oct 1971 – Dec 1995 (24.2 years) then it quits ~20 GB
b. NGM model data for Oct 1984 – 1999 (14.5 years), ~880 MB/yr ~12.8 GB
c. Data from GCIP models (1995 – on). Status in Oct 1999:

<table>
<thead>
<tr>
<th>GCIP Summary</th>
<th>Model</th>
<th>Range</th>
<th>Years</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS609.1</td>
<td>MAPS</td>
<td>Aug 96 – Aug 99</td>
<td>3.02</td>
<td>136.0 GB</td>
</tr>
<tr>
<td>DS609.2</td>
<td>Eta</td>
<td>May 95 – Jul 99</td>
<td>4.25</td>
<td>330.0 GB</td>
</tr>
<tr>
<td>DS609.3</td>
<td>GEM</td>
<td>Jan 97 – Jun 99</td>
<td>2.50</td>
<td>28.6 GB</td>
</tr>
<tr>
<td>-</td>
<td>Maps, big</td>
<td>Jan 98 –</td>
<td>1.42</td>
<td>39.2 GB</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>533.8 GB</strong></td>
</tr>
</tbody>
</table>

On the MSS:
- Eta data is stored twice; total volume is 864 GB (Oct 99)
- Total with LFM and NGM is 897 GB

10. Data for very high atmosphere (70 – 1000 km), mostly 1966 – 99

This includes many datasets for CEDAR: several types of radars, solar indices, some model data (~57 datasets)

11. NOAA GAC satellite data: world 4 km, 5-chan data

Period Nov 78 – 1999, 20.8 years
At NCAR: About 6 years
(GAC is not double-stored at NCAR)
Note: The actual amount of GAC where the files are mixed in with TOVS is 1032.8 GB. This is included in the total of about 2100 GB.

12. NOAA 1 km data at NCAR

Gilmore Creek 1979 (4 months) and 1982 – 84 (36 months) 210.3 GB

13. Advanced archives from NCEP global operations, 1990 – on

This archive has the analyses and forecasts from global operational runs. It includes the analyses in sigma coordinates.

<table>
<thead>
<tr>
<th>Set</th>
<th>Type</th>
<th>Period</th>
<th>Years</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>84.0</td>
<td>MRF 10-day forecast</td>
<td>Jan 90 – Feb 99</td>
<td>9.2</td>
<td>42.7 GB</td>
</tr>
<tr>
<td>84.2</td>
<td>Upper Air Sigma-Spectral</td>
<td>Sep 90 – Feb 99</td>
<td>8.5</td>
<td>84.7 GB</td>
</tr>
<tr>
<td>84.5</td>
<td>Flux fields incl. Precip.</td>
<td>Mar 90 – Feb 99</td>
<td>9.3</td>
<td>64.0 GB</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>191.4 GB</strong></td>
</tr>
</tbody>
</table>

Data has backup; total on MSS is 383 Gbytes.
Lots of Data Comes from Computer Models

- Weather analysis and forecast models
- Climate models, etc.
- More computing power, then more data

A. Information about data stored at 3 centers is given
   a. NCAR
   b. ECMWF, European Center (in England)
   c. Main computers at NASA Goddard

B. So see the next 3 pages

Roy Jenne
21 Aug 2000
Data Support Activities and Plans, 1999 – 2001

The Data Support Section (DSS) maintains a large, organized archive of computer-accessible research data that is made available to scientists around the world. The archive represents an irreplaceable store of observed data and analyses and is used for major national and international atmospheric and oceanic research projects. The DSS group started working in 1965 and has been working on large projects and building the data archives ever since.

There are now about 500 distinct datasets in the archive, ranging in size from less than 1 MB to over 1 TB. The total volume of data in the DSS archive was 2.4 terabytes in August 1990 and 13.9 terabytes in Aug 2000. We have been adding a lot of reanalysis data and other analyses. The change of data storage with time has been as follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>Data Support Section</th>
<th>Total NCAR Mass Store</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bit Files</td>
<td>Volume</td>
<td>Bit Files</td>
</tr>
<tr>
<td>13 Aug 1990</td>
<td>61,335</td>
<td>2.437 TB</td>
<td>---</td>
</tr>
<tr>
<td>4 Aug 1991</td>
<td>65,518</td>
<td>2.689 TB</td>
<td>715,000</td>
</tr>
<tr>
<td>3 Aug 1992</td>
<td>80,538</td>
<td>3.085 TB</td>
<td>1,060,000</td>
</tr>
<tr>
<td>Aug 1993</td>
<td>103,314</td>
<td>4.072 TB</td>
<td>1,351,271</td>
</tr>
<tr>
<td>15 Sep 1994</td>
<td>119,703</td>
<td>4.751 TB</td>
<td>1,849,466</td>
</tr>
<tr>
<td>14 Feb 1995</td>
<td>123,877</td>
<td>5.085 TB</td>
<td>1,966,990</td>
</tr>
<tr>
<td>24 Jan 1996</td>
<td>137,680</td>
<td>5.950 TB</td>
<td>2,486,471</td>
</tr>
<tr>
<td>28 Aug 1996</td>
<td>143,340</td>
<td>6.770 TB</td>
<td>2,888,639</td>
</tr>
<tr>
<td>28 Feb 1997</td>
<td>151,509</td>
<td>7.513 TB</td>
<td>3,289,224</td>
</tr>
<tr>
<td>17 Oct 1997</td>
<td>159,945</td>
<td>8.482 TB</td>
<td>4,046,678</td>
</tr>
<tr>
<td>2 Sep 1998</td>
<td>167,073</td>
<td>10.032 TB</td>
<td>5,038,611</td>
</tr>
<tr>
<td>7 Sep 1999</td>
<td>185,608</td>
<td>11.942 TB</td>
<td>6,737,448</td>
</tr>
<tr>
<td>25 Aug 2000</td>
<td>192,404</td>
<td>13.875 TB</td>
<td>8,187,688</td>
</tr>
</tbody>
</table>

Note: Gene Harano says (in Sep99) that the total NCAR mass store archives are increasing at a rate of about 5 Tbytes per month. This is consistent with the growth (see above) from 147.4 TB to 206.9 TB (or 59.5 TB) in the 12.2 months from Sep 1998 to Sep 1999.

The DSS staff provides assistance and expertise in using the archive and help researchers locate data appropriate to their needs. Users may obtain copies of data by network access, on various tape media, or they may use data directly from the NCAR MSS. DSS staff also assist scientists by providing data access programs (to read and unpack data), other software for data manipulation, and dataset documentation. At a later point we will present more information about the use of the DSS archives.

A. Main Accomplishments During FY1999 (Oct 98 – Sep 99)

1. We delivered observations to ECMWF for reanalysis of years 1957 – 98. We delivered 90% of the necessary data. We are also doing checks on new data (for old years) and updates not available before. Several of the new datasets have also been sent.
Computing Power at ECMWF

(Royal Meteorological Society)

Roy Jenne
14 Dec 1998

Sustained computing power at ECMWF (Dec 1998)

Jun 1996: Fujitsu with 47 processors 30 Gflops
Oct 1997: Add Fujitsu with 116 processors (add 75 Gflops)
Dec 1998: 110 Gflops sustained power at ECMWF
Nov 1999: Add a third Fujitsu system; then about 200 Gflops sustained
July 2000: A Fujitsu upgrade to a total of 400 Gflops sustained
July 2000 – Dec 2002: 400 Gflops sustained

Note: The Cray C90-16 produced about 6 Gflops on their forecast models compared with about 5 Gflops on typical climate models. The above Gflops ratings are for forecast work.

The following message was sent to me in Dec 1998, from Adrian Simmons at ECMWF.

Roy,

We currently have on the floor a VPP700/116 and a VPP700E/48 (the 700E is as the 700, but with a slightly faster clock. The combined performance of these two machines is around 110 Gflops sustained. You are on the mark with the 75 Gflops you assign to the 116-processor system.

Our Council has recently approved a two-year extension of our contract with Fujitsu, so we now know the position to the end of 2002. We will take delivery of a third Fujitsu system in November 1999 which will take the net performance of our Fujitsu systems to around 200 Gflops sustained. This third system will be upgraded by 31 July 2000 to take the net performance to 400 Gflops sustained. We then stay at this level until the end of 2002.

Some of the details remain commercial-in-confidence, but if you have any further queries, I’ll be happy to give you what answers I can.

With best regards,
Adrian Simmons

Summary of ECMWF data storage:

<table>
<thead>
<tr>
<th>Date</th>
<th>Data Archived</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 Jan 1990</td>
<td>2.0 Tbytes</td>
</tr>
<tr>
<td>01 Dec 1992</td>
<td>10.0 Tbytes</td>
</tr>
<tr>
<td>01 June 1996</td>
<td>45 Tbytes</td>
</tr>
<tr>
<td>Oct 1998</td>
<td>~100 Tbytes</td>
</tr>
<tr>
<td>Oct 2000</td>
<td>Est. a little under 250 Tbytes</td>
</tr>
</tbody>
</table>
The Mass Store at Goddard Computing

Roy Jenne
9 Aug 2000

We will give some information about the mass store at Goddard, and the amount of computing power that they have.

This information is from Nancy Palm (301/286-8541 at Goddard) and is valid on 7 Aug 2000.

1. Data on Mass Store

   The unique data on the mass store:

   They now have 92.4 Terabytes of unique data and 4.32 million files. They are trying to make a second copy of most data but this is not completed. They now have a total of 162 TBytes in the mass store system.

2. Amount of Computing Power

   The main computer is a Cray T3E with 1024 processors. All of their computers have 854 Gflops peak and they usually achieve about 8 to 10% of this in real sustained computer power. Thus they have about 75 Gflops of real computing power. This power is producing archived data at the rate of about 4 TB per month.

75 Gflop of computing power.
162 TBytes on the mass store.
Handle Lots of Data and Control Costs

Roy Jenne
25 Aug 2000

We see that the amount of data that is being generated in the science disciplines is increasing rapidly. This fact is often used to claim that the budgets for data handling should be increased a lot. People should look at these arguments with rigor, because they are often wrong (but not always).

To handle a lot of data, we should ask how much the tasks need to cost if: (1) we use good engineering practices; (2) if we do the necessary work, but not all of the details that one could think of; (3) we note that the cost and effectiveness of computers and storage hardware has increased enormously and we use best practices to take advantage of these technology gains.

