Astrophysics with Terabytes

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Living in an Exponential World

- Astronomers have a few hundred TB now
  - 1 pixel (byte) / sq arc second ~ 4TB
  - Multi-spectral, temporal, … _1PB

- They mine it looking for
  new (kinds of) objects or
more of interesting ones (quasars),
density variations in 400-D space
correlations in 400-D space

- Data doubles every year
The Challenges

Exponential data growth:
Distributed collections
Soon Petabytes

New analysis paradigm:
Data federations,
Move analysis to data

New publishing paradigm:
Scientists are publishers
and Curators
Why Is Astronomy Special?

• Especially attractive for the wide public
• Community is not very large
• It has no commercial value
  – No privacy concerns, freely share results with others
  – Great for experimenting with algorithms
• It is real and well documented
  – High-dimensional (with confidence intervals)
  – Spatial, temporal
• Diverse and distributed
  – Many different instruments from
    many different places and
    many different times
• The questions are interesting
• There is a lot of it (soon petabytes)
The Virtual Observatory

• Premise: most data is (or could be online)
• The Internet is the world’s best telescope:
  – *It has data on every part of the sky*
  – *In every measured spectral band: optical, x-ray, radio..*
  – *As deep as the best instruments (2 years ago).*
  – *It is up when you are up*
  – *The “seeing” is always great*
  – *It’s a smart telescope: links objects and data to literature on them*

• Software became the capital expense
  – *Share, standardize, reuse..*
<table>
<thead>
<tr>
<th>Spectrum Services</th>
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<tr>
<td>Search, plot, and retrieve SDSS, 2dF, and other spectra</td>
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The Spectrum Services web site is dedicated to spectrum related VO services. On this site you will find tools and tutorials on how to access close to 500,000 spectra from the Sloan Digital Sky Survey (SDSS DR1) and the 2 degree Field redshift survey (2dFGRS). The services are open to everyone to publish their own spectra in the same framework. Reading the tutorials on XML Web Services, you can learn how to integrate the 45 GB spectrum and passband database with your programs with few lines of code.
The SkyServer Experience

- Sloan Digital Sky Survey
- About 500 attributes per "object" with 400M objects
- Spectra for 1M objects
- Currently 2.4TB fully public
- Prototype eScience lab
  - Moving analysis to the data
  - Fast searches: color, spatial
- Visual tools
  - Join pixels with objects
- Prototype in data publishing
  - 160 million web hits in 5 years

http://skysserver.sdss.org/
Database Challenges

- Loading the Data
- Organizing the Data
- Accessing the Data
- Delivering the Data
- Analyzing the Data (spatial…)

• Wrote automated table driven workflow system for loading
  – Two-phase parallel load
  – Over 16K lines of SQL code, mostly data validation

• Loading process was extremely painful
  – Lack of systems engineering for the pipelines
  – Lots of foreign key mismatches
  – Fixing corrupted files (RAID5 disk errors)
  – Most of the time spent on scrubbing data

• Once data is clean, everything loads in 1 week
• Reorganization of data is about 1 week
Data Delivery

- **Small requests (<100MB)**
  - Anonymous, putting data on the stream
- **Medium requests (<1GB)**
  - Queues with resource limits
- **Large requests (>1GB)**
  - Save data in scratch area and use asynch delivery
  - Only practical for large/long queries
- **Iterative requests/workbench**
  - Save data in temp tables in user space
  - Let user manipulate via web browser
- **Paradox:** if we use web browser to submit, users want immediate response even from large queries
Data Organization

- Jim Gray: 20 queries, now 35 queries
- Represent most typical access patterns
- Establishes a clean set of requirements that both sides can understand
- Also used a regression test during development
- Dual star-schema centered on photometric objects
- Rich metadata information stored with schema
MyDB: Workbench

- Need to register ‘power users’, with their own DB
- Query output goes to ‘MyDB’
- Can be joined with source database
- Results are materialized from MyDB upon request
- Users can do:
  - Insert, Drop, Create, Select Into, Functions, Procedures
  - Publish their tables to a group area
- Data delivery via the CASJobs (C# WS)

