Part 10. Databases

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EXPLORING TERABYTE ARCHIVES IN ASTRONOMY

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1. Introduction

Astronomy is about to undergo a major paradigm shift, with data sets becoming larger, and more homogeneous, for the first time designed in the top-down fashion. In a few years it may be much easier to "dial-up" a part of the sky, when we need a rapid observation than wait for several months to access a (sometimes quite small) telescope. With several projects in multiple wavelengths under way, like the SDSS, 2MASS, GSC-2, POSS2, ROSAT, FIRST and DENIS projects, each surveying a large fraction of the sky, the concept of having a "Digital Sky," with multiple, TB size databases interoperating in a seamless fashion is no longer an outlandish idea. More and more catalogs will be added and linked to the existing ones, query engines will become more sophisticated, and astronomers will have to be just as familiar with mining data as with observing on telescopes.

The Sloan Digital Sky Survey, hereafter the SDSS, is a project to digitally map about 1/2 of the Northern sky in five filter bands from UV to the near IR, and is expected to detect over 200 million objects in this area. Simultaneously, redshifts will be measured for the brightest 1 million galaxies. The SDSS will revolutionize the field of astronomy, increasing the amount of information available to researchers by several orders of magnitude. The resultant archive that will be used for scientific research will be large (exceeding several Terabytes) and complex: textual information, derived parameters, multi-band images, and spectra. The catalog will allow astronomers to study the evolution of the universe in greater detail and is intended to serve as the standard reference for the next several decades. As a result, we felt the need to provide an archival system that would simplify the process of "data mining" and shield researchers from any underlying complex architecture. In our efforts, we have invested a considerable amount of time and energy in understanding how large, complex data sets can be explored.

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2. Accessing Terabytes of Data

2.1. GENERAL CONSIDERATIONS

Today's approaches to accessing astronomical data do not scale into the Terabyte regime—brute force does not work! Assume a hypothetical 500 GB data set. The most popular data access technique today is the World Wide Web. Most universities can receive data at the bandwidth of about 15 kbytes/sec. The transfer time for this data set would be 1 year! If the data is residing locally within the building (access via Ethernet at 1 Mbytes/sec), the transfer time drops to 1 week. If the astronomer is logged on to the machine which contains the data, all of it on hard disk, then with SCSI bandwidth it still takes 1 day to scan through the data. Even faster hardware cannot support hundreds of "brute force" queries per day. With Terabyte catalogs, even small custom datasets are in the 10 GB range, thus a high level data management is needed. In order to identify possible solutions we need to look at how the archives will be used.

2.1.1. *Who Will Be Using the Archives?*

One can identify three major classes of users. *Power users* are the most sophisticated, with a lot of resources, whose research is centered around the archive. They spend a large fraction of their time querying the archive or performing a lot of small scale exploratory tests, before launching a moderate number of very intensive queries. These are mostly statistical in nature, with a large output volume. *The general astronomy public* will most likely do frequent but casual lookup of certain objects or regions. The archives help their research but the research is not statistical. This class of users will perform a very large number of small queries, which include a lot of cross-identification requests. *The wide public* will be an important component as they can browse a virtual telescope. This usage of the large archives can have an enormous public appeal, but it also needs special packaging. This could amount to an extremely large number of simple requests.

2.1.2. *How Will the Data Be Analysed?*

The data is inherently multidimensional, each object is represented by several fluxes, position on the sky, size, redshift, *etc.* Searching for special categories of objects, like quasars, involves defining complex domains in this N-dimensional space. Spatial relations will be investigated, like finding nearest neighbours, or other objects satisfying a given criterion within an angular distance. The output size of the objects satisfying a given query can be so large that intermediate files simply cannot be created. The only

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way to analyze such data sets is to send them directly into analysis tools, thus these will have to be linked to the archive itself.

2.2. TYPICAL QUERIES

We expect that most of the queries will be of exploratory nature, no two queries will be exactly alike, at least for a while. Generally, scientists will try to explore the multi-color properties of the objects in the SDSS catalog, starting with small queries of limited scope, then gradually making their queries more complex on a hit-and-miss basis. Several typical types of activities need to be supported: manual browsing, where one would look at objects in the same general area of the sky, and manually/interactively explore their individual properties, the creation of sweeping searches with complex constraints, which extend to a major part of the sky, searches based upon angular separations between objects on the sky, cross-identifications with external catalogs, creating personal subsets, and creating new "official" data products.