We should also note that when designing scientific instruments, there are usually options about how much data to generate. When these decisions are made, there should be some pressure to optimize the overall value of the data for science and operations.

If people can figure out a rather low-cost way to handle the data, then we do not have to worry much about the impact. But if data systems are allowed to become more expensive than necessary, then it impacts too much on budgets and on the other things we need to do as given in Table 1.

---

**TABLE 1. FUNCTIONS NEEDED FOR RESEARCH AND OPERATIONS**

1. Sensors to measure data (and satellite missions, etc.)
2. Data systems to store data and deliver it.
3. Computers to handle the calculations.
4. People that make other data products.
5. People who do research using the data, and who also do theoretical research.
6. People who develop and deliver operational products (such as forecasts from the National Weather Services). NCEP prepares computer forecasts.
7. Other infrastructures: buildings, libraries, etc.
Cosmic Flood

Forget megabytes and gigabytes — new telescopes are bringing terabytes of information to Earth. Will astronomers ever be able to study it all? Sharon Begley.

Photons that arrive night after night as relentlessly as a swollen Mississippi are overwhelming astronomers with a deluge of data.

by Sharon Begley

It's not that Susan McMahon wishes bad luck on any of her colleagues at the Jet Propulsion Laboratory. Nor is it that McMahon, manager of the planetary-data service at JPL, wasn't as eager as everyone else for the Galileo probe and orbiter to uncover Jupiter's secrets. But when a slew of radio commands failed to deploy Galileo's high-gain antenna in April 1991, McMahon couldn't stifle a little "Thank God!"

With data now arriving only via the low-gain antenna — at a significantly lower rate than it would have over the high-gain — McMahon's Planetary Data System can just about keep up with the incoming bytes. "If we'd had to deal with the data return from the high-gain antenna," says McMahon, "we couldn't have. As it is, we're hanging on by our fingernails. Once Cassini (the mission to Saturn) and Mars Global Surveyor start returning data, I don't even want to think about what's going to happen."

She'd better think about it anyway. Astronomers are being buried in a deluge of data, a flood of photons that arrives night after night as relentlessly as the Mississippi overflowing its banks. Researchers are almost (or already, depending whom you ask) overwhelmed by it, missing nuggets of gold that wash past in a sea of junk or get buried forever in the muck. Space missions are declared over, their budgets for data analysis zeroed out, long before all the nuggets are panned; data collected years ago sit in storage media — anybody out there remember seven-track magnetic tape? — for which the players are about as rare as slide rules. It will only get worse. The all-sky surveys underway or on the drawing boards — with names like 2MASS, MAP, ROSAT, GALEX and SDSS — will produce terabytes upon terabytes of data.

The Sloan Digital Sky Survey, for instance, which is using a new telescope at Apache Point, New Mexico, to map half the northern sky in five wavelengths from UV to the near infrared, will detect more than 200 million objects. It will create an archive of 40 terabytes, says astrophysicist and SDSS investigator Alexander Szalay of Johns Hopkins University. "Even before these big surveys, we have been just barely keeping our heads above water," says astrophysicist Robert Nichol of Carnegie Mellon University. "With the Sloan survey, the faucet is being opened and the deluge is starting."

If this were a movie, a spectral visitor would give us an admonitory preview of what could happen if astronomy doesn't get its data house in order. Consider the cautionary tale offered by the National Space Science Data Center, at NASA's Goddard Space Flight Center. Formed in the mid-1960s, NSSDC stores data from as far back as the 1960s Explorer missions, which collected space physics data on, for instance, the Van Allen radiation belts that girdle Earth. The data from about 1,000 experiments that flew on some 400 missions comes to 10 terabytes, says director Joseph King. The problem is how those 10 terabytes are stored. King rules a realm of 4- and 8-millimeter tapes; a few years ago he had 7-track tapes. Soon, no one will even know how to read them. "Are the bit representations in ASCII or IBM binary?" asks King. "We've got data from computers that are no longer around, and if you want to read those data someone would have to show you, bit by bit, what binary representation was being used." Soon there won't even be machines capable of playing the old archives — which is why King's staff is transferring everything they can to CD-ROMs and optical disks.
Why care about old data? “These archives include huge unmined data sets,” says King. When someone realizes that and tries to dig one up, though, it can be like trying to read hieroglyphics without the Rosetta stone. Data from the Apollo missions were stored on 12-inch magnetic tape reels, for instance. “The tapes wound up in some storage space the university got hold of in a high school basement,” recalls astronomer Floyd Herbert of the University of Arizona. “We were interested in some of the magnetic field data, but no one had a functioning (compatible) tape drive. We wound up copying the data onto 8 mm videotape, with software that lets you translate from one data storage medium to another. However, if we had waited a few more years we wouldn’t have been able to do even that.”

And that would be a colossal waste. “All of us in this business of data analysis say NASA doesn’t fund enough of it,” says Herbert. “If they did, they’d get a lot more out of what was so expensive to collect in the first place.” That’s become a common refrain. “There is some tendency, with NASA’s ‘faster, better, cheaper’ mantra, that the data analysis teams are getting less support,” says planetary astronomer William Hartmann of the Planetary Sciences Institute in Tucson. “So we have these massive databases but no one around to look at them.”

Once a mission is officially over, it is nearly impossible to get NASA funding to comb through the data. The assumption is that the cream has been skimmed. But Hartmann argues that old data can be good data. “Even with the Viking images there is interesting science to be done,” he says. “But there is no money to do it.” Hartmann himself would like to comb through all the Mars images in the archives and calculate crater densities: the more impact craters, the older the landform. Without financial support, he prays for student volunteers.

Even more basic than analyzing data sets is storing them, and astronomers may be in trouble here, too. Take Brian Skiff’s asteroid search at Lowell Observatory in Flagstaff, Arizona. Using a wide-field telescope with a digital detector, he scans the skies for near-Earth asteroids, especially those that might get too close for comfort. “We generate 8 gigabytes of data a night,” he says. “With data coming in at such a prodigious rate, we don’t have a place to store it.” But they can’t send it to the tempting little trash icon. In Skiff’s line of work, old data are crucial to calculating trajectories. “If one night we see something interesting,” says Skiff, “we want to be able to go back (to the object’s earlier appearance) and calculate its path. So we’re trying to keep as much as we can, copying it onto tape that holds 50 to 100 gigabytes.”

The key here is data compression. Skiff uses software that inventories each image and identifies those containing anything other than blank sky; it marks those with the computer equivalent of “there is information in this pixel,” and compresses all the rest into something called “empty.” That process squeezes the data by a factor of two or three.

Astronomers are not, of course, the only ones caught in a data deluge. The nation’s supersecret spymasters who work for the National Security Agency (NSA) receive so much raw data every day — from intercepted cell-phone calls, communications satellite transmissions, faxes, and e-mail — that it can reportedly analyze only 1 percent of what comes in, according to James Banford, author of a book on the NSA. In high-energy physics, researchers at Fermilab in Chicago routinely look for needles in haystacks: To discover the top quark, in 1995, they combed through more than 50 million collisions between subatomic particles to find a mere three dozen top candidates. The data came to 30 terabytes.

Starting in 2000, Fermilab and the European Laboratory for Particle Physics (CERN) in Geneva, Switzerland, are facing the prospect of experiments that will generate petabytes of data per year. So what’s the problem? “Brute force does not work,” says Hopkins’ Szalay. “You can’t simply scale up today’s approaches to analyze data of this magnitude.”

Think of it this way: Let’s say Professor Nova is interested in a 500 gigabyte data set. Her university can receive data over the World Wide Web at the standard 15 kilobytes per second; at this rate she would have to wait a year for it. Her colleague, Prof.
Cobe, is lucky enough to sit in the same building where the data are stored; using Ethernet, it takes him ... a mere week to download. Even the principal investigator who is logged on to the very machine on whose hard drive all of the 500 gigabytes reside would need a full day to scan through it all. "Even faster hardware cannot support hundreds of such brute force queries a day," says Szalay.

To wrestle the data from the new sky surveys into submission, therefore, will take nothing less than "a paradigm shift," says Szalay. "We need new tools to properly digest, warehouse, query, and analyze our data. The key to the scientific enterprise of the future will be the ability to manage, index, access, interpret, and analyze these enormous data sets."

How much are we talking about? Take OGLE, the Optical Gravitational Lensing Experiment. Begun in 1992 at the Las Campanas Observatory in Chile, and since 1996 using the dedicated Warsaw Telescope there, OGLE searches for the galaxy's dark matter by looking for microlensing events. Gravitational lensing results from the ability of massive objects to bend light, kind of like a bowling ball positioned in the center of a trampoline deflects — downward — the path of a line of ants marching from one side to the other. Gravitational lensing bends light from a background galaxy into multiple paths, so the light reaching us is 10 or 100 times brighter. OGLE looks for such signatures. Taking data every night, says Bohdan Paczynski, the Princeton University astronomer who first proposed using lensing to spot dark matter, OGLE is collecting some 300 gigabytes per year. With a new detector coming on line late this year or early 2000, the rate will increase 16-fold, and OGLE will be swamped by 4 to 5 terabytes per year.

OGLE's collaborators aren't worried about storage — they've gone to digital linear tape, which stores 20 gigabytes per cartridge. The problem is access. "We try to put our data — processed and with the errors cleaned out — in the public domain almost immediately," says Paczynski. "In the best case, that's about a year after we take it."

The only practical way to share the data is over the Internet, but remember Szalay's calculation: 500 gigabytes would take a year to stream over a standard connection.

MACHO has already discovered this. This collaboration searches for Massive Compact Halo Objects, also by gravitational lensing. Its primary aim, says astronomer Charles Alcock of Lawrence Livermore National Laboratory, is to test the hypothesis that much of the dark matter in the Milky Way's halo is made up of MACHOs, non-luminous objects such as brown dwarfs or planets whose signature would be the amplification through lensing of light from extragalactic stars. Because such events are so rare, the team monitors millions of stars for years to get a statistically meaningful detection rate.

The data archive of the Space Telescope Science Institute has about 16.6 gigabytes of storage space dedicated to images and spectra of Saturn. If the rate of 4 terabytes per year was so expensive to collect in the first place...