=> Sending analysis to the data!
Public Data Release: Versions

- June 2001: EDR
  - *Early Data Release*
- July 2003: DR1
  - *Contains 30% of final data*
  - *150 million photo objects*
- 3 versions of the data
  - *Target, Best, Runs*
- Total catalog volume 5TB
- Published releases served ‘forever’
  - *EDR, DR1, DR2, ….*, soon DR5
  - *Personal (1GB), Professional (100GB) subsets*
  - *Next: include email archives, annotations*
- $O(N^2)$ – only possible because of Moore’s Law!
Mirroring

• Master copies kept at 2 sites
  – *Fermilab, JHU*: 3 copies of everything running in parallel
  – *Necessary due to cheap hardware*

• Multiple mirrors for DR2, DR3
  – *Microsoft has multiple copies*
  – *Japan, China, India, Germany, UK, Australia, Hungary, Brazil*

• Replication
  – *First via Sneakernet, 3 boxes with 1TB of disks*
  – *Now: distributed from StarTap at UIC, using the UDT protocol (Grossman et al)*
  – *Transferred 1TB to Tokyo in about 2.2 hours*
Web Interface

- Provide easy, visual access to exciting new data
  - *Access based on web services*
- Illustrate that advanced content does not mean a cumbersome interface
- Understand new ways of publishing scientific data
- Target audience
  - *Advanced high-school students, amateur astronomers, wide public, professional astronomers*
- Multilingual capabilities built in from the start
  - *Heavy use of stylesheets, language branches*
- First version built by AS+JG, later redesigned by Curtis Wong, Microsoft
Tutorials and Guides

• Developed by J. Raddick and Postdocs
  – How to use Excel
  – How to use a database (guide to SQL)
  – Expert advice on SQL
• Automated on-line documentation
  – Ani Thakar, Roy Gal
  – Database information, Glossary, Algorithms
  – Searchable Help
  – All stored in the DB, and generated
  – DB schema and metadata (documented from a single source, parsed differently)
• Templated for others, widely used
  – Now also for sensor networks
Visual Tools

• Goal:
  – Connect pixel space to objects without typing queries
  – Browser interface, using common paradigm (MapQuest)

• Challenge:
  – Images: 200K x 2K x 1.5K resolution x 5 colors = 3 Terapix
  – 300M objects with complex properties
  – 20K geometric boundaries and about 6M ‘masks’
  – Need large dynamic range of scales (2^13)

• Assembled from a few building blocks:
  – Image Cutout SOAP Web Service
  – SQL query service + database
  – Images+overlays built on server side -> simple client
Spatial Information for Users

- What resources are in this part of the sky?
- What is the common area of these surveys?
- Is this point in the survey?
- Give me all objects in this region
- Give me all “good” objects (not in bad areas)
- Cross-matching these two catalogs
- Give me the cumulative counts over areas
- Compute fast spherical transforms of densities
- Interpolate sparsely sampled functions (extinction maps, dust temperature, …)
• SDSS has lots of complex boundaries
  – 20,000 regions
  – 6M masks (bright stars, satellites, etc), represented as spherical polygons
• A GIS-like library built in C++ and SQL
• Now converted to C# for direct plugin into SQL Server 2005 (17 times faster than C++)
• Precompute arcs and store in database for rendering
• Functions for point in polygon, intersecting polygons, polygons covering points, all points in polygon
• Fast searches using spherical quadtrees (HTM)
• Visualization integrated with web services
Things Can Get Complex

Green areas: A→ (E₃) should find B if it contains an A and not masked.