2.3. THE MAIN PROBLEM: SWEEPING SEARCHES

2.3.1. *Geometric Indexing*

At this point we can identify the main problem in searching such archives: fast, indexed, but complex searches of Terabytes in k-dimensional space, with the added complexity that constraints are not necessarily parallel to the axes. This means that the traditional indexing techniques well established with relational databases will not work, since we cannot build an index on all concievable linear combinations of five or more attributes. On the other hand, one can use the fact that the data are very geometric in nature, every object is a point in this k-dimensional space. One can quantize the data into containers. Each container has objects of similar colors, from the same region of the sky. These containers represent a coarse grained density map of the data, and enable us to build a multidimensional index tree which can tell us which containers are fully inside, or outside our query, and which ones are partially contained. Only these latter containers have to be searched through, while the other two categories can either be accepted or rejected in full. If the containers are stored physically together, the cache efficiency in the retrieval will be very high—if an object satisfies our query, it is likely that most of its "friends" will as well.

2.3.2. *The Organization of Searches*

Most of the queries, at least the part which is on sky positions and colors, is inherently geometric. The simplest, primitive constraint is a half-space, one side of a multi-dimensional hyperplane. The Boolean combinations of

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these half-spaces are allowed, in such a way the queries are represented by k-dimensional polyhedra. First these queries are evaluated against the coarse-grained map, represented in the form of a tree structure, the so called k-d tree, and intersections are determined. From these intersections the time necessary to perform the query and the total output volume can be predicted. At the same time a list of containers is created, which needs to be searched for the actual data. At this point all the containers not intersecting with the query can be discarded, without ever touching the data itself. This can yield very substantial perfomance gains. Next, this list of containers is sent to the database for the final search, which is done in a quantized, container-by-container fashion. The actual searches can thus be also evaluated in parallel, if there is adequate hardware available.

3. A Case Study: The Sloan Digital Sky Survey Archive

3.1. THE SDSS

The Sloan Digital Sky Survey (SDSS) is a collaboration between the University of Chicago, Princeton University, the Johns Hopkins University, the University of Washington, Fermi National Accelerator Laboratory, the Japanese Promotion Group, the United States Naval Observatory, and the Institute for Advanced Study, Princeton, with additional funding provided by the Sloan Foundation and the National Science Foundation. In order to perform the observations, a dedicated 2.5 meter Ritchey-Chretien telescope was constructed at Apache Point, New Mexico, USA. This telescope is designed to have a large, flat focal plane which provides a 3° field of view. This design results from an attempt to balance the areal coverage of the instrument against the detector's pixel resolution.

The survey has two main components: a photometric survey, and a spectroscopic survey. The photometric survey is produced by drift scan imaging of 10,000 square degrees centered on the North Galactic Cap using five broad-band filters that range from the ultraviolet to the infrared. The photometric imaging will use an array that consists of 30 2K × 2K imaging CCDs, 22 2K × 400 astrometric CCDs, and 2 2K × 400 Focus CCDs. The data rate from this camera will exceed 8 Megabytes per second, and the total amount of raw data will exceed 40TB. The spectroscopic survey will target over a million objects chosen from the photometric survey in an attempt to produce a statistically uniform sample. This survey will utilize two multi-fiber medium resolution spectrographs, with a total of 640 optical fibers, $3''$ in diameter each, that provide spectral coverage from 3900–9200 Å. The telescope will gather about 5000 galaxy spectra in one night. The total number of spectra known to astronomers today is about 50,000—only 10 days of SDSS data! Whenever the Northern Galactic cap is not

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accessible from the telescope site, a complementary survey will repeatedly image several areas in the Southern Galactic cap to study fainter objects and identify any variable sources.

3.2. THE DATA PRODUCTS

The SDSS will create four main data sets: a photometric catalog, a spectroscopic catalog, images, and spectra. The photometric catalog is expected to contain one hundred million galaxies, one hundred million stars, and one million quasars, with magnitudes, profiles, and observational information recorded in the archive. The anticipated size of this product is about 250GB. Each detected object will also have an associated image cutout ("atlas image") for each of the five filters, adding up to about 700GB. The spectroscopic catalog will contain identified emission and absorption lines, and one dimensional spectra for one million galaxies, one hundred thousand stars, one hundred thousand quasars, and about ten thousand clusters, totaling about 50GB. In addition, derived custom catalogs may be included, such as a photometric cluster catalog, or QSO absorption line catalog. Thus the amount of tracked information in these products is about 1TB.

The collaboration will release the data to the public after an initial verification period. The actual distribution method is still under discussion. This public archive is expected to remain the standard reference catalog for the next several decades, presenting additional design and legacy problems. Furthermore, the design of the SDSS science archive must allow for the archive to grow beyond the actual completion of the survey. As the reference astronomical data set, each subsequent astronomical survey will want to cross-identify its objects with the SDSS catalog, requiring that the archive, or at least a part of it be dynamic.