GLOSSARY OF GIGANTIC NUMBERS

- mega-: million; $10^6$
- giga-: billion; $10^9$
- tera-: trillion; $10^{12}$
- peta-: quadrillion; $10^{15}$
All astronomical data will eventually be interconnected through high-speed networks to allow astronomers to make discoveries without ever again being frustrated by bad weather.

Using the 50-inch telescope at Mt. Stromlo and Siding Spring Observatories in Australia, MACHO takes images of the Large and Small Magellanic Clouds, gathering gigabytes of data per night. Since the project started in July 1992, it has amassed 6 terabytes of data on 66 million stars and will add 1 terabyte per year, says Alcock.

Whose data is it, anyway? Astronomical tradition is to let the principal investigators milk it for all the papers they can. “In the beginning all of us felt very powerfully that we should have the rights to these data, but it quickly became clear that it was too much,” says Alcock. “Once that set in, people quickly became more generous — or at least they didn’t complain too loudly.” The problem is, with gigabytes or terabytes, you can’t just say, Here it is. Astronomers want processed data — reduced, calibrated, usable. A plan to share the MACHO data within two years foundered on the lack of funds to set up a web server through which astronomers could access it. “No one knew what it meant to have this much data,” Alcock says. “The process of making it all available to the community would require more people and resources than we have. We can’t do it on a web server. We’re hoping to get it out on CD-ROMs.” The irony is that few astronomers will use it. They won’t have the computational capacity to reduce it. Says Alcock, “Our ability to gather data is increasing rapidly, but our ability to make sense of it isn’t keeping up.”

The Sloan Digital Sky Survey will contain at least 10 times more data, by the end of its planned five-year run, than any other sky catalog: 40 trillion bytes, enough to fill 20 million floppy disks. No, they’re not going to actually fill and stack those disks. But even with the data stored on CDs or more advanced media, retrieval could be a nightmare: Standard cross-referencing could take longer than waiting for tenure, and astronomers could not compare Sloan data to those in other star catalogs. That would not be good. The Sloan archive will become “the standard reference to study the evolution of the universe,” says Szalay. Unless someone figures out how to cross-reference and index the data — to make it “queryable” — the archive will be approximately as useful as the pages of a 20-volume encyclopedia that have been torn out of their bindings and cut into one-inch squares.

Luckily, one scientist’s problem is another’s opportunity. Just when the data deluge threatens to drown astronomy, in
rides — trumpet fanfare, please — the equivalent of the National Guard to pluck survivors off their roofs and whisk them to safety. Szalay and others think they have solved the problem, by designing an archival system based on parallel programming that will let astronomers using the Sloan data analyze several terabytes per hour. Without getting into the cyber-arcana, Szalay and colleagues are developing a sophisticated search engine to bridge the chasm between the data they can store and the data they can mine. Data will be coded and stored in cyber-containers: Each storage space will hold similar objects — blue galaxies, say — from the same region of the sky. This storage scheme will allow an astronomer to submit a query such as this: Find all the objects similar to one set of objects (say, type I supernovae) and dissimilar from another set (not in the Southern Hemisphere, for instance). Or this: How many clusters of galaxies have an ancient central galaxy? This is an example of a correlation — a cluster linked to an ancient galaxy — and it may prove to be a common kind of query posed to the Sloan database. “In the past,” says CMU’s Nichol, “we needed correlations in just position, color, and brightness. Today, the correlations we can look for and the amount of information we have to draw from has expanded dramatically.”

“How dramatically? ‘There are trillions of high-order correlations, each requiring billions of computations,’” says Andrew Moore, an assistant professor of computer science and robotics at Carnegie Mellon University. 

Yet he’s undaunted. In November 1998 Carnegie Mellon received $1.6 million from the National Science Foundation (NSF) to create smart and nimble computer programs to “patrol astrophysical data and make discoveries about how the universe evolved into its current structure,” says Moore. “Basically, we’re proposing to help automate the process of scientific discovery where there is too much information for a human being to even have the chance to spot patterns, regularities, and anomalies.” His money is on an algorithm he developed in 1997, dubbed “all-dimensions trees.” The algorithm scans data, discover correlations, or make counts, 50 to 1,000 times faster than standard brute-force methods. The new software, says Nichol, also a member of the Sloan Survey team, will mean “a new epoch of data analysis.”

Call it the dawning of the age of the “National Virtual Observatory.” In Szalay’s vision, all astronomical data will eventually be archived, indexed, cross-referenced, and interconnected through high-speed networks and patrolled in such a way as to allow astronomers to make discoveries without ever again freezing their behinds at a telescope on long cold nights or getting wiped out by bad weather.

“Astronomers will have to be just as familiar with mining data as with observing on telescopes,” says Szalay. He even suggests a heresy: that there would be a higher return from assembling the requisite archive than from building the next great telescope. “This is a new paradigm, a new way of doing science,” says Hopkins’ James Crocker, director of program management for the Sloan survey. “To answer questions you will go into the data base and ‘data mine.’ So you are looking at this data set rather than the sky.”

But the time to consider it is now, not in 5 years. By then, many of the tera-surveys will have completed their archives; they will exist on different computing platforms. Trying to integrate them all will require rebuilding each from scratch.

A virtual observatory presents at least one epistemological problem, though. Data bases such as MACHO, OGLE, and Sloan are so big “they can be looked at only with computer programs,” points out MACHO’s Alcock. “We can program our computers to search through the haystack and find a needle, but only if we know what the needle looks like.

But the big discoveries in astronomy since World War II — such as pulsars, quasars, and the cosmic microwave background — were completely unexpected. Almost by definition, we don’t have algorithms to look for the unexpected — we can only tell the computer what it should look for, so in a sense we are blind to discoveries that we can’t foresee.” That, however, may simply be the price astronomers have to pay for deliverance from the cosmic flood.

Sharon Begley is science editor of Newsweek.
Survey Maps Galaxy Redshifts

The largest-yet three-dimensional map of the cosmos suggests it has a Swiss cheese geometry, consistent with results from previous, smaller surveys. The new map contains more than 100,000 galaxies in two fan-shaped arcs and was pieced together over two years by Australian, British, and American astronomers using a 4-meter robotic telescope in Australia. They found that galaxies congregate in huge superclusters and filaments, which are separated from one another by voids — regions of space up to 200 million light-years across that have very few galaxies.

The team used the Anglo-Australian Telescope in New South Wales, a wide-angle telescope with a 2° field (2dF) of view, which is four times the diameter of the full moon. A robot inside the telescope places each of 400 hair-like glass fibers in position to simultaneously obtain light from individual galaxies. By measuring how much the light from each galaxy is Doppler shifted to longer (redder) wavelengths, the astronomers find how far away each galaxy lies from Earth — the farther away the galaxy, the faster the expansion of the universe carries it away from Earth and the more its light is redshifted. The 2dF Galaxy Redshift Survey eventually will map the positions of 250,000 galaxies. (The Sloan Digital Sky Survey, a North American mapping experiment with similar goals, is in the process of mapping about 1 million galaxies.)

An analysis of the motions of galaxies in the 2dF map, reported at the June meeting of the American Astronomical Society in Rochester, New York, should help those worried that the universe might one day collapse. The 2dF results imply that the density of matter in the universe is less than the so-called critical value and the universe will continue to expand. If the measured density of matter had been greater than the critical value, the survey would have indicated that the universe is headed for a “big crunch” finale.

The 2dF galaxy redshift survey shows a universe with long chains of galaxies, giant superclusters, and enormous voids. Matthew Colless (ANU), et al., 2dF Galaxy Redshift Survey

Two recent balloon experiments — BOOMERANG and MAXIMA — that studied the microwave radiation left over from the Big Bang suggest that the universe is “flat” (see “Unveiling the Flat Universe,” August 2000). A flat universe expands forever and light travels through it along relatively straight lines. “There is no great cosmic discrepancy between our results and the balloon experiments,” says Gavin Dalton, an astronomer at Oxford University and a member of the 2dF team. “The balloon experiments measure the total density of matter and energy, whereas the galaxy survey measures only the matter content.”

The difference is the energy density of the vacuum itself, also called the cosmological constant, or quintessence. The combination of the two types of experiments measures the value of this constant, and that result is consistent with those reported during the past two years from observations of supernovae located at great distances from Earth. — R.G.
Europe’s Science Machine

The Very Large Telescope will revolutionize astronomy in the 21st century.

by Gaver Schilling

On a desolate mountaintop in northern Chile, European astronomers are gearing up to complete the world’s most powerful optical observatory. Called the Very Large Telescope (VLT), it will be an astronomical workhorse for decades to come, providing scientists with record-breaking light-gathering power and a vision much sharper than the Hubble Space Telescope’s.

The Very Large Telescope consists of four identical 8.2-meter telescopes perched atop 8,635-foot-high (2,632-meter) Cerro Paranal (see “King of the Mountain,” March 1999). This summer, the fourth and final telescope will see first light, and by mid-2001 the quartet will be conducting routine science observations.

New stars are forming in the Chamaeleon 1 complex. All photos: European Southern Observatory

When all 4 scopes are in production they will get more than 20 Gbytes of data each night (or 7.3 terabytes each year).
spawned by far-traveling neutrinos. But Haeshim Lee, an astrophysicist at Chungnam University in Taean and head of the telescope’s theoretical division, doubted that HANUL would work, and some experimentalists worried that the magnets would be too costly to build. Haeshim Lee aired his doubts in an angry letter circulated among scientists and government officials in June 1998 and later quit the project. (A toned-down version of his critique was published in the Korean Physical Society’s monthly journal in September 1999, prompting coverage of the affair last month in an online newsletter, Korean American Science and Technology News, published by Moo Young Han, a physicist at Duke University.)

Worried about the status of the project, KOSEF called an emergency meeting in April 1999. Lee and other division heads urged agency officials to replace Song and to give the project greater flexibility. KOSEF declined to act on Song’s status, with one official explaining that “we manage the research budget, not the team itself.” But in June it cut off funding for HANUL, noting that the scientists had not chosen where to assemble the prototype and could not meet an August deadline for its completion.

“I don’t know what to say. I’m just so disappointed,” says Jewan Kim, a physicist at Seoul National University who had helped build support for HANUL. “We had many meetings, but people just don’t agree. There’s nothing you can do about it.” Song blames the project’s failure on disagreements over physics and cost, on stifling bureaucratic requirements, and on a “lack of warm personalities.”