Yellow areas: A → (E₃→) is an edge case may find B if it contains an A.
Indexing Using Quadtrees

- Cover the sky with hierarchical pixels
- COBE – start with a cube
- Hierarchical Triangular Mesh (HTM) uses trixels
  - Samet, Fekete
- Start with an octahedron, and split each triangle into 4 children, down to 20 levels deep
- Smallest triangles are 0.3”
- Each trixel has a unique htmID
So triangles correspond to ranges. All points inside the triangle are inside the range.
Comparing Massive Point Datasets

- Want to “cross match” $10^9$ objects with another set of $10^9$ objects
- Using the HTM code, that is a LOT of calls ($\sim 10^6$ seconds ~ a year)
- Want to do it in an hour
- Added 10 databases running in parallel and a bulk algorithms based on ‘zones’
## Trends

### CMB Surveys
- 1990 COBE: 1000
- 2000 Boomerang: 10,000
- 2002 CBI: 50,000
- 2003 WMAP: 1 Million
- 2008 Planck: 10 Million

### Angular Galaxy Surveys
- 1970 Lick: 1M
- 1990 APM: 2M
- 2005 SDSS: 200M
- 2008 VISTA: 1000M
- 2012 LSST: 3000M

### Time Domain
- QUEST
- SDSS Extension survey
- Dark Energy Camera
- PanStarrs
- SNAP...
- LSST...

### Galaxy Redshift Surveys
- 1986 CfA: 3500
- 1996 LCRS: 23000
- 2003 2dF: 250000
- 2005 SDSS: 750000

Petabytes/year by the end of the decade…
Data reside in multiple databases
Applications access data dynamically
Typical data set sizes in millions to billions
Typical dimensionality 3-10
Attributes are correlated in a non-linear fashion
One cannot assume a global metric
Data have non-negligible error
Current examples:
  - 2-3 point angular correlations of about 10 million galaxies
  - 3D power spectrum of about 1 million galaxy distances
  - Image shear due to gravitational lensing in 2.5 Terapixels
  - Compare 1 million galaxy spectra to 100M model spectra
Next-Generation Data Analysis

- Looking for
  - Needles in haystacks – the Higgs particle
  - Haystacks: Dark matter, Dark energy
- Needles are easier than haystacks
- ‘Optimal’ statistics have poor scaling
  - Correlation functions are $N^2$, likelihood techniques $N^3$
  - For large data sets main errors are not statistical
- As data and computers grow with Moore’s Law, we can only keep up with $N \log N$
- A way out?
  - Discard notion of optimal (data is fuzzy, answers are approximate)
  - Don’t assume infinite computational resources or memory
- Requires combination of statistics & computer science
Working with Simulations

- Galaxy Formation Simulations
  - Collaboration with V. Springel, S. White and G. Lemson
  - Loading the ‘Millennium’ galaxies/halos into a database, build Peano-Hilbert curve spatial index
  - 20 queries: focused on merger history of halos
  - Semi-analytic star formation: linkage with population synthesis models

- Statistical studies (with Jie Wang)
  - 50 separate realizations of the large scale structure in Millennium
  - Analyzing non-Gaussian signatures on large scales (PDF, 4th moments)
  - Currently loading these into the DB for analysis of nonlinearities on large scales

- Next: build fast ray tracing algorithms along light cone inside the DB
Simulation of Turbulence

- Collaboration with C. Meneveau, S. Chen, G. Eyink, R. Burns and E. Vishniac
  - Take a $1024^3$ simulation and store 1024 timesteps in a database
  - Use hierarchical Peano-Hilbert curve index within each time step, atoms are $64^3$ cells
  - Database is tens of TB => build a cluster of cheap servers
  - Currently 100TB in place, loader works
  - Implementing low-level analysis tools inside DB
  - Interpolation schemes done, FFTW ported
  - Cheap disks => redundant data storage in dual space
• Collaboration with K. Szlavecz, A. Terzis, J. Gray, S. Ozer
  – *Building 200 node network to measure soil moisture for environmental monitoring*
  – *Expect 200 million measurements /yr*
  – *Deriving from the SkyServer template we were able to build and end-to-end system in less than two weeks*
  – *Built a OLAP datacube, conditional sums along multiple dimensional axes*
Summary

• Data growing exponentially
• Analyzing so much data requires a new model
• More data coming: Petabytes/year by 2010
  – Need scalable solutions
  – Move analysis to the data
  – Spatial and temporal features essential
  – 20 queries!
• Same thing happening in all sciences
  – High energy physics, genomics, cancer research, medical imaging, oceanography, remote sensing, …
• eScience: an emerging new branch of science