3.3. THE SDSS ARCHIVES

The survey archive is split into two orthogonal functionalities and the corresponding distinct components: an *operational archive*, where the raw data is reduced and mission critical information is stored; and the *science archive*, where calibrated data is available to the collaboration for analysis and is optimized for such queries. In the operational archive data is reduced, but uncalibrated, since the calibration data is not necessarily taken at the same time as the observations. Calibrations will be provided on the fly, via method functions, and several versions will be accessible. The Science Archive will contain only calibrated data, reorganized for efficient science use, using as much data clustering as possible. If a major revision of the calibrations is necessary, the Science Archive and its replications will

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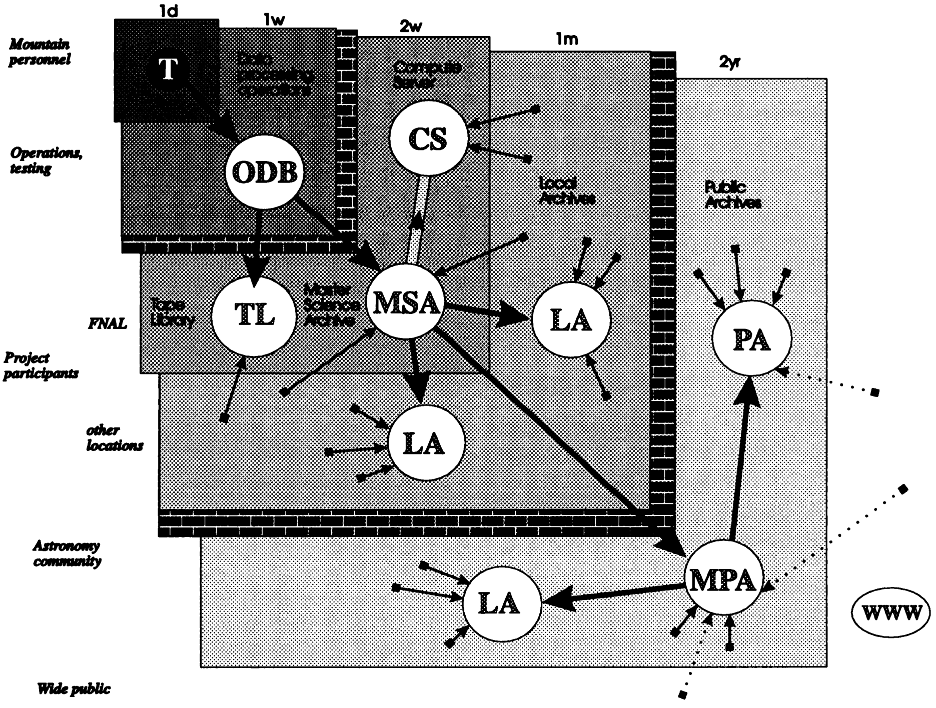

Figure 1. A conceptual data-flow diagram of the SDSS data. The data is taken at the telescope (T), and is shipped on tapes to FNAL, where it is processed within one week, and ingested into the operational archive (ODB), protected by a firewall, accessible only the personnel working on the data processing. Within two weeks, data will be transferred into the Master Science Archive (MSA). From there data will be replicated to local archives (LA) within another two weeks. The data gets into the public domain (MPA, LA) after two years of science verification, and recalibration, if necessary. These servers will provide data for the astronomy community. We will also provide a WWW based access for the wide public, to be defined in the near future.

have to be regenerated from the ODB. At any time the Master Science Archive (see Figure 1) will be the standard to be verified against.

High level requirements for the archive included (a) easy transfer of the binary database image from one architecture to another, (b) easy multi-platform availability and interoperability, (c) easy maintainance for future operating systems and platforms. In order to satisfy these, the Science Archive employs a three-tiered architecture: the user interface, the query support component, and the data warehouse. This distributed approach

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provides maximum flexibility, while maintaining portability, by isolating hardware specific features. The data warehouse, where most of the low-level I/O access happens, is based upon an OODBMS (Objectivity/DB), where the porting issues depend mainly on the database vendor. Objectivity's database image is binary compatible, can be copied between different platforms, since the architecture is encoded on every page in the archive.

4. Summary

We are in the middle of designing and constructing an extremely ambitious archival system, aiming to provide a useful tool for almost all astronomers in the world. We hope that our efforts will be successful, and the resulting system will substantially change the way scientists do astronomy today. The day when we have a "Digital Sky" at our desktop may be nearer than most astronomers think. Given the enormous public interest in astronomy, we hope that the resulting archive will also provide a challenge and inspiration to thousands of interested high-school students, and a lot of fun for the web-surfing public. To serve a TB archive even to the scientific community is quite a challenge today. To offer it to the wide public will be a task that we have not even started to appreciate. We hope that the pace of current hardware and software technologies in the area of large object databases will accelerate even further, and integration of applets into the standard set of scientific data analysis tools will soon begin. We are very excited to be at the front line when all this is happening, and we are quite convinced that this effort would have been orders of magnitude harder, if not impossible without our total reliance on object oriented databases, and object technology in general. We feel that the technology has matured to the point when it provides real solutions to real problems.

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