Others regret the loss of a chance to explore neutrino energies in a range between those covered by two other major experiments, the massive Super-Kamiokande underground water detector in Japan and the larger but less acute AMANDA project in Antarctica, which monitors a huge volume of ice. “The HANUL project was trying to make a bridge between these two techniques. It certainly was worthwhile,” says Francis Halzen, a physicist at the University of Wisconsin, Madison, and a co-PI for AMANDA.

Five months after losing funding, Lee still hopes to resurrect HANUL elsewhere and somehow include Korea in it. He says that the experience leaves him eager to find international collaborations that can improve Korea’s academic environment: “Korea needs more pure research projects so that young people can learn to think for themselves. I thought that, in a small way, I could accomplish that. But I guess the project came a little too early.”

—MICHAEL BAKER

Michael Baker is a writer in Seoul.

**COMPUTER SCIENCE**

**Physicists and Astronomers Prepare for a Data Flood**

New accelerators and sky surveys that will spew data by the terabyte are spurring a search for new ways to store and disseminate the flow.

The end of a millennium is a time for warnings, and some scientists are joining in: They are predicting a flood. But unlike most millennial doomsayers, the scientists are looking forward to being inundated. Their flood is a torrent of data from new physics and astronomy experiments, and they hope it will sweep some long-awaited treasures within reach, such as the Higgs boson, a hypothetical particle that endows everything else with mass, and a glimpse of life-supporting planets in other solar systems. The greater the torrent of data, the better the chance that scientists will pull these and other prizes from it—providing they can find ways to store and channel the flow.

The quantities of data expected in the next decade will be staggering. Planned experiments at the Large Hadron Collider (LHC), a giant particle accelerator due to be up and running in 2005 at CERN, the European particle physics center near Geneva, “will write data to a disk-based database at a rate of 100 megabytes per second,” says Julian Bunn of the California Institute of Technology’s (Caltech’s) Center for Advanced Computing Research, “and we expect these experiments to run for 10 to 15 years. That is over 100 petabytes of data, roughly the equivalent of 10 million personal computer hard disks. (A petabyte is 10^15 bytes.) RHIC, an accelerator at Brookhaven National Laboratory in Upton, New York, that collides heavy nuclei to create a primordial state of matter called quark-gluon plasma, is already spewing out data at a rate of nearly a petabyte a year—about 1000 times the volume of data in the largest biological databases.

Astronomy is contributing to the torrent as well. Johns Hopkins University astrophysicist Alex Szalay expects the Sloan Digital Sky Survey (SDSS), which aims to image 200 million galaxies and measure distances to a million of them, to produce about 40 terabytes of information. (A terabyte is 10^12 bytes.) Several planned sky surveys at other wavelengths, such as radio and infrared, will contribute tens of terabytes more.

Organizing the data and making them available to the global community of scientists without swamping computers or networks will require rethinking the ways data are stored and disseminated. Researchers at institutions including Johns Hopkins, the Fermi National Accelerator Laboratory (Fermilab), Caltech, and Microsoft Corp. are doing just that. By sorting the data as they flood in and dynamically reorganizing the database to reflect demand, they hope to provide prompt, universal access to the full data archives. “The volume and complexity of the data are unprecedented,” says Caltech particle physicist Harvey Newman. “We need a worldwide effort to get the computing capacity.”

Two trends have converged to create the database challenge. New particle detectors and telescopes are starting to take in data at an unprecedented rate. And the experiments themselves have ever larger numbers of far-flung, data-hungry collaborators. The full data sets will have to be stored in central
repositories because of their volume: It could take months to transmit a full copy of a petabyte-sized data set over the fastest affordable Internet connection. But to make a mammoth central reservoir usable, says Szalay, "we need a double paradigm shift," encompassing both data storage and dissemination.

He and colleagues at Johns Hopkins, Caltech, and Fermilab are tackling the first step—organizing databases to make them easier to search. Current scientific databases often store data sequentially, as it is churned out by the experiment, which makes retrieving a specific subset of data (all blue galaxies in the SDSS, for example) very slow. Says Szalay, "We have to divide and conquer the data."

His team has designed software for the Sloan Survey that automatically preselects the stars and galaxies in each new image from the survey's telescope in New Mexico, putting them into separate buckets called objects. Electronic "labels"—"blue galaxies" or "11th magnitude stars"—indicate the contents of the buckets, and the database software will link each bucket to the other buckets to form what's called an object-oriented database. The SDSS data spigot is already open, and Szalay's software is hard at work distributing data into the appropriate buckets.

Presorting the data in this way dramatically decreases the computer time needed to find relevant information. "It's like the difference between picking a song from a cassette tape and one from a compact disc," says physicist Bruce Allen of the University of Wisconsin, Madison. To find a song on a tape, you have to fast-forward through all the other songs, but a CD player can skip over "Twinkle, Twinkle, Little Star" and go directly to "Blue Moon." Similarly, when the whole SDSS object-oriented database is complete, the computer will be able to respond to a request for blue galaxies by going straight to the appropriate bucket.

Data from particle physics experiments will be sorted and stored in much the same way. Collision events could be sorted by the "curvature of a particle track in a magnetic field or the energy collected from an electron shower," suggests Bunn. Ongoing projects such as the Particle Physics Data Grid and the Globally Interconnected Object Databases—two Caltech-based projects—are already testing object-oriented database technologies for particle physics.

The scientists are hoping that they can link and search the database objects with inexpensive, off-the-shelf software, such as Oracle or Objectivity. Whereas a high-end, custom-built database costs about a dollar per megabyte of stored information, says Microsoft database expert Jim Gray, a commercial database costs only a penny per megabyte. Preliminary work he and his colleagues did with 100-gigabyte Oracle databases stored on an off-the-shelf PC network looks promising, he says: "We think this is a design for the future."

Szalay's second paradigm shift would affect not the database itself but the computer network, transforming it from the traditional client-server computer network architecture to a hierarchical computer grid. In the client-server model, the database is stored at a single location. The client requests information from the server computer, and the server sends it back. But even if the data are presorted, as in an object-oriented database, millions of data requests from thousands of scientists in every corner of the world could quickly bring even the most powerful supercomputer to a screeching halt. "A single computer would be swamped," says Bunn. "We are obliged to do something radically different."

What's more, even with a projected 1000-fold increase in network bandwidth in the next few years, network access "will remain a scarce resource," says Newman. So a collaboration of particle physicists and astronomers funded by the National Science Foundation's Knowledge Discovery Initiative and headed by Szalay is drawing up plans to distribute both the SDSS and LHC databases over multiple computers, arranged in a hierarchy. At the highest level, one complete copy of the presorted object-oriented database will be split into pieces and distributed among a handful of "Tier-0" centers. To protect against any errors that may creep into the presorted data, a copy of the raw data will also be stored at the Tier-0 centers.

Below the Tier-0 centers will be a series of three increasingly specialized layers of data-storing centers. Every Tier-0 center will be electronically linked to several Tier-1 regional centers, serving a particular region or country. The Tier-1 regional centers in turn will be connected to local universities (Tier-2) and finally to individual researchers (Tier-3). Each tier will house a copy of a progressively smaller piece, or cache, of the total database.

The exact contents of a given cache will change over time. Initially, "we will assess how people might use the system," says Newman, and then load each cache with the information most likely to be used by researchers connected to that branch of the hierarchy. For example, universities with large cosmology groups might choose to store a list of the sky coordinates of all the galaxies observed by the SDSS but ignore all the stars in the data set. Then, when a researcher queries the database for the locations of galaxies, his computer only has to go as far as the next tier for the information. On the other hand, another astronomer at the same university who wants the colors of nearby stars might have to search all the way up to a Tier-0 center. But because "caching will be triggered by access patterns," as Newman puts it, data will constantly be redistributed among the centers to make the system as efficient as possible.

So will it work? Yes, says computer scientist Krystof Sliwa of Tufts University in Medford, Massachusetts. He and his collaborators have constructed a detailed computer program to simulate the behavior of the proposed grids. "It's a classic optimization problem," says Sliwa. "We look at the cost and time required to do a set of jobs." Sliwa's models indicate that the existing Internet could handle the data requests to a layered computer network housing a petabyte-scale database. Newman cautions, however, that bottlenecks might develop as many users try to access the grid at once.

If these schemes succeed in making the giant databases of the future accessible and flexible, many scientists believe that querying will itself become a new research mode, opening a new era of computer-aided discovery. "These databases will be so information-rich, they will enable science that their creators never envisioned," says Caltech astronomer George Djorgovski. One approach is to model the properties of a new object and then go look for it in the database, says Djorgovski, "but that builds in prejudices." He prefers the idea of unleashing software that automatically searches the database for entries with common properties, revealing unsuspected new classes of phenomena. "You will rediscover the old stuff," but now and then, he says, "you'll pull something completely new from the floodwaters.

--MARK SINCHELL
Mark Sincell is a science writer in Houston.
Drowning in data

Biology

Like so many others, biologists are confronted by a tidal wave of information. Unfortunately, few of them know how to swim

Once upon a time, biology was simple. Its practitioners cultivated things in Petri dishes and flowerpots, or studied them through fieldglasses. They might count them, measure their lengths, or even weigh them. But the numbers—and the crunching needed to interpret those numbers—rarely taxed their mathematical skills beyond a level that they would have learned at school.

That is, however, changing fast. Biological data are flooding in at an unprecedented rate. The amount of information stored, for example, in the international repository of genetic sequences known as GenBank is doubling every 14 months. As a result, many of the challenges in biology, from gene analysis to drug discovery, have actually become challenges in computing. Indeed, the process of change is so rapid that some of the subject’s potentates are afraid that progress may grind to a halt unless a huge injection of numeracy takes place pretty soon.

The mightiest of those potentates inhabit America’s National Institutes of Health (NIH)—the body responsible for disbursing the lion’s share of federal money available for biomedical research. And earlier this month the NIH issued a report that talked of “the alarming gap between the need for computation in biology and the skills and resources available to meet that need” and recommended spending up to $66m on rectifying matters through a network of biocomputing centres across the country.

An embarrassment of riches

The main reason for this shotgun marriage with information technology is that biology has belatedly realised that it is, itself, an information technology—even though the technologist is natural selection rather than Bill Gates. An organism’s physiology and behaviour are dictated largely by its genes. And those genes are merely repositories of information written in a surprisingly similar manner to the one that computer scientists have devised for the storage and transmission of other information—that is, digitally.

There are superficial differences, of course. The genetic code has four elements (the four so-called bases, sometimes referred to as its letters), rather than the two of a binary coding system. And the bases are grouped together in threes, known as codons, rather than in the eight-bit bytes of computing. But the similarities are more striking, so the subject is suddenly lending itself to a serious amount of computerisation.

At the same time, there has been rapid progress in the machines that supply the raw material—the sequences of genetic letters and codons in chromosomes. A single high-throughput gene-sequencing machine can now read hundreds of thousands of bases per day, and newer technologies, such as “gene chips”, should make the analysis even faster. That will produce even more data that have to be stored and annotated for subsequent study. And even for those who do not work directly on the genes themselves, similar technological changes are appearing. Robotic screening machines, for example, in which hundreds of compounds in tiny wells are tested to see if they react with a particular biological target, can analyse thousands of compounds in a day.

The result is a mind-boggling amount of information. According to Anthony Kerlavage of Celera, a company formed last year with the intention of sequencing the entire human genome using private money (and beating government-financed projects in the process), a genetics laboratory can easily produce 100 gigabytes of data a day—that is about 20,000 times the volume of data in the complete works of Shakespeare or J. S. Bach.

The analysis of such data poses problems beyond mere volume control. Having sequenced a particular piece of DNA, for example, it is useful to compare it with a central database (such as GenBank) of existing sequences to see what it resembles. But this requires more than just a straightforward database search. The program involved must know what constitutes a biologically meaningful resemblance, and it must also be able to deal with the errors that inevitably creep into the sequencing process. As a result, devising new search algorithms requires extensive knowledge of sequencing theory, together with a keen biological intuition.

And there’s the rub. The real problem about the growing quantification of biology is not the change in the subject but the lack of change in its practitioners. For a sudden in-
Europe Opens Institute to Deal With Gene Data Deluge

CAMBRIDGE, U.K.—An 18th century manor park 13 kilometers south of Cambridge may seem an unlikely setting for the latest in 20th century biological science and technology. But the tree-covered grounds of Hinxton Hall have recently sprouted several new buildings that will be home to Europe’s largest center for genome research. And this month marks another milestone in Hinxton’s transformation when the European Bioinformatics Institute (EBI) formally opens its doors there for the first time.

Bioinformatics has become a buzzword in biology as the explosion in protein- and gene-sequence data turns molecular biology into an information science. With complete or partial sequence data now available for 300,000 genes and 100,000 proteins across all species, a researcher can quickly glean clues to the function of a newly sequenced gene or the structure of a freshly isolated protein—if she or he can find the relevant data amid the swarm of literature citations and widely dispersed information stored in computers. That’s where bioinformatics’ computational methods and databases come in.

The mission of EBI, an outstation of the European Molecular Biology Laboratory (EMBL) in Heidelberg, Germany, is to find ways to stitch these information fragments into a coherent tapestry of easily accessible data. Other centers in other countries—notably the United States and Japan—have similar goals, but the focus at EBI will be on Europe. “It makes sense to expand and develop European databases because of the explosion of activity and existence of strong, cohesive research groups in Europe,” says Guy Dodson, a protein structure chemist at the University of York. The institute will directly administer two databases, the EMBL nucleic-acid sequence database and SWISS-PROT, a protein amino-acid sequence database; it will also provide an access point for researchers to explore more than 40 other databases scattered around the world, allowing European labs to develop software links to them. Says Graham Cameron, head of services at EBI: “There is a huge awareness now of the importance of databases. I was appalled at the lack of computer awareness when we began 13 years ago. Now there are many professional and robust databases.”

Indeed, the institute has come a long way from its cramped beginnings at EMBL in 1982. Then it had a staff of two researchers, and its initial database contained just 0.5 megabases (a megabase is a million base pairs) of nucleotide sequence. EBI research coordinator and Cambridge University biology professor Michael Ashburner says this database now contains more than 300 megabases and is growing by 75% each year. And institute head Paolo Zanella now supervises a staff of 40, which will be expanded to 70 over the next couple of years. EBI’s projected annual budget is $8.5 million, supplied by EMBL and the European Union.

While the proliferation of databases has encoding these proteins, because the data are stored in incompatible formats.

So the EBI intends to make the incompatible mesh. “We are working to link our core databases with others developed by our collaborators to make them fully interoperable,” says Cameron. EBI is working with the U.S. National Center for Biotechnology Information, part of the National Library of Medicine in Bethesda, Maryland, to improve integration of protein and nucleotide sequence data. In addition to administering SWISS-PROT, EBI is starting a project with bioinformatics researchers at Brookhaven National Laboratory in New York to develop standards for representing protein structure data.

The institute is also closely involved with many European research groups as a result of links created by EMBnet—a 20-node network initially set up by EMBL to coordinate access to data at the national level for users in Europe. The experience of creating this network will help EBI programmers develop access through other channels, such as the World Wide Web. “We are seeking a loose federation of databases,” says Cameron.

Service isn’t EBI’s only mission, however. The institute already has two research groups working to develop software tools to validate protein structure data and has plans to fund two additional research groups. The research mission, scientists say, is a natural, given EBI’s neighborhood. The Hinxton campus is also home to the Sanger Center, Europe’s largest gene-sequencing laboratory. The Medical Research Council’s Human Genome Mapping Project has also relocated to the site. “The potential for exchange of biological knowledge at Hinxton is quite unique,” says Rodrigo Lopez, an EMBnet manager at the Biotechnology Centre of Oslo in Norway, noting that the combination of sequencing expertise and database design should give EBI some real advantages in genome database development and ensure it a prominent role in the international scene.

“With the EBI, Europe really now has something to hang on the table,” Lopez says.

Ashburner and his colleagues hope the bashing will soon be over. “There’s enough information for genome explorers to begin to ask powerful questions about function and evolution,” he says. With the advent of EBI, the researchers think, such explorations will yield information treasures to match investigators’ wildest dreams.

-Nigel Williams
Help! The data are coming

Some branches of science have learnt how to cope with huge amounts of information. Biologists haven’t. There is a dearth of essential skills which is only now starting to be taken seriously.

Terabytes, exabytes, yottabytes: bytes by the zillion are heading this way, thanks to the appetites of particle physicists, Earth scientists and organismal and molecular biologists (see Briefing on pages 517–520). So how will researchers cope?

The particle physicists are well versed in handling such data. They seem to be crossing their fingers and hoping that the off-the-shelf hardware and software will be available in time to allow them to analyse the copious output of their next-generation colliders. Given the history of the technology, their expectations are well founded.

Molecular biologists, on the other hand, appear to have eyes for data that are bigger than their stomachs. As genomes near completion, as DNA arrays on chips begin to reveal patterns of gene sequences and expression, as researchers embark on characterizing all known proteins, the anticipated flood of data vastly exceeds in scale anything biologists have been used to.

Biologists are waking up to the challenge, albeit belatedly. Last week, for example, an expert panel told Harold Varmus, director of the US National Institutes of Health (NIH), that his agency needs to do much more in this direction. As panel co-chair David Botstein rightly emphasized, the big issue is training. Nevertheless, sheer supercomputer power (and, for that matter, medium-sized computer power, too) will be essential. To that end, the panel recommended support for the development of existing supercomputing facilities established for other disciplines, as opposed to new facilities for biology. The strain on existing facilities is enormous, so serious investment will be required, but, the panel argues, not in a way that re-invents wheels. This approach also has the advantage of leveraging NIH dollars at centres that already house needed expertise and infrastructure.

But, equally urgently, the NIH needs to help develop a new generation of computer-wise researchers. The panel recommended that five to twenty “National Programs of Excellence in Biomedical Computing” be established. It’s a measure of the speed of the revolution, and of the dearth of expertise in the community, that it’s not obvious where in the United States such programmes would be launched. Just as urgent is the need for computer specialists in laboratories, and a change in attitude that sees them as invaluable rather than second-class citizens. In short, computer experts at $85,000 a year are, like it or not, an increasingly necessary component of grant applications.

It would be wrong to leave the US agenda in this area solely in the hands of the NIH. The National Science Foundation has traditionally been the focus of support for supercomputing in the research community, while the Department of Energy has supported most of the country’s particle physicists. Both agencies have made their own investment in informatics, and sharing what they learn with biologists is an urgent necessity as increasing NIH spending.

Other countries and regions face similar shortages of skills. Meanwhile, private companies are busily sequencing and computing and licensing. There is, therefore, an urgent underlying message that all scientifically ambitious countries should heed: strong government funding for the quantitative analysis of data is essential if the results of fundamental biological research are to remain a public good.

A cause worth funding

A German synchrotron would be good for the Middle East.

It’s too easy for Nature to urge the world to spend more money on science. On the whole, that temptation is resisted. But there are honourable exceptions. A proposal — as yet unfunded — to establish a joint synchrotron radiation facility in the Middle East is one such, and deserves immediate attention.

The government of Germany is understood to be receptive to the idea of giving away a fully functioning synchrotron radiation source for use by scientists in the Middle East (see pages 507–508). The synchrotron is to be the focus of a broader centre for research excellence for scientists from throughout the region, as well as other parts of the world. The project’s founders envisage a facility similar in aim to the European Laboratory for Particle Physics (CERN), which brought together scientists from countries that had fought each other during the Second World War.

Scientists nominated by many of the region’s governments will discuss the project at a meeting organized by the United Nations Educational, Scientific and Cultural Organization in Paris next week. Israel is expected generously to agree not to bid to host the synchrotron — as its scientific competence would well qualify it to — allowing the facility to be housed in one of its neighbouring countries. There appears to be no shortage of potential hosts, with Cyprus, Egypt and the Palestinian Authority among the contenders.

But the proposal needs funds in no small measure. There are several potential sources. These include the European Union and the US government, as well as states within the Middle East itself. The issue of funds for the project will also be raised at the World Conference on Science in Budapest later this month. Nature’s advice to any potential funder is not to hold back, for this will be a worthwhile investment. Initiatives such as this do not come around often. When they do, they should be supported unhesitatingly.

After a troubled half-century, the peoples of the Middle East are making the slow transition to peace. It is sometimes hard to imagine, but there was a time not too long ago when the Christians, Jews and Muslims of the Middle East lived in relative harmony, when philosophers and scientists were recruited to the region’s leading institutions of learning because of their expertise, and not on the basis of their faith or geographic identity.

Is it too optimistic to suggest that next week’s meeting in Paris may mark the return of such happier times? Probably. But the meeting will be a valuable and long-awaited beginning. And if the project succeeds, it could be a step closer to the day scientists from Israel and its neighbours are free to travel to — and work in — one another’s laboratories, exchange information and cooperate in research. That alone would be a major step forward.
It’s sink or swim as a tidal wave of data approaches

Enormous amounts of data are being amassed in fields as diverse as genomics and astronomy. If this information is to be used effectively to speed the pace of discovery, scientists need new ways of working. This requires investment in computers, new statistical tools, and a liberal approach to data sharing.

Three years ago — several lifetimes in the Information Age — the Microsoft Corporation went in search of a database that it could use to test web-based technology for serving up large amounts of information to the public in a user-friendly way. The bigger and more interesting the archive, the better. The New York Stock Exchange had a terabyte (trillion bytes) or so of transaction data, the Mormon church just over two terabytes of genealogical records, but neither of these quite fit the bill.

Then Microsoft approached the US Geological Survey (USGS), which is midway through photographing the entire United States from the air at high resolution. The resulting store of images constitutes about 9 terabytes of uncompressed data, but will grow to 12 terabytes, more than the total amount of printed material in the US Library of Congress. Satisfied, Microsoft signed a cooperative agreement with the USGS, and last year went online with its Terraserver, now among the largest databases accessible on the web.

Such boasts are short-lived in a time when scientists are dreaming up mega-projects with ever more prodigious output. The US space agency NASA’s Earth Observing System will crank out a terabyte of satellite data every day, and a petabyte (1,000 terabytes) every three years. The Large Hadron Collider at the European Laboratory for Particle Physics (CERN) in Switzerland will spew numbers at 20 times that rate.

Information from the collider will flow as fast as everyone on Earth were each talking into 20 telephones simultaneously. In 15 years it will produce 100 petabytes of stored data — equivalent to generating the total printed content of all US academic research libraries every four months.

Database experts are already bracing for what they call the ‘exabyte (1,000 petabyte) challenge’. All the words ever spoken by human beings amount to about five exabytes. In case we need them, and we probably will soon, terms have already been coined for 1,000 exabytes (zettabyte) and 1,000 zettabytes (yottabyte, or 10^24 bytes).

Managers of large projects such as the Earth Observing System used to brag about such eye-popping numbers as if they somehow demonstrated scientific productivity. But now they are worried. "People recognize there’s a problem," says Robert Grossman of the University of Illinois at Chicago’s National Center for Data Mining. He has a favourite graph showing the amount of data increasing by more than five orders of magnitude since the early 1980s, while the number of statisticians to analyse the data has remained constant (see page 520).

Are scientists ready for the flood? High-energy physicists, astronomers, climate modelers and others accustomed to supercomputers and high-throughput experiments may be able to cope — given ever more powerful machines, smarter analysis software, and faster networks for gaining access to the databases. But many biologists are still in denial, never having faced the amount of information now pouring into databases such as GenBank and SwissProt.

"Biologists haven’t really thought about how they’re going to use this data — and the fact that it’s going to take real money to do it," says Sylvia Spengler, co-director of the Lawrence Berkeley National Laboratory’s Center for Bioinformatics and Computational Genomics in California.

Aravinda Chakravarti of Case Western Reserve University in Ohio, who has been involved in strategic planning for the Human Genome Project, agrees. "The problem is very, very real. Most biologists have no idea of the informatics needs of their projects and how this is likely to change. They are largely unprepared, and the National Institutes of Health has not done enough."

To extract the most knowledge from the vast amounts of raw data now piling up in archives around the world, biologists will need to invest in upgraded computers, more training, and more computer-savvy staff. And they will quickly learn that computer science postdocs are pricier than biology postdocs. The unhappy alternative, warns Spengler, will be to turn over the data to some outsider with the necessary computational skills. In the ‘post-genomic’ era, it will be a case of learn to work the database, or wait on the sidelines.

Rising to the exabyte challenge

The technical hurdles associated with massive data archives — for biology, physics or any other discipline — may ultimately prove easier to solve than the sociological ones. But they are still daunting. CERN’s Large Hadron Collider (LHC), for example, will produce copious amounts of energy and trajectory data for billions of particle collisions every year, for at least 15 years. So important did CERN and its collaborators consider the...
Scientists around the world have moved aggressively in recent years to identify and rescue valuable stores of data — particularly atmospheric and oceanographic records extending back a century or more — before they are lost to the ravages of time.

The records range from handwritten nineteenth-century ships' logs, to weather observations from colonial Africa, to decaying magnetic tape from early weather satellites. The treasures still turn up regularly on dusty shelves and in basements, and even more could be salvaged if a greater public investment were made.

"Every few months we hear about a major archive," says Sydney Levitus of the US National Oceanographic Data Center in Maryland. As an example he cites the Scripps Institution of Oceanography's discovery of 180,000 ocean temperature profiles taken by the US Navy during the Second World War.

No one knew these data existed. But they neatly filled a gap in the North Pacific for which there had been no contemporary record. Altogether, some two million ocean temperature profiles have been added to the centre's World Ocean Database in the past five years, nearly doubling the previous amount.

Part of the credit goes to a campaign to digitize archives already known to exist. But some credit goes to the six-year-old Global Ocean Data Archaeology and Rescue (GODAR) programme, which Levitus heads and which is conducted in association with the Intergovernmental Oceanographic Commission.

GODAR partners meet annually to report on significant data archives in their countries that might be worth saving and converting to digital form for easy electronic sharing. "There's been incredible international cooperation," says Levitus. The Russian Navy has released declassified ocean data, as have the US and British navies.

Most of this historical information, which was gathered for operational purposes, "has never been touched" by scientists, says Thomas Karl, chief of the US National Climatic Data Center. More than 100,000 chlorophyll profiles and 600,000 plankton observations have been added to the database, along with measurements of salinity and ocean chemistry.

The addition of the temperature profiles has already had an important scientific impact, says Levitus. "These data taken together allow us for the first time to compute the interannual variability of the heat storage in the upper ocean," a key factor in climate-change research.

The US National Oceanographic and Atmospheric Administration has its own data rescue programme. It aims to preserve and eventually digitize millions of old paper, film and tape records stored at three data centres. The task is enormous, and the waiting list is long.

With current funding of $5 million a year, the agency reckons it will take 18 years to rescue 137 million paper records, and 42 years to salvage 450 terabytes of environmental data stored on outdated computer cartridges and disks. The programme has made great strides, says Karl, "but a lot more could be done".

Ironically, records from the computer age are among the most perishable, with storage media fast becoming outdated. Geostationary Operational Environmental Satellite (GOES) weather data from the 1970s are housed at the University of Wisconsin, where the late meteorologist Verner Suomi had the foresight to transfer them to tape.

But the tapes are deteriorating, and the number of machines that can read them is dwindling. The high-resolution GOES data could yield "potential treasure," says Karl. But the tapes remain in storage because of a lack of money to convert them.

Spurred in part by the signing of the Kyoto treaty on carbon dioxide reductions, scientific organizations around the world have grasped the importance of tracking down and preserving as much climate-related data as possible, says Levitus. "The consciousness has really been raised."

The Belgian government, working with the World Meteorological Organization, has helped African nations to digitize weather observations from the colonial era. Similar work is under way in Caribbean countries, and the European Commission is funding an effort called MEDAR to retrieve data on the Mediterranean Sea.

Funding is sparse for these ad hoc programmes. But enthusiasm is high. The Australian Oceanographic Data Centre recently advertised in a marine science newsletter in an attempt to root out hidden treasures held by individual scientists. Centre head Ben Searle estimates that 70 to 80 per cent of the marine and coastal data that has been collected in Australia resides in filing cabinets and on personal computers, and its existence is unknown to all but the owners.

Karl says the tremendous effort that has gone into data rescue should be a sobering lesson for designers of modern electronic databases, who can expect to have to "migrate" terabytes of data periodically to updated storage media, or risk finding themselves some day with a "dead archive". It won't be glamorous work, he says. But "we'll all have to pay some tax to do this".

The LHC's data system will push the state of the art in several areas, including high-performance storage for computer data, where capacity may be less of a problem than speed of transfer between tapes and other media. Fortunately, the commercial world is working on the same problem. LHC data managers therefore hope to buy the storage system and database software essentially off the shelf, then modify them.

The four individual LHC experiments have already made a decision to forsake tried-and-true Fortran code and switch to more versatile object-oriented programming (of which C++ and Java are common varieties). This will require "a different mindset" for CERN programmers, says Julian Bunn, a CERN physicist working at the California Institute of Technology, which is collaborating on the LHC data system.

It was a bold step, not taken lightly. NASA's Earth Observing System data system (EOSDIS) crashed on the rocks of object-oriented programming in the early 1990s, when the tools were newer. The project suffered delays and cost overruns as a result.

The LHC data system will be distributed, with a central archive at CERN and regional centres serving users nearest to them. Scientists tapping into the database, though, will have the impression of a single repository. Bunn worries most about networking — moving around enormous volumes of data, quickly and seamlessly, among ten regional centres, the central archive at CERN, and up to 2,000 individual users around the world.

A new, higher-capacity Internet should be available by then. But millions of users worldwide will be soaking up the bandwidth by downloading movies and shopping online. Even dedicated scientific networks are likely to fill up quickly, says Bunn.

The life expectancy of the archive is equally problematic. "We've never been faced with maintaining a 20- or 25-year database," says Bunn. As the LHC matures, the calibration of its instruments will become more refined, and all those petabytes of data will have to be regularly reprocessed, adding to the volume of data the system has to churn. Project managers only expect 100 petabytes from the collider itself. But they are designing their system to handle ten times more data.

What's worth keeping?

Computational demands will become greater as scientists build more linkages and capabilities into their databases. Services such as the US National Center for Biotechnology Information have already begun to merge scientific journals and databases into unified searchable libraries (see Briefing, Nature 397, 195–200; 1999).
Catalogue of life could become reality

Taxonomists have long dreamt of creating a master 'catalogue of life'. For various reasons — lack of money and competing schemes for going about the job being the two most prominent — it has not yet happened. But the 1992 global biodiversity treaty may be a spur to further action.

Frank Bisby of the Centre for Plant Diversity and Systematics at the University of Reading, England, hopes that the Species 2000 project to federate as many as 200 databases into a single searchable archive of all the world's 1.7 million known species "is about to turn from a plan into a reality".

Other groups with similar ambitions have signed on as partners, including the US-Canadian Integrated Taxonomic Information System and the Global Plant Checklist based in Australia and Europe.

Today, the prototype Species 2000 'dynamic checklist' searches just three databases. But up to 30 links are expected by the end of the year. Bisby is also discussing links to the geospatial database created by the University of California at Santa Barbara's Alexandria Digital Library, so that species data could be combined with geographic information.

Funding so far has been "ridiculously fragile," he says. But he is optimistic that the Global Environment Facility and the European Union will help pay some of the estimated $140 million cost of the basic (non-georeferenced) system.

Bisby and other taxonomists have been envious of the ample funding bestowed on molecular biologists, when "we think of ourselves as being of equal stature". Chris Thompson, a US Department of Agriculture researcher and former vice-chairman of Species 2000, says: 'We've just been ineffectual at selling our vision.'

Species 2000 is at www.sp2000.org

A data workshop sponsored by the US National Science Foundation last year produced an even more ambitious vision: digital journals that would link not only to the data used in an experiment, but to the programs that created or analysed the data, so that readers could verify the results of an experiment or run their own variations. The workshop participants called this 'deep citation'.

"That scares me a bit," admits Bunn. He understands the appeal to scientists who want to recompute some controversial result for themselves. But who would be allowed access to the data and the computational resources, and on what terms? It's an idle worry today, he says, but "I guess it will come".

Uncertainty about what information to keep — a particular problem in young fields such as genomics — will be a big contributor to database bloat. Are all expressed sequence tags sent to GenBank worth keeping? And all single nucleotide polymorphisms? Before scientists have thoroughly analysed the data, no one can say. Until then, says Spengler, "you have to be a pack rat" to avoid throwing away something important.

It's unwise to cater to every scientist's whim about what data should be archived, says Graham Cameron, joint head of the European Bioinformatics Institute (EBI) outside Cambridge, England, which maintains, among others, the SwissProt and EMBL nucleotide sequence databases. "You could soak up any amount of money" trying to store everything, he says. Database managers have to judge what data are used most often by scientists, and what might be used in the future.

This is not easy. "Complexity fights its way in," says Cameron. The EBI recently decided to establish a public domain repository for DNA microarray-based gene expression data, despite concerns that such an archive might be premature (see Nature 398, 646; 1999). Cameron calls this a "strategic" commitment, even though "technically we may not be at the stage yet to do it right".

Maynard Olson, a geneticist at the University of Washington who has been deeply involved in the Human Genome Project, thinks that the rush to produce a 'quick-and-dirty' draft of the human genome may lead to headaches later, as a mountain of low-quality data is harder to analyse than a smaller, more refined dataset.

Who will pay?

With the web firmly established as a primary avenue of scientific communication, the notion of a database as a large repository in a single location has become passé. Grossman, of the National Center for Data Mining at Chicago, says "the tide is shifting pretty dramatically to distributed systems," which can be loose federations of independently operated databases using common data standards and transfer protocols.

The federations may not be as efficient as centrally managed archives — "every link you build sets up a dependency," says Cameron — but they have real advantages, such as allowing specialists to keep and curate their own data.

Concern about ownership remains an obstacle to database sharing. Researchers at the University of Kansas Natural History Museum hope they have found one solution in a data retrieval protocol called Z39.50, which has proven successful in the bibliographic community. A Z39.50 query retrieves and pools data from multiple sources — perhaps museums in different locations that hold specimens from the same taxon or region. Each museum retains control of its own database, but the pooled results add up to something no single collection could offer — enough data points to allow detailed analysis of biodiversity patterns.

But the issue of data ownership will not go away easily, especially for information with perceived commercial value, and this could prevent many scientists from making the most of the current data bonanza. At least some new information on the human genome — particularly products derived from raw sequence data — will be off limits to those who do not pay private companies such as Celera for access rights (Novartis, Upjohn and other large companies have already done so). Scientists worry that proposed changes to US intellectual property laws could push researchers to view their data as commodities to be sold rather than as information to be shared (see Nature 394, 410; 1998).

Cameron at the EBI places some of the blame on stingy governments. SwissProt reluctantly began charging commercial users for access to its database only after government funding dried up. The present situation is "not ideal," he says, but it reflects the "inability of the public funding mechanism in Europe" to recognize the importance of free genomic data.

The commercialization of research databases could also shut poorer developing nations out of the scientific mainstream. But the ramifications go beyond North-South politics. So agitated did European nations become over US companies' practice of gathering free European meteorological data, then repackaging them into commercial databases sold back to Europeans, that the World Meteorological Organization passed a resolution several years ago allowing countries to restrict access to certain kinds of commercially valuable weather data.

Until that time, the information had always been shared freely among nations. "No question about it, it was a step back," says Michael Crowe, science planning officer at the US National Climatic Data Center. Data exchange and intellectual property rights are "becoming a thornier and thornier issue," he says.

The good news in today's data explosion

Data factory: handling experimental results from CERN's Large Hadron Collider (above), currently under construction, has presented a daunting challenge to physicists.
is that not a day passes without some government agency, academic consortium or private company developing a clever web interface or piece of data analysis software that makes sifting through the petabytes that much easier.

Any number of indexes and 'master directories' of environmental and global-change data have opened online in the past two years — perhaps too many, says Thomas Karl, director of the US National Climatic Data Center. "I know this is heresy for the head of a data centre," he says. But advertising a one-stop shop for climate data is 'some data manager's pipedream'. Savvy scientists will never buy the idea of a single place that has it all.

Most researchers are accustomed to studying a relatively small data set for a long time, using statistical models to tease out patterns. "At some fundamental level that paradigm has broken down," says Grossman. "You can't be afraid of data today."

Soon the question for scientists will be "how do you manage a terabyte in front of you?" — an even more difficult challenge considering that a computer may need to generate 1,000 times that amount in the course of manipulating the data.

Mining for data

Various schemes have been proposed to extract knowledge from such large stores of information, including supercomputer-powered scientific 'visualisation' and what's been called 'data mining', or the semi-automated discovery of patterns, associations and statistically significant structures. Data mining borrows tricks from other fields such as artificial intelligence and neural networks to produce software that can plough through large datasets, looking for nuggets that humans would take forever to find.

Astronomers at the California Institute of Technology used a program called Skicat to automatically sort through three terabytes of image data from the Palomar Observatory Sky Survey. Using decision trees and classification rules, the system was able quickly and accurately to classify very faint objects, effectively tripling the number of objects in the catalogue and accelerating the pace at which high-redshift quasars were discovered. The program was developed by a Jet Propulsion Laboratory software engineer (who later moved to Microsoft).

Scientists at the EBI have mined large stores of yeast gene expression data. Astronomers at Australia's Mount Stromlo and Siding Springs Observatories used mining programs to hunt through data on 20 million stars taken nightly for four years, making more efficient the search for Compact Halo Objects (MACHOS).

Data mining is sometimes overhyped, admits Grossman. Some call it "data analysis with better marketing," while others worry that machines searching blindly for subtle associations in large datasets could do "very stupid things" such as correlate heart attacks with the stars. Human judgement will always be necessary, he says. Data mining is just a tool, albeit a powerful one.

Richard Gibbs, a gene sequencer at Baylor College of Medicine in Texas, believes it is imperative in the era of high-throughput genomics for biologists not to turn over all the action to computer scientists, who might miss biologically important information. Francis Collins, head of the US National Human Genome Research Institute (NHGRI), agrees. "When I give talks to young scientists seeking advice about areas of future intense scientific excitement, computational biology is my number one recommendation," he says. Money alone will not effect change, although training grants in bioinformatics have been stepped up by federal agencies such as the National Institutes of Health (NIH) and the Department of Energy, and private groups such as the Pharmaceutical Research and Manufacturers of America Foundation.

Lisa Brooks, programme director for genome informatics at the NHGRI, says there are two pressing needs when it comes to training. One is for biologists to learn to use publicly available genome analysis software (developed at NIH and elsewhere) through courses, online tutorials, and mentoring with other scientists.

That, she says, is the relatively easy part. Much harder will be building up a corps of scientists who can come up with new statistical approaches to analysing large volumes of genomic data. Today, according to Brooks, "only a small proportion of biologists are capable of developing the tools".

Bioinformatics is still fairly new, and many training programmes are taking only a few students, says Collins. The discipline has had trouble establishing itself.

"Computational biologists in academia often find themselves without a clear career track or an academic home," he says. "Their efforts are seen as too applied to earn respect in departments of computer science, and too ethereal to be accepted in biochemistry or physiology. We need a new mindset."

Gibbs agrees, and says that scientists have no choice but to adapt to a data-rich world. "We've all been doing it slowly, but we've all got to do it faster. The accelerated pace of this is just leaving everybody breathless."
Managing STACS and STACS of Data

Researchers use tape systems to feed massive application needs.

By Mark Hall

THE WASHINGTON state legislature has a data management problem. Its constituent hot line has topped 2 terabytes (TB) of online storage and keeps growing.

The politicians see the hot line data as critical to their future, says Kevin Hayward, a database administrator at the state capital in Olympia. “If you’re not communicating with the people who have elected you, they’re not going to re-elect you,” he says.

Hayward is confronting what’s quickly becoming the most complex problem facing information technology: managing amounts of data that are growing faster than expected.

Delta Air Lines Inc. in Atlanta, for example, put more than 80TB online in less than one year. And Critical Path Software Inc. in Portland, Ore., created the same amount of information in half that time. Adding more disk storage systems with many more servers is too expensive, and using proprietary storage-area network (SAN) products could prove risky if your vendor of choice doesn’t prevail in the SAN standard contest.

The storage problem is only going to get worse because of e-commerce, says Richard Winter, president of Winter Corp. in Waltham, Mass. Web shoppers’ “clickstream” data is creating an immense amount of information,” says Winter. Web sites need to collect and analyze everything — what people looked at, compared with, visited repeatedly and ordered or dropped from a shopping cart, he says.

Although e-commerce CIOs don’t have many low-cost, streamlined alternatives to the data management problem today, the future looks a bit brighter because of work that’s being done by researchers at Lawrence Berkeley National Laboratory’s National Energy Research Scientific Computing Center (NERSC) in Berkeley, Calif. They have developed a way to use tape systems that operate as if all the tape data resides on disks.

STACS of Data

Arie Shoshani, head of the scientific data management group at NERSC, has been working for years with data-intensive applications, such as those used in high-energy physics. And he knows that moving large files from tape to disk takes time. For example, a typical ITB application running in the NERSC supercomputer center could take as long as 30 hours just to load data.

When you’re exploring the fundamentals of the universe, you can expect to wait a while, Shoshani says. But when some programs demand to search 300TB and beyond, waiting months for data to be searched — not even processed — is too long ever when charting the moments after the Big Bang.

Adding the necessary online disk storage systems isn’t practical because of the high costs. “Disk prices are coming down, but tape system costs are going down at roughly the same rate, and there is still a 10-to-1 ratio in favor of tape,” Shoshani says.

That ratio helped inspire him and fellow researchers to seek solutions for efficiently managing data on tape. They created the Storage Access Coordination System (STACS) by working closely with physicists, climate modelers and scientists as they developed their data-hungry applications.

“Most systems store data in the order in which they are received,” Shoshani notes. “But that may not be the best order for analyzing the data for the science involved.”

In one instance, scientists captured the results of millions of particle collisions, called “events,” which are created in an accelerator. When they need to analyze these events, physicists typically only want a subset of the millions of events. To search all 300TB of available data requires that they read 10,000 30GB tapes — a daunting prospect when all they want is a small subset.

That’s where STACS comes in. It handles the queries the application makes of the stored data. The system minimizes the number of files and tapes that have to be read by using a specialized index of the millions of events. It optimizes retrieval by grouping queries that request the same data. It also schedules bundles of files that will need to be processed at the
Most systems store data in the order in which they are received, but that may not be the best order for analyzing the data for the science involved.

ARIE SHOSHANI, NATIONAL ENERGY RESEARCH SCIENTIFIC COMPUTING CENTER

time or in parallel.

STACS' inventors designed the specialized index to understand how data in the files — properties of "events" in the particle physics case — relate to requested queries.

By deriving advance information on all the files needed for the query, STACS can grab files before the query processing. This makes applications seem as swift as if the files were in disk cache when they were needed.

Shoshani says business-intelligence users will need something like STACS if they continue amassing data at current rates.

But it's doubtful that even the most data-rich Web site can compare in storage needs with the physics community's next big assignment: the Atlas Project, a high-energy physics accelerator that will begin producing in 2005 up to two petabytes of data per year.

Future computers may use only very large-capacity disks to handle even the largest jobs. Until then, Shoshani says, there's tape.

June 12, 2000

Computer world
Using Tapes to Send Large Amounts of Data

The typical method used to send large quantities of data to a user is to move the data from computer storage to tapes and then send the tapes to users. When a number of users want the same data it may be better to build a master tape first.

1. Build master tapes with the data.

When several users need the same data, we should consider building a master tape and copying it several times. This may be cheaper than obtaining the data from computer storage for each user.

The idea of building a master tape is similar to the idea of preparing a master CD-ROM, from which many copies can be made.

2. Tapes needed to hold one Tbyte of data.

There have been rapid gains in the ability to store large amounts of data onto a small tape. Table 1 shows that in 1960, about 83,000 tapes were needed to move (or store) one Tbyte of data. In 1997 there is technology to store one Tbyte on only 30 tapes. The higher cost STK Redwood Technology holds 50 Gbytes on one tape (20 tapes per Tbyte).

<table>
<thead>
<tr>
<th>Date of Technology</th>
<th>Device</th>
<th>Holds</th>
<th>Data rate</th>
<th>Drive cost May 1997</th>
<th>Tapes per Tbyte</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>1/2 in</td>
<td>12 MB</td>
<td>0.9 MB/sec</td>
<td>83,300</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>1/2 in, 1600 BPI</td>
<td>40 MB</td>
<td>3 MB/sec</td>
<td>25,000</td>
<td></td>
</tr>
<tr>
<td>1980-1996</td>
<td>9 track, 6250</td>
<td>125 MB</td>
<td>3 MB/sec</td>
<td>8000</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>IBM 3480</td>
<td>200 MB</td>
<td>3 MB/sec</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>Sep 1991</td>
<td>IBM 3480 (c)</td>
<td>420 MB</td>
<td>3 MB/sec</td>
<td>2380</td>
<td></td>
</tr>
<tr>
<td>Sep 1996</td>
<td>Exabyte 8900 (c)</td>
<td>20 GB</td>
<td>3 MB/sec</td>
<td>$4500</td>
<td>50</td>
</tr>
<tr>
<td>1993</td>
<td>DLT 2000 (c)</td>
<td>15 GB</td>
<td>1.25 MB/sec</td>
<td>$2200</td>
<td>67</td>
</tr>
<tr>
<td>Apr 1995</td>
<td>DLT 4000 (c)</td>
<td>20 GB</td>
<td>1.5 MB/sec</td>
<td>$4200</td>
<td>50</td>
</tr>
<tr>
<td>Jan 1997</td>
<td>DLT 7000 (c)</td>
<td>35 GB</td>
<td>5.0 MB/sec</td>
<td>$7000</td>
<td>29</td>
</tr>
</tbody>
</table>

Note: The Exabyte 8900 is also called the Mammoth drive.

3. Time necessary to copy a tape.

The data rate to read these small tapes is quite good, but the tapes hold a lot of data. Therefore, it is useful to determine how long it would take to copy a tape. Table 2 shows that a tape can usually be copied in 2 or 3 hours, even if it holds 20 to 35 Gbytes, this is impressive.
Table 2. Tape technology for bulk data.
All of the tape drives have compression built in. The numbers below are for no compression. Therefore the tape capacity and the effective data rates are really better than the numbers given here.

| Type drive | Tape holds | Data rate (MB/s) | A tape (Hrs) | 10 GB (Hrs) | Tape drive cost ($)
<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Exabyte 8205</td>
<td>7 GB</td>
<td>0.5 MB/s</td>
<td>3.9</td>
<td>5.6</td>
<td>$1200</td>
</tr>
<tr>
<td>Exabyte 8900</td>
<td>20 GB</td>
<td>3.0</td>
<td>1.85</td>
<td>0.93</td>
<td>4500</td>
</tr>
<tr>
<td>DLT 4000</td>
<td>20 GB</td>
<td>1.5</td>
<td>3.70</td>
<td>1.85</td>
<td>4300</td>
</tr>
<tr>
<td>DLT 7000</td>
<td>35 GB</td>
<td>5.0</td>
<td>1.94</td>
<td>0.56</td>
<td>7000</td>
</tr>
</tbody>
</table>

4. What is the cost to copy a tape?

We saw in Table 2 that a tape with 10 GB or more can be copied in 2 or 3 hours. Since this can be done on a low cost workstation, does it really need to cost users $10,000 or more to obtain a copy of 10 Gbytes? If a data center charges $1000 to copy one Gbyte of data then the cost for a user is $10,000. This is a lot of money to charge to prepare a copy of one tape.

<table>
<thead>
<tr>
<th>Data charges for 1 Gbyte</th>
<th>Cost to obtain 10 Gbytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2000</td>
<td>$20,000</td>
</tr>
<tr>
<td>$1000</td>
<td>$10,000</td>
</tr>
<tr>
<td>$500</td>
<td>$5,000</td>
</tr>
<tr>
<td>$50</td>
<td>$500</td>
</tr>
</tbody>
</table>

It is possible to use the capability of technology to sharply reduce typical prices to send large datasets.

5. What is the effort and cost to move one Tbyte?

- It is best to use tapes
- Copy about 40 tapes to move one Tbyte
- It will take 2 to 4 hours to copy each tape
- The media costs are about $3000 per Tbyte of data
- These tapes are small in size

6. The user will need some helpful software

- To select certain files from a tape
- To select part of the records from a file, during input
- To help unpack the format
- To help input the data to some common display tools
COST OF MEDIA PER TBYTE
(FOR ONE COPY OF DATA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Type</th>
<th>Media</th>
<th>Media Cost/TB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>IBM 3480</td>
<td>$7</td>
<td>$35,000</td>
</tr>
<tr>
<td>1996</td>
<td>DLT or Exb</td>
<td>$90</td>
<td>$4,500</td>
</tr>
<tr>
<td>2000</td>
<td>DLT or Exb</td>
<td>est. $90</td>
<td>$900</td>
</tr>
</tbody>
</table>

MEDIA FOR NEWER BIG SYSTEMS

<table>
<thead>
<tr>
<th>Year</th>
<th>Type</th>
<th>Hold</th>
<th>Media</th>
<th>Media Cost/TB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>IBM</td>
<td>20 GB*</td>
<td>$50</td>
<td>$2,500</td>
</tr>
<tr>
<td>1997</td>
<td>STC**</td>
<td>50 GB</td>
<td>$50</td>
<td>$1,000</td>
</tr>
<tr>
<td>2004</td>
<td>Same</td>
<td>e400 GB</td>
<td>$60</td>
<td>$150</td>
</tr>
</tbody>
</table>

*available ~Nov 98

DATA HELD BY A SILO
(A SILO HOLDS 5000 TAPES)

<table>
<thead>
<tr>
<th>Year</th>
<th>Each</th>
<th>Total Silo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>175 MB</td>
<td>0.87 TB</td>
</tr>
<tr>
<td>1990</td>
<td>~400 MB</td>
<td>2.0 TB</td>
</tr>
<tr>
<td>~1995</td>
<td>~900 MB</td>
<td>5 TB</td>
</tr>
<tr>
<td>1997</td>
<td>50 GB</td>
<td>275 TB</td>
</tr>
<tr>
<td>2004</td>
<td>400 GB</td>
<td>2200 TB</td>
</tr>
</tbody>
</table>

Sep 